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AEC RESEARCH AND DEVELOPMENT REPORT

SAVANNAH RIVER LABORATORY COBALT-60 POWER AND HEAT SOURCES

QUARTERLY PROGRESS REPORT

APRIL - JUNE 1970

DU PONT
REG. U. S. PAT. OFF.

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April - June 1970

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August 1970

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AIKEN, S. C. 29801

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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

Rhenium and tungsten-25% rhenium capsules for long-term heating tests have been TIG-welded satisfactorily. Most tungsten welds still are not crack-free. (p 1)

Destructive examination of radioactive capsules heated for up to 10,000 hr at up to 1000°C was postponed until next quarter. (p 9)

A project was approved and design work begun on vacuum furnaces and other equipment for the new shielded ^{60}Co capsule test facility. (p 10)

Temperature excursions in simple ^{60}Co heat sources during some fire and burial conditions were calculated. Testing under these conditions is being planned. (p 10)

"Haynes" 188 was proposed as the outer capsule material for the 30 kw(t) demonstration unit, based on oxidation and compatibility tests at SRL. (p 14)

The two highest power ^{60}Co capsules ever made were fabricated to fuel the 3 kw(t) demonstration test with thermoelectric power conversion. (p 26)

Much of the ^{60}Co produced to date in control rods of ^{252}Cf-producing charges contains over 500 Ci/g of cobalt. This material is available to private industry for research and development on thermal applications, under the AEC's ^{60}Co loan program. (p 28)

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. Development of specific heat source concepts is not at present included in the scope of the SRL program.

MATERIALS TECHNOLOGY AND DEVELOPMENT

CAPSULE FABRICATION AND TESTING

Welding of Refractory Metal Capsules

Welding techniques for test capsules of tungsten, rhenium, and tungsten-25 wt % rhenium (W-25 Re) are being developed. Cracking of welds made in tungsten capsules has not been eliminated, but W-25 Re capsules are now being welded satisfactorily. Most welds in rhenium capsules have been satisfactory, but defects in the capsule material have caused difficulties in fabricating capsules for compatibility tests.

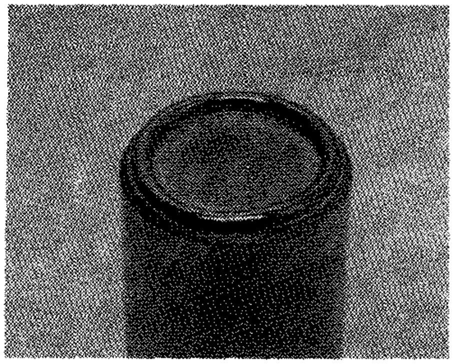
Tungsten

Destructive examination of ten tungsten welds, Figure 1a, revealed cracking in all welds. Control of the welding atmosphere, cooling of the cap during welding, and high welding speeds helped minimize cracking but did not eliminate it. No cracks penetrated the capsule wall in any capsules welded at the higher speed (45 in./min) with cooling of the cap. However, the short cracks observed by metallographic examination may propagate through the weld during later thermal cycling. Cross sections of welds, Figure 1b, show the weld configuration and intergranular nature of cracks.

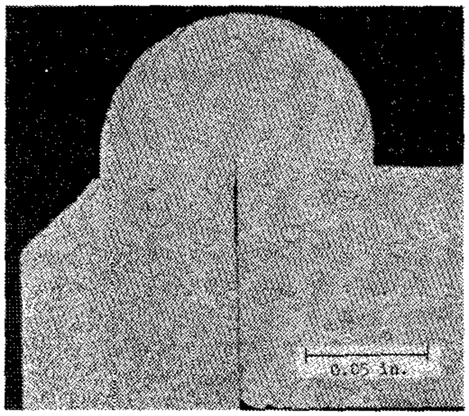
Tungsten-25 wt % Rhenium

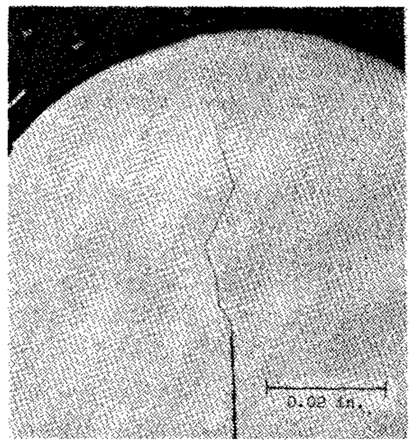
Four additional welds in W-25 Re capsules were made and evaluated. Nondestructive testing showed no leaks in any of the welds. No cracks were found in two of the welds, and only minor cracks in the other two. Typical configurations are shown in Figure 1c. Helium cooling of the cap, stress relief after welding, and several different welding currents were used to establish optimum conditions for welding.

Eight W-25 Re capsules for compatibility tests were welded using the conditions developed for those welds that had no cracks. Each capsule contains eleven cobalt metal wafers and one W-25 Re spacer. Nondestructive tests showed all capsules to be leak-tight. Capsules were helium leak tested, bubble tested, and heated to 1200°C for 1-1/2 hr. After heating they were again helium leak tested. No leaks were detected.



a) Capsule Weld

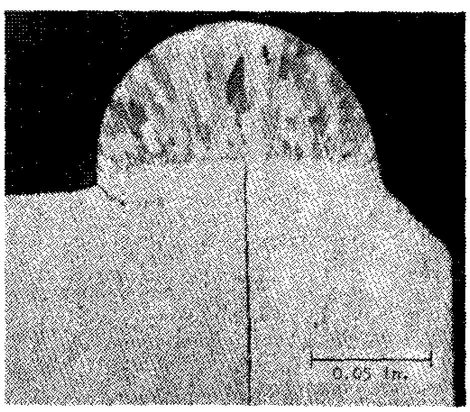


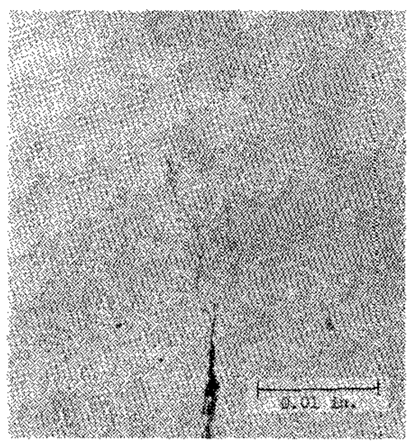


low magnification - crack free

high magnification - cracked

b) Tungsten - Cross Sections





low magnification - small crack

high magnification - small crack

c) Tungsten-25 wt % Rhenium - Cross Sections

FIGURE 1. WELDS IN TUNGSTEN AND TUNGSTEN-25 wt % RHENIUM CAPSULES

Rhenium

Two small (0.5-in.-dia x 0.5-in.-long) rhenium capsules were welded for metallographic evaluation prior to fabrication of capsules for long-term compatibility tests. Some porosity was observed in the welds, but they were otherwise sound. No leaks were observed in the welds by nondestructive test methods. One end of one capsule had a leak near the center of the cap. Microscopic examination revealed cracks in the cap material.

Eighteen rhenium capsules containing either CoO, $Co_{0.5}Mg_{0.5}O$, or $CoAl_2O_4$ were fabricated for exposures of either 1000 or 5000 hr at 1500, 1700, or 1850°C to measure the compatibility between rhenium and the oxides, Table I. Leaks, such as the one observed in the center of the cap of one rhenium weld-development capsule, were discovered in 12 of the capsules. Leaks were discovered initially by the helium leak test or bubble test. Running a weld bead around the center of the caps was partially successful in sealing the capsules. Six of the twelve leaking capsules were sealed by this method. The six rejects will be replaced with new capsules.

All satisfactory capsules were cycled to the test temperature for one hour and again helium leak tested and bubble tested. Three additional capsules were found to be leaking in the welded region, and will be rewelded or replaced.

Electron Beam Welds

Two tungsten capsules and two W-25 Re capsules were electron beam (EB) welded as an alternative to tungsten-inert-gas (TIG) welding. Leaks were detected in three of the capsules, leaving one W-25 Re capsule suitable for long-term compatibility testing.

TABLE I

^{59}Co HIGH TEMPERATURE FUELS COMPATIBILITY PROGRAM

Capsule Material and Temperature	Fuel Material	Heating			Remarks
		Time, hr	Startup	Termination	
		Preliminary Tests			
"Inconel" 600; foils of Ir, Rh, Re, Pt (1200°C)	$Co_{0.5}Mg_{0.5}O$	200	5/69	6/69	Oxide reduced by "Inconel" 600
"Inconel" 600; foils of Ir, Rh, Re, Pt (1200°C)	$Co_{0.5}Mg_{0.5}O$	500	6/69	7/69	Oxide reduced by "Inconel" 600
Rhenium (1525°C)	CoO	200	7/69	7/69	No detectable interaction
Rhenium (1525°C)	$Co_{0.5}Mg_{0.5}O$	200	7/69	7/69	No detectable interaction
Rhenium (1525°C)	$CoAl_2O_4$	200	7/69	7/69	No detectable interaction
Tungsten (1620°C)	CoO	260	12/69	12/69	Reaction
Tungsten (1620°C)	$CoAl_2O_4$	260	12/69	12/69	Reaction
TZM (1620°C)	CoO	260	12/69	12/69	Reaction
TZM (1620°C)	$Co_{0.5}Mg_{0.5}O$	260	12/69	12/69	Reaction
TZM (1620°C)	$CoAl_2O_4$	260	12/69	12/69	Reaction
"Inconel" 600 (1000°C)	CoO	1,000	7/70	9/70	Capsule fabricated
"Inconel" 600 (1000°C)	$Co_{0.5}Mg_{0.5}O$	1,000	7/70	9/70	Capsule fabricated
"Inconel" 600 (1000°C)	$CoAl_2O_4$	1,000	7/70	9/70	Capsule fabricated
		1500°C Tests			
Rhenium; foils of Ir, Rh	CoO	1,000	7/70	9/70	Capsule fabricated
Rhenium; foils of Ir, Rh	$Co_{0.5}Mg_{0.5}O$	1,000	10/70	12/70	
Rhenium; foils of Ir, Rh	$CoAl_2O_4$	1,000	7/70	9/70	Capsule fabricated
Rhenium; spacers of W-25 Re	CoO	1,000	10/70	12/70	
Rhenium; spacers of W-25 Re	$CoAl_2O_4$	1,000	10/70	12/70	
Rhenium	CoO	1,000	10/70	12/70	
Rhenium	$Co_{0.5}Mg_{0.5}O$	1,000	7/70	9/70	Capsule fabricated
Rhenium	$CoAl_2O_4$	1,000	7/70	9/70	Capsule fabricated
Rhenium	CoO	5,000	10/70	5/71	
Rhenium	$Co_{0.5}Mg_{0.5}O$	5,000	10/70	5/71	
Rhenium	$CoAl_2O_4$	5,000	10/70	5/71	
Rhenium	Best Oxide	10,000	10/70	12/71	Capsule ordered
Rhenium	Best Oxide	50,000	10/70	6/76	Capsule ordered
Iridium	CoO	1,000	10/70	12/70	
Iridium	$Co_{0.5}Mg_{0.5}O$	1,000	10/70	12/70	
Iridium	$CoAl_2O_4$	1,000	10/70	12/70	
		1700°C Tests			
Rhenium	CoO	1,000	10/70	12/70	
Rhenium	$Co_{0.5}Mg_{0.5}O$	1,000	7/70	9/70	Capsule fabricated
Rhenium	$CoAl_2O_4$	1,000	7/70	9/70	Capsule fabricated
Rhenium	CoO	5,000	10/70	5/71	
Rhenium	$Co_{0.5}Mg_{0.5}O$	5,000	10/70	5/71	Capsule machined
Rhenium	$CoAl_2O_4$	5,000	7/70	2/71	Capsule fabricated
Rhenium	Best Oxide	10,000	10/70	12/71	Capsule ordered
Rhenium	Best Oxide	50,000	10/70	7/76	Capsule ordered
Iridium	CoO	1,000	10/70	12/70	
Iridium	$Co_{0.5}Mg_{0.5}O$	1,000	10/70	12/70	
Iridium	$CoAl_2O_4$	1,000	10/70	12/70	
		1850°C Tests			
Rhenium	$Co_{0.5}Mg_{0.5}O$	1,000	7/70	9/70	Capsule fabricated
Rhenium	$CoAl_2O_4$	1,000	7/70	9/70	Capsule fabricated
Rhenium	$Co_{0.5}Mg_{0.5}O$	5,000	7/70	2/71	Capsule fabricated
Rhenium	$CoAl_2O_4$	5,000	7/70	2/71	Capsule fabricated
Rhenium	Best Oxide	10,000	10/70	12/71	Capsule ordered
Rhenium	Best Oxide	50,000	10/70	6/76	Capsule ordered
Iridium	$Co_{0.5}Mg_{0.5}O$	1,000	10/70	12/70	
Iridium	$CoAl_2O_4$	1,000	10/70	12/70	

Capsules for Compatibility Tests

Capsules were fabricated for the compatibility tests of CoO, $CoAl_2O_4$, and $Co_{0.5}Mg_{0.5}O$ with iridium, rhodium, rhenium, W-25 Re, and "Inconel"* 600 during 1000-hr exposures at 1500°C (1000°C for "Inconel" 600) described in Table I. Foils of iridium and rhodium were stacked alternately with oxide wafers and encapsulated in rhenium capsules. Compatibility of the oxides with W-25 Re will be determined by using spacers of W-25 Re in a rhenium capsule. Nondestructive examination of the capsules revealed leaks in the welds in one of the rhenium capsules containing the iridium and rhodium foils. The three "Inconel" 600 capsules and the other two rhenium capsules are leak tight and will be placed in test.

Heating Tests of Capsules with Unirradiated Cobalt Metal

Superalloy Capsules

Metallographic examination is nearly complete on the three capsules removed from test last quarter after 10,000 hr ("Haynes"** 25 at 850°C, "Inconel" 600 at 900°C, and "Inconel" 600 at 1000°C). There were no significant dimensional changes; in previous tests the diameters of "Haynes" 25 capsules increased 0.006 to 0.008 in. during heating for 10,000 hr at 1000°C. The depths affected by oxidation of the external surfaces of the three capsules were commensurate with previous tests. In contrast to previous tests, there was little bonding between the cobalt and the capsules in any of the three capsules.

One "Inconel" 600 capsule containing wafers contaminated with caustic residue attained its goal exposure of 10,000 hr at 900°C. The capsule was intact, as indicated by helium leak test. Metallographic examination is in progress.

Thirteen capsules remain in test, Table II. Four of these (two "Hastelloy"*** X, and one each of "Hastelloy" C and "Haynes" 25) will be removed from test during the next quarter after 20,000 hr at 1000°C. Goal exposures of the remaining capsules are 20,000 and 50,000 hr.

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* Trademark of International Nickel Co.

** Trademark of Union Carbide Corp.

*** Trademark of Union Carbide Corp.

TABLE II

Summary of ^{59}Co Capsule Heating Tests
All Co Metal Wafers 0.745-in. diameter

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	
	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	Examination in progress
	20,000	900	95	1	11-68	3-71	
	→ 10,000[e]	900	95	1	3-69	5-70	Examination in progress
	50,000	900	95	1	11-68	7-74	
	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	
	10,000[d]	1,000	95	1	11-68	1-70	Examination in progress
"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	
	20,000	1,000	95	1	5-68	9-70	
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	
"Haynes" 25 (m.p. 1330°C)	10,000	850	95	1	11-68	1-70	Examination in progress
	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
	50,000	1,000	95	1	10-67	6-73	
	20,000	1,000	95	1	5-68	9-70	
"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	
	20,000	1,000	95	2	5-68	9-70	

[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.
→ New information reported.

Refractory Metal Capsules

Heating tests for up to 10,000 hr at 1200 and 1400°C will be started shortly with nine capsules of W-25 Re, Table III. Eight of the capsules were sealed by TIG welding and one by EB welding; no leaks were detected by bubble tests or helium-leak tests. The 1000-hr tests will be completed in the coming quarter.

Heating tests for up to 10,000 hr at 1200°C are expected to be started during the coming quarter with five capsules of pure tungsten sealed by TIG welding, Table III.

TABLE III

Summary of Planned ^{59}Co-Refractory Metal Capsule Heating Tests[a]

Capsule Material	Heating Time, hr	Heating Temp, °C	Approx. Starting Date	Approx. Completion Date	Wafer Diameter, inch	Welding Technique
Tungsten	1,000	1200	9-70	11-70	0.745	TIG
	1,000	1200	9-70	11-70	0.745	TIG
	5,000	1200	9-70	4-71	0.745	TIG
	5,000	1200	9-70	4-71	0.745	TIG
	5,000	1200	1-71	8-71	1.490	TIG
	5,000	1200	10-70	5-71	0.745	EB
	10,000[b]	1200	9-70	11-71[b]	0.745	TIG
	10,000[b]	1200	10-70	12-71[b]	0.745	TIG
	10,000[b]	1200	1-71	3-72[b]	1.490	TIG
	10,000[b]	1200	1-71	3-72[b]	1.490	TIG
	10,000	1200	10-70	12-71	0.745	EB
	50,000	1200	10-70	7-76	0.745	TIG
Rhenium	1,000	1200	11-70	1-71	0.745	TIG
	5,000	1200	11-70	6-71	0.745	TIG
	5,000	1200	11-70	6-71	0.745	EB
	10,000[b]	1200	11-70	1-72[b]	0.745	TIG
	10,000[b]	1200	11-70	1-72[b]	0.745	TIG
	10,000	1200	11-70	1-72	0.745	EB
	50,000	1200	11-70	8-76	0.745	TIG
	1,000	1400	11-70	1-71	0.745	TIG
	5,000	1400	11-70	6-71	0.745	TIG
	10,000	1400	11-70	1-72	0.745	TIG
W-25 wt % Re	1,000	1200	8-70	10-70	0.745	TIG
	5,000	1200	8-70	3-71	0.745	TIG
	5,000	1200	8-70	3-71	0.745	EB
	10,000[b]	1200	8-70	10-71[b]	0.745	TIG
	10,000[b]	1200	8-70	10-71[b]	0.745	TIG
	10,000	1200	10-70	12-71	0.745	TIG
	50,000	1200	8-70	5-76	0.745	TIG
	1,000	1400	8-70	10-70	0.745	TIG
	5,000	1400	8-70	3-71	0.745	TIG
	10,000	1400	8-70	10-71	0.745	TIG

a. One capsule containing ~10 Co wafers 0.073-in.-thick and one 0.060-in.-thick spacer will be heated at each listed condition.

b. Test time may be extended to 20,000 hr, or more, depending on results of other 10,000-hr tests.

Heating tests of rhenium capsules will not be started until November, pending delivery of the capsules by the vendor.

Heating Tests of Capsules with Radioactive Cobalt Metal

Superalloy Capsules

Eleven capsules removed from test in 1969 after 5000 and 10,000 hr at 900 and 1000°C are being stored in the High Level Caves (HLC). The examination of these capsules has been delayed until the coming quarter because the HLC metallographic facility was required for the examination of other items.

Nine capsules remain under test at 900 and 1000°C for 20,000 to 50,000 hr, Table IV.

TABLE IV

Summary of ^{60}Co Capsule Heating Tests

All Co metal wafers 0.745-in. diameter

Capsule Material	Heating		Wall, mils	No. of Capsules	Activity		Approx. Starting Date	Approx. Completion Date	Remarks
	Time, hr	Temp, °C			Spec, Ci/g	Total, Ci			
"Inconel" 600 (m.p. 1370°)	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
	10,000	~900	50	1	150[b]	9,000	5-67	10-68	Increased Co/capsule reaction
	10,000	900	95	1	255[c]	36,500	2-68	8-69	Begin destructive examination 8-70
	20,000	900	95	1	288[c]	13,700	7-68	10-70	
	50,000	900	95	1	282[c]	13,400	7-68	3-74	
	5,000	1,000	95	1	295[c]	14,000	9-68	4-69	Begin destructive examination 8-70
	10,000	1,000	95	1	288[c]	13,700	9-68	11-69	Begin destructive examination 8-70
	20,000	1,000	95	1	263[c]	12,500	9-68	1-71	
	50,000	1,000	95	1	255[c]	12,100	9-68	5-74	
	10,000	850	95	1	(d)	-	9-68	11-69	Begin destructive examination 8-70
'Hastelloy" C m.p. 1270°C)	100	850	50	1	120	9,000	1-67	1-67	Capsule intact
	10,000	900	95	1	276[c]	13,100	7-68	8-69	Begin destructive examination 8-70
	10,000	1,000	95	1	282[c]	13,400	9-68	11-69	Begin destructive examination 8-70
	50,000	1,000	95	1	270[c]	12,800	9-68	5-74	
Haynes" 25 m.p. 1330°C)	5,000	1,000	95	1	263[c]	12,500	9-68	4-69	Begin destructive examination 8-70
	10,000	1,000	95	1	288[c]	13,700	9-68	11-69	Begin destructive examination 8-70
	20,000	1,000	95	1	282[c]	13,400	9-68	1-71	
	50,000	1,000	95	1	295[c]	14,000	9-68	5-74	
	10,000	850	95	1	(d)	-	9-68	11-69	Begin destructive examination 8-70
Hastelloy" X m.p. 1260°C)	5,000	1,000	95	1	250[c]	11,900	9-68	4-69	Begin destructive examination 8-70
	10,000	1,000	95	1	263[c]	12,500	9-68	11-69	Begin destructive examination 8-70
	20,000	1,000	95	1	263[c]	12,500	9-68	1-71	
	50,000	1,000	95	1	301[c]	14,300	9-68	5-74	

Excursion to >1100°C for 3-6 hr.
Activity as of 2-67.
Activity as of 6-68.
Capsule contains ^{59}Co but was heated along with ^{60}Co capsules.

Refractory Metal Capsules

Capsule tests with irradiated cobalt are now scheduled to begin early in FY-1972 in a new shielded cell in the Isotopes Process Development Laboratory (IPDL). Construction of the shielding walls and service piping and conduit to the cell are ∿90% complete. Completion of this phase of the program is being delayed to facilitate the construction and installation of the in-cell operating and process equipment. The project for this equipment has been authorized and design of the equipment is ∿75% complete. Purchase orders have been placed for the major equipment items, including the high temperature vacuum furnaces.

SAFETY TESTS

The safety of cobalt heat sources in accidents that permit heat source temperatures to rise severely is being studied. Such accidents include loss of internal cooling, fires, and burial. In Phase I of this study, the magnitudes of temperature excursions are being calculated. In Phase II, tests at the temperatures calculated will be run to measure reactions within heat sources, reactions with the environment, and release of ^{60}Co to air and water.

The heat sources in Table V are typical of those being considered in the temperature excursion calculations in Phase I. The fuel form diameters selected are 0.745 and 1.49 in. (standard cobalt wafers) or one of three other diameters in the range of 1.27 to 2.86 in.

For the initial calculations, shields of tungsten with a nominal thickness of 6 in. were selected. They would reduce the radiation at the exterior to the order of 50 mR/hr for the highest power sources considered.

Under normal operating conditions, the radial ΔT in long cylinders of 450 Ci/g cobalt metal fuel forms ranges from 10 to 400°C in the diameter range of 0.745 to 2.86 in.

Temperatures attainable in burial were shown to be much more severe than those encountered in loss of cooling accidents or in fires. The outside surface temperature of a 95-kw tungsten-shielded source would be ∿1000°C if it had no internal cooling or external insulation. The insulation can be selected to melt or disintegrate before excessive internal temperatures are reached in accidents. Corresponding temperatures for smaller sources are progressively lower as shown in Table VI. The temperatures are

TABLE V

TYPICAL ^{60}Co HEAT SOURCE ARRANGEMENTS FOR SAFETY STUDY

Item	Power,[a] kw	Number of Capsules per Heat Source[c]	Fuel Form Dimensions, in. Diameter	Length	Relative Weight of Shielded Source[b]
1	0.33	1	0.745	0.745	
2	2.6	1	1.49	1.49	
3	9.3	1	2.27	2.27	1 (for comparison with 8, 9, 10 below)
4	18.5	1	2.86	2.86	1 (for comparison with 11, 12, 13 below)
5	42.3	3	1.49	8	
6	56.4	4	1.49	8	
7	95.2	6	1.49	9	
8	9.3	3	0.745	7	2.0
9	9.3	3	1.27	2.41	1.2
10	9.3	1	1.49	5.25	1.5
11	18.5	6	0.745	7	1.8
12	18.5	6	1.27	3.16	1.3
13	18.5	1	1.49	10.5	2.8

[a] For cobalt metal, 450 Ci/g. Oxide fuel forms and lower activities will be considered for many of the same size sources.

[b] Relative to corresponding L = D case, Item 3 or 4.

[c] Multiple capsules are in an annular ring at the center of the shield. Adjacent capsules have about 1 capsule-diameter space between them.

TABLE VI

CALCULATED EXCURSION TEMPERATURES FOR LOSS OF COOLING AND BURIAL

Item	Power, kw	Loss of Cooling: Temperature of source exposed to air - No internal cooling or insulation, °C	Burial in Dune Sand[a]: Time to reach 1300°C, the melting point of dune sand, min.
1	.33	-	- (Max. Temp. ~400°C)
2	2.6	391	7200[b]
3	9.3	600	180
4	18.5	736	80
5	42.3	813	70
6	56.4	889	50
7	95.2	1001	35
8	9.3	504	420
9	9.3	574	240
10	9.3	543	270
11	18.5	641	150
12	18.5	695	100
13	18.5	579	300

[a] No internal cooling

[b] Below about 2.5 kw the sand would not melt

calculated assuming that the shield surface has an emissivity of 0.6.

If the uninsulated shield of a 0.745-in.-dia. ^{60}Co cylinder at 450 Ci/g (5.3 kw/ft) was exposed to a standard fire, 30 minutes at 800°C, its outside temperature would increase from about 460 to 730°C and its central axis temperature would increase from about 700 to 920°C. The temperature would not rise much higher if the fire continued indefinitely.

On the other hand, if a 2.5 kw ^{60}Co source with a tungsten shield was buried deeply in dune sand, the outside temperature of the shield would reach a maximum temperature of about 1300°C, the initial melting point of the sand. The temperature drop through the shield would be about 50°C. The corresponding outside temperature of a 0.33 kw shielded source would be only about 400°C. Buried sources larger than 2.5 kw would reach the melting point of dune sand in the times shown in Table VI. Corresponding temperatures and times are being calculated for other principal soils, which have melting points in the range of 1200 to 2050°C.

Power above that required to reach the melting point of the sand, or other soil, would probably not increase the outside temperature of a shielded or unshielded source substantially, because the source would sink continuously as additional soil melted or would lose heat continuously by convection of the melt and radiation from the melt to the roof and walls of the cavity. Thus the melting point of the highest melting soil sets an upper limit on accident temperatures and on planned conditions for tests in Phase II. Higher surface temperatures would be possible if insulation stable at such temperatures were selected, or if the sources were exposed to launch pad aborts or reentry from space. However, the space aspects of ^{60}Co safety are not included in the present study.

The tests planned in Phase II are to be primarily constant-temperature furnace tests of ^{59}Co-Ni forms, with and without protective capsules and jackets of shield material. The test shields are to be about 1.2 in. OD. The fuel forms currently planned for inclusion are cobalt metal, CoO, and $Co_{0.5}Mg_{0.5}O$. The capsules will be "Haynes" 25, tungsten, or rhenium. The shields will be steel or tungsten. The reactions within heat sources, the reaction with air, water, and representative soils, and the release of ^{60}Co to air and water will be determined.

HEAT SOURCE DEMONSTRATION TESTS

WANL 30 kw(t) UNIT

SRL is providing technical assistance in the program to design, fabricate, and test an experimental heat source containing 30 kw(t) of ^{60}Co. Westinghouse Astronuclear Laboratory (WANL) is the contractor for this project.

Heat Source Design

The heat source detailed design is fairly firm at this time with only two major items to be resolved: 1) flat-plate versus domed head for the lower closure of the pressurized core, and 2) detailed heat pipe design and fabrication. The original three coolant-effluent ducts have been replaced by a single 3-in.-dia. duct.

Materials of construction have been selected as follows:

Biological Shield	- Carbon Steel
Inner Core	- Ni 200 or Ni 201
Outer Core	- Stainless Steel
Fuel Capsules	- Inner 0.070-in. "Haynes" 25 Outer 0.090-in. "Haynes" 188

The overall thermal efficiency was calculated to be ∿89%. Optimum insulation thicknesses are 3/4 in. (primary) between core and shield and 1-1/2 in. (secondary) outside the shield. Power required to pump the working gas through the core is estimated to be ∿300 watts, which is about 1% of the ^{60}Co energy.

The estimated weight of the heat source is as follows:

Biological Shield	- 33,530 pounds
Core	- 1,390
Heat Pipes	- 540
	35,460 pounds

Capsule Material Tests

"Haynes" 188 was proposed as the material for the outer fuel capsule because of (1) its superior oxidation resistance and (2) its compatibility with "Haynes" 25, the preferred inner capsule material, and nickel, the inner core material.* Results of the SRL tests on which this selection was based are described below.

Oxidation Tests in Still Air

Heat source core and capsules must not oxidize during normal or emergency operating conditions to an extent that would interfere with discharging fuel capsules or compromise capsule integrity.

Samples of candidate core and capsule materials are being heated in box furnaces at 1000°C (normal heat source operating temperature) for up to 10,000 hr and 1125°C (emergency cooling operating condition) for up to 3000 hr. Oxidation rates determined in these tests will be interpreted as maximum values; actual rates in the heat source should be smaller because of the limited access of air through seams in the shielding.

Materials examined to date and conditions to which they were exposed are given in Table VII. Results of the examination are summarized in the following paragraphs.

TABLE VII

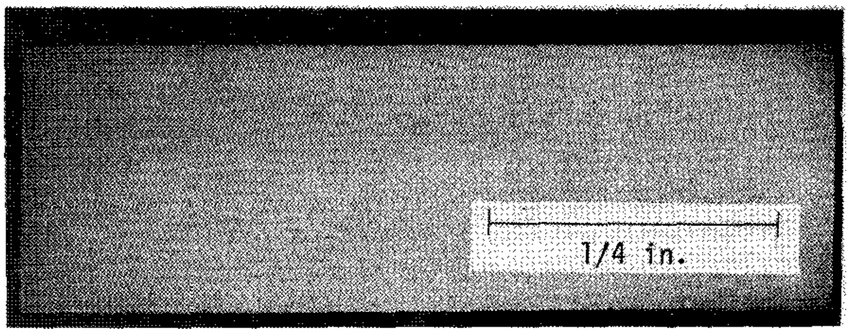
OXIDATION TEST MATERIALS AND CONDITIONS

	1000°C	1125°C
500 hours	"Haynes" 188 "Haynes" 25 "Hastelloy" X Nickel 200 304 Stainless Steel	"Haynes" 188 "Haynes" 25 "Hastelloy" X Nickel 200 304 Stainless Steel
1000 hours	"Haynes" 188 "Haynes" 25 304 Stainless Steel	"Haynes" 188

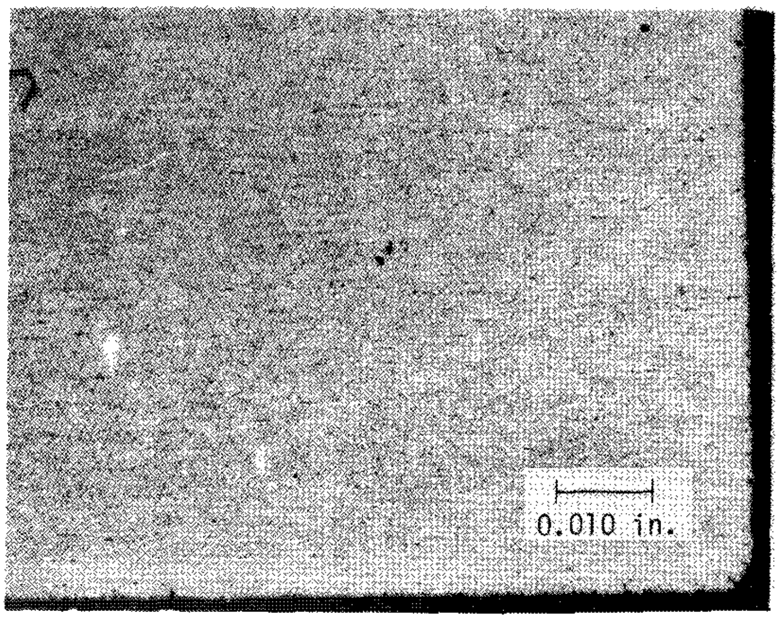
* Nickel 201, the low-carbon version of Nickel 200, is now the preferred material for the inner core because it has better creep strength than Ni 200 and is not subject to embrittlement by intergranularly precipitated carbon. Oxidation and compatibility characteristics are expected to be the same for the two materials. Ni 200 is being used in the current tests.

"Haynes" 188

The oxidation resistance of "Haynes" 188 at 1125°C after 1000 hr, Figure 2, was good, with a depth affected by oxidation of only 0.004 in. Heating of longer exposure specimens of this material continues.



magnification 6X



magnification 50X

FIGURE 2. Oxidation of "Haynes" 188 Exposed 1000 hr at 1125°C in a Box Furnace

"Haynes" 25

"Haynes" 25 showed good oxidation resistance at 1000°C with only 0.004 in. depth affected in 1000 hr, Figure 3. At 1125°C oxidation was severe in 500 hr, Figure 4. Microstructure of remaining metal changed by preferential oxidation. Heating of longer exposure specimens of this material at 1125°C was discontinued.

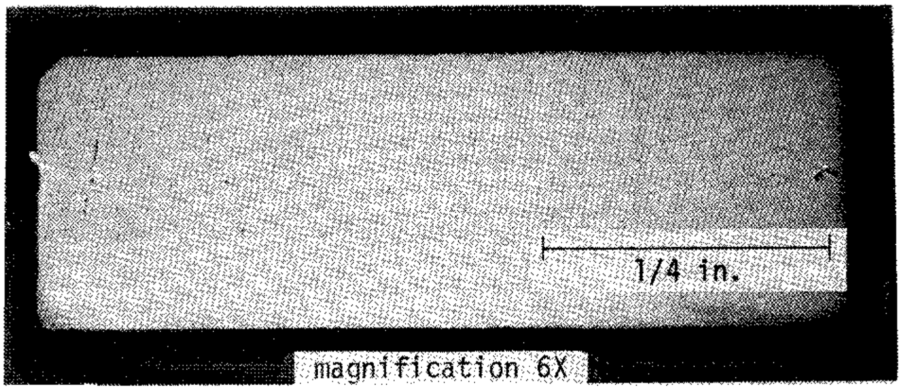
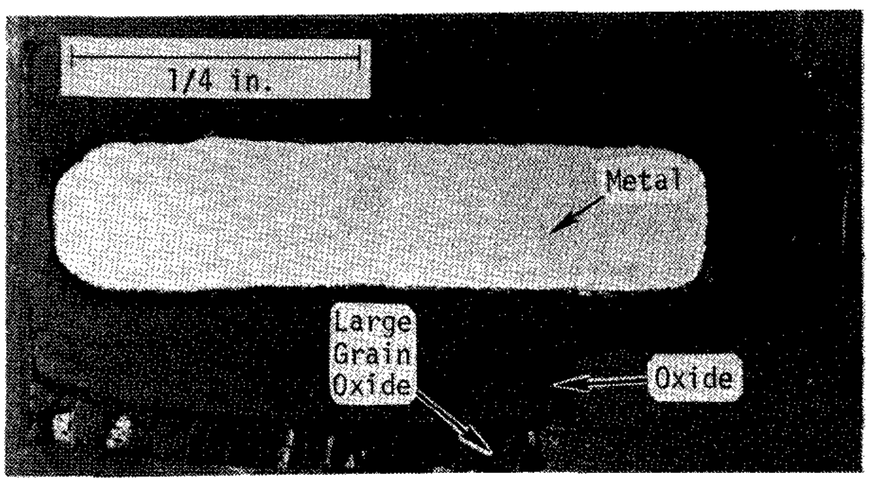


FIGURE 3. "Haynes" 25 Heated 1000 hr at 1000°C

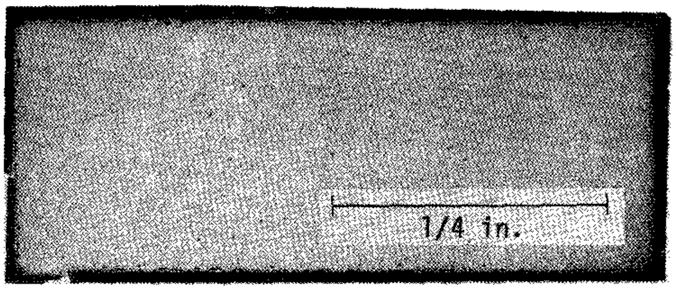


magnification 6X

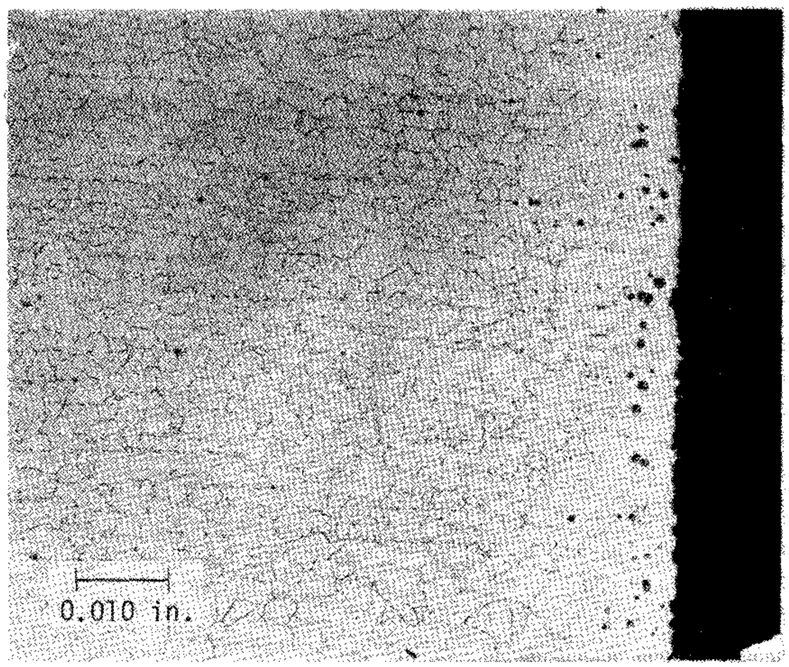
FIGURE 4. Oxidation of "Haynes" 25 Heated 500 hr at 1125°C in a Box Furnace (Originally this specimen was the same size as the one in Figure 3.)

"Hastelloy" X

"Hastelloy" X showed fair oxidation resistance at 1125°C after 500 hr, Figure 5; the depth affected was ∿0.010 in. Heating of longer exposure specimens of this material continues.



magnification 6X

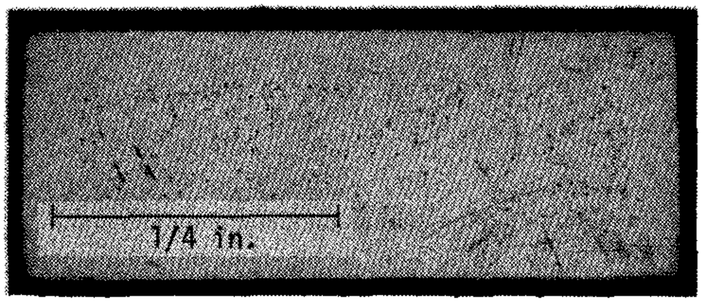


magnification 50X

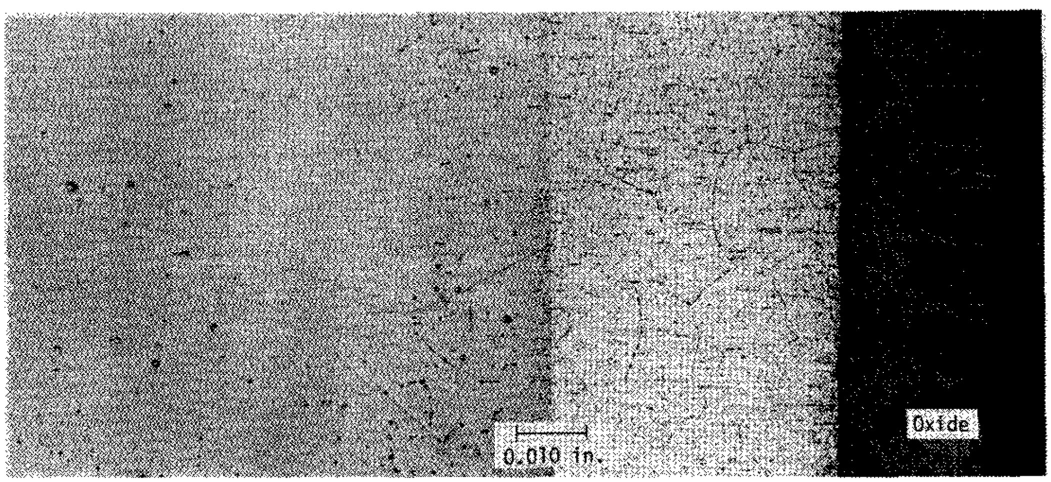
FIGURE 5. Oxidation of "Hastelloy" X Exposed 500 hr at 1125°C in a Box Furnace

Nickel 200

Exposure for 500 hr at 1125°C caused internal oxidation of Nickel 200 to a depth of 0.050 in., Figure 6. However, an adherent oxide formed and dimensions of specimens changed little.



magnification 6X

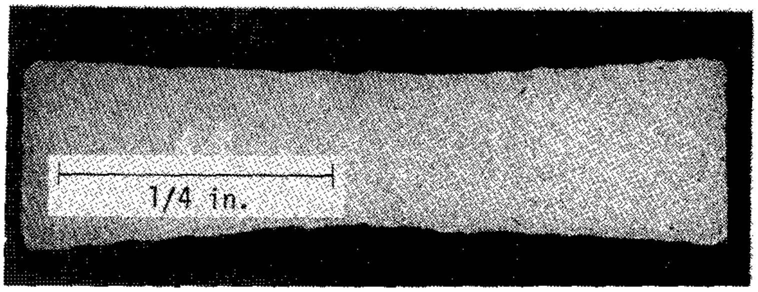


magnification 50X

FIGURE 6. Oxidation of Nickel 200 Exposed 500 hr at 1125°C in a Box Furnace
(Original size of specimen same as "Haynes" 188 specimen in Figure 2.)

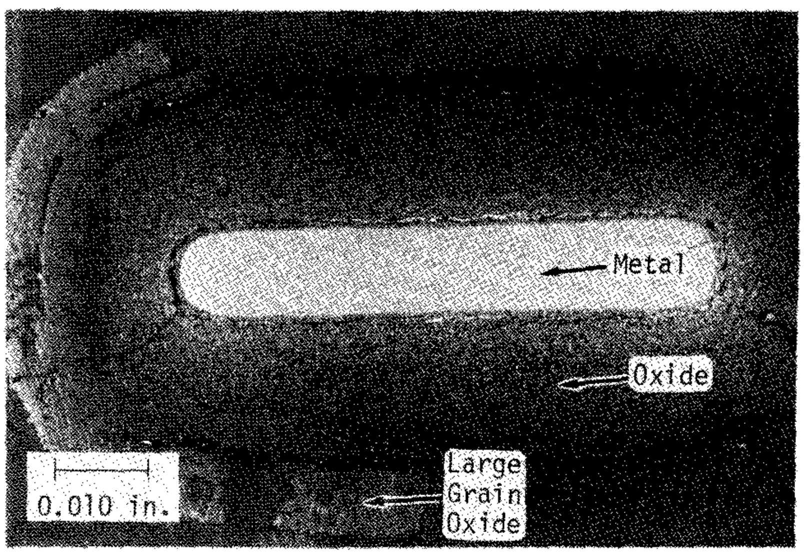
304 Stainless Steel

Oxidation resistance of 304 stainless steel at 1000°C and 1125°C was poor. Penetration was 0.014 in. in 1000 hr at 1000°C, Figure 7. Oxidation was severe at 1125°C in 500 hr, Figure 8. Further testing of this material at 1125°C was discontinued.



magnification 6X

FIGURE 7. 304 Stainless Steel Heated 1000 hr at 1000°C



magnification 6X

FIGURE 8. Oxidation of 304 Stainless Steel Heated 500 hr at 1125°C in a Box Furnace

Tests in Limited Air

In these planned tests, cylinders of core-cladding materials will be sealed in a tube furnace with the only opening to the atmosphere being a 1/8-in.-dia. x 8-in.-long diffusion path. The gap between a cylindrical specimen and the furnace wall will be the same as the gap between a capsule and the fuel hole in the core of the heat source. The amount of oxidation at the end near the opening and the variation along the gap between the specimen and the tube will be determined by metallographic examination of sections of the specimen after suitable exposures.

Compatibility Tests

Tests are in progress that will show the interaction between nickel and both clean and preoxidized (1000°C for one week in air) "Hastelloy" X, "Haynes" 25, and "Haynes" 188, and between "Haynes" 25 (primary cladding) and "Haynes" 188, or "Hastelloy" X (secondary cladding) at 1000°C for 1000, 5000, and 10,000 hr and at 1125°C for 500, 1000, and 3000 hr.

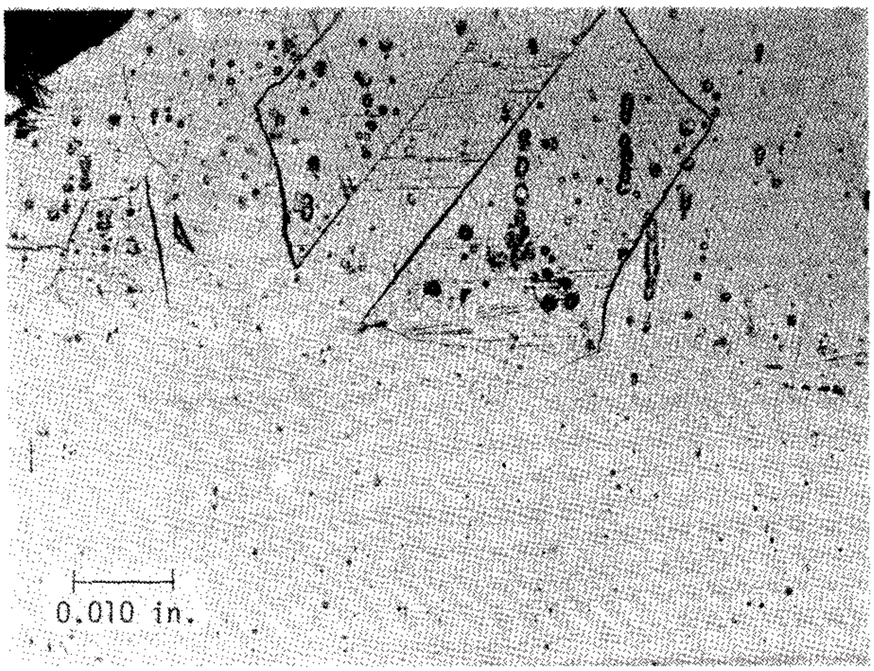
Capsules exposed for 500 and 1000 hr at 1125°C have been examined. The results are summarized in Table VIII and discussed further below.

TABLE VIII

RESULTS OF COMPATIBILITY TESTS

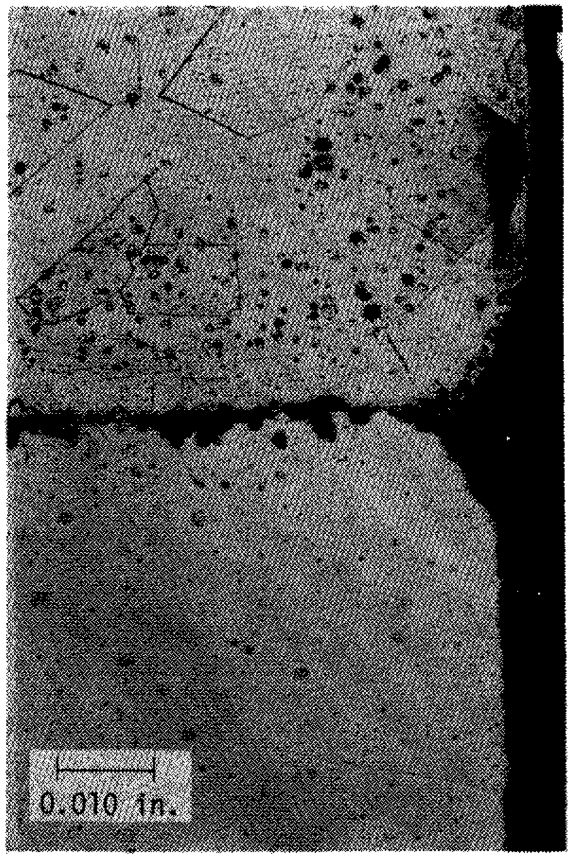
		Width of Affected Zone After Exposure at 1125°C	
	Material Tested	500 Hours	1000 Hours
Nickel 200	"Haynes" 188	0.008 in. in Ni 200 0.004 in. in "Haynes" 188	0.002 in. in Ni 200 0.002 in. in "Haynes" 188
	Preoxidized "Haynes" 188	No Reaction	No Reaction
	"Haynes" 25	0.008 in. in Ni 200 0.008 in. in "Haynes" 25	0.002 in. in Ni 200 0.012 in. in "Haynes" 25
	Preoxidized "Haynes" 25	No Reaction	No Reaction
	"Hastelloy" X	0.012 in. in Ni 200 0.020 in. in "Hastelloy" X	0.020 in. in Ni 200 0.030 in. in "Hastelloy" X
	Preoxidized "Hastelloy" X	0.012 in. in Ni 200 0.020 in. in "Hastelloy" X	0.020 in. in Ni 200 0.030 in. in "Hastelloy" X
"Haynes" 25	"Haynes" 188	Spotty bonding but no zone detectible	
	"Hastelloy" X	0.015 in. Total	0.025 in. Total

"Haynes" 188 bonds to but reacts very little with Nickel 200 at 1125°C in 1000 hr, Figure 9. Preoxidizing the "Haynes" 188 inhibits the reaction, Figure 10.



magnification 50X

FIGURE 9. "Haynes 188 - Nickel 200 Reaction After 1000 hr at 1125°C



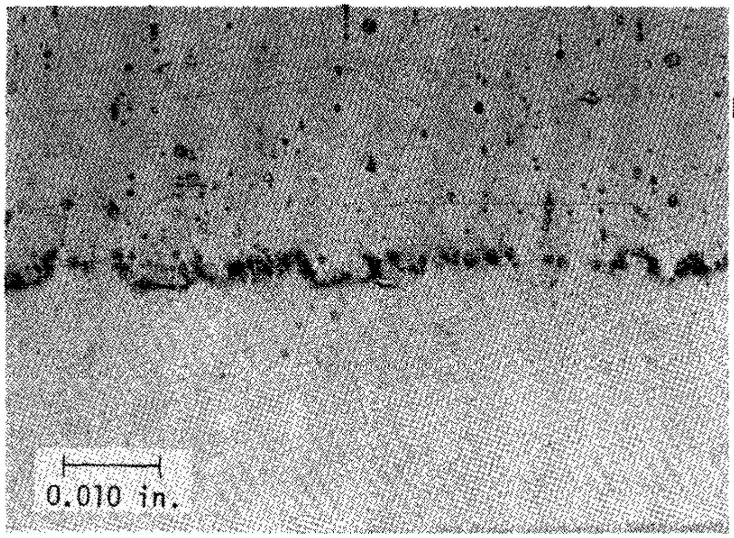
Nickel 200

"Haynes" 188

magnification 50X

FIGURE 10. Preoxidized "Haynes" 188 - Nickel 200 Couple After 1000 hr at 1125°C

"Haynes" 25 has small reaction with Nickel 200 at 1125°C for 1000 hr, Figure 11. Preoxidizing the "Haynes" 25 inhibits the reaction.

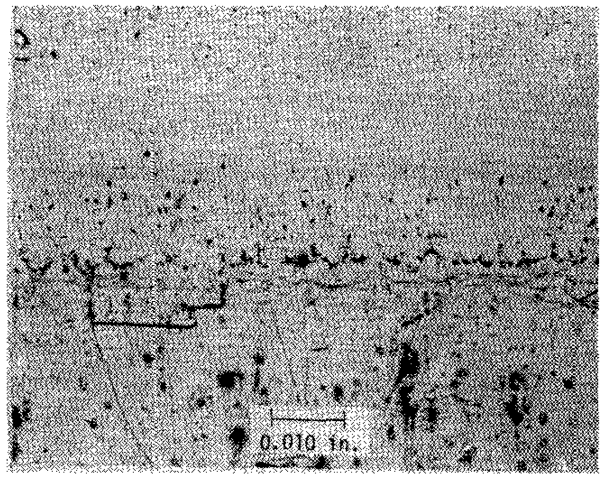


magnification 50X

FIGURE 11. "Haynes" 25 - Nickel 200 Reaction After 1000 hr at 1125°C

The preoxidized "Haynes" 25 - Nickel 200 couple came apart easily when the capsule was sectioned for examination.

"Hastelloy" X reacts with Nickel 200 readily, Figure 12. Preoxidizing the "Hastelloy" X has no effect on reaction, Figure 13.



magnification 50X

FIGURE 12. "Hastelloy" X - Nickel 200 Reaction After 1000 hr at 1125°C

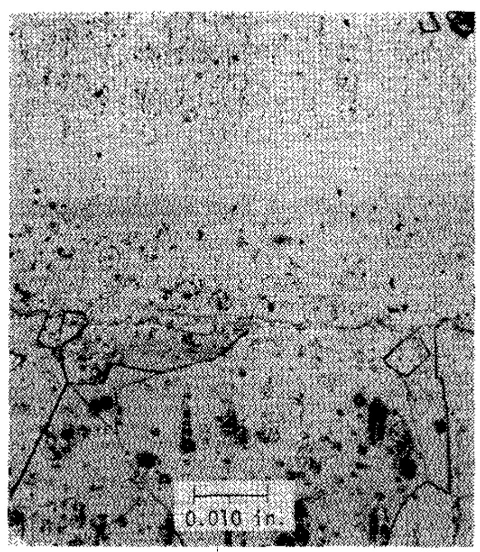


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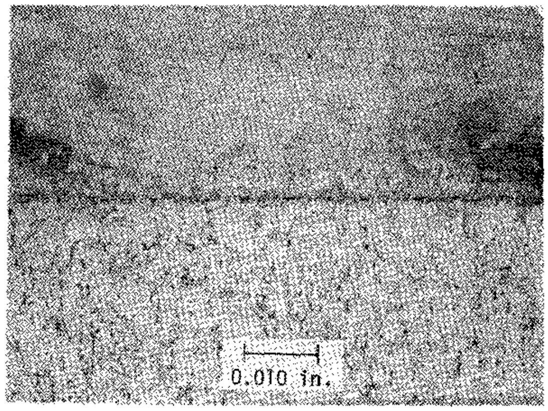
FIGURE 13. Preoxidized "Hastelloy" - Nickel 200 Reaction After 1000 hr at 1125°C

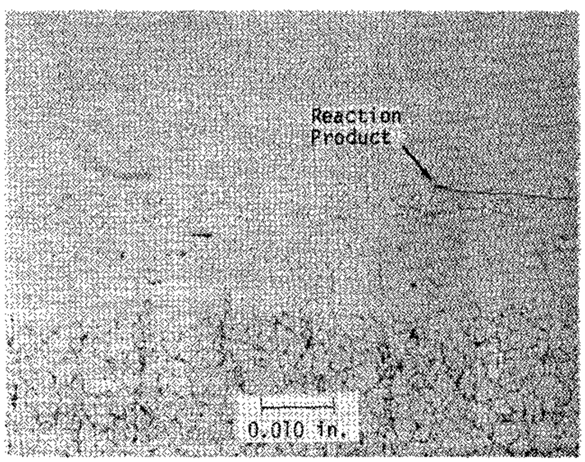
"Haynes" 188 reacts little with "Haynes" 25 after 1000 hr at 1125°C, Figure 14.



magnification 50X

FIGURE 14. "Haynes" 188 - "Haynes" 25 Reaction After 1000 hr at 1125°C

"Hastelloy" X reacts readily with "Haynes" 25 forming a fairly thick zone, Figure 15. The zone contains no voids that would interfere with heat transfer.



magnification 50X

FIGURE 15. "Hastelloy" X - "Haynes" 25 Reaction After 1000 hr at 1125°C

SRL Demonstration of 3 kw(t) Unit

Two "Inconel" 600 capsules for the demonstration of the operation of the WANL thermoelectric module (TEM) at SRL were loaded with ∿100,000 Ci of ^{60}Co each and closed by TIG welding. The nickel-plated ^{60}Co wafers loaded into the capsules had been irradiated to a specific activity of about 550 Ci/g in the Cf-I reactor campaign. Because the specific activity was higher than the desired 450 Ci/g, unirradiated cobalt wafers were intermingled in the wafer stack in the capsules to provide an effective specific activity of ∿450 Ci/g. Each capsule is 4 in. long and 0.85 in. in diameter and contains a stack of 10 irradiated wafers 0.073-in. thick and 17 or 18 unirradiated wafers 0.040-in. thick. These are the highest power ^{60}Co capsules ever fabricated. Capsule surface temperatures reached about 800°C during handling in air.

The 14,000-lb ductile iron shield casting, Figure 16, was found to be cracked through the center section (internal crack). The crack was first noticed at the start of internal machining; extensive machining failed to remove the crack. A new casting will be provided by the foundry. The resulting 5-month interval to obtain and machine the new casting will delay fueling of the generator until December or January, Figure 17.

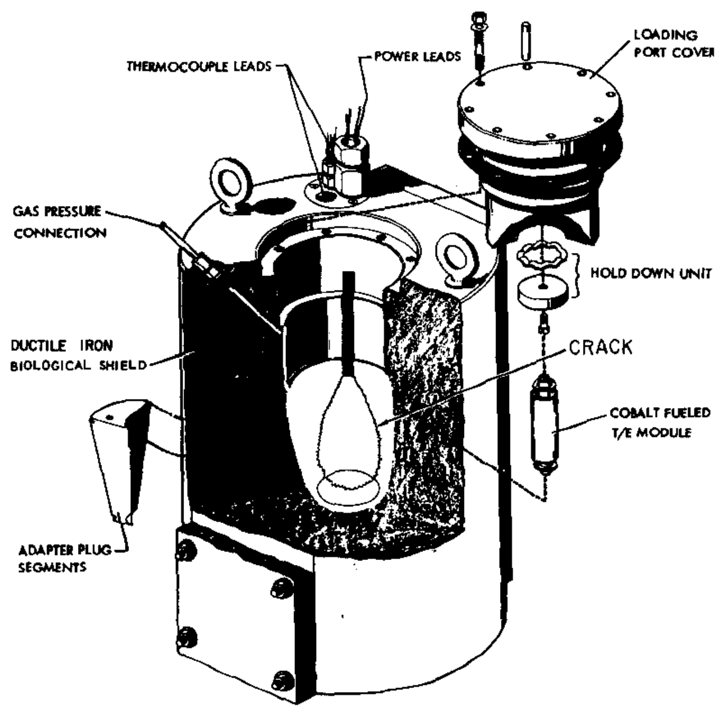


FIGURE 16. Co-60 DEMONSTRATION TEST

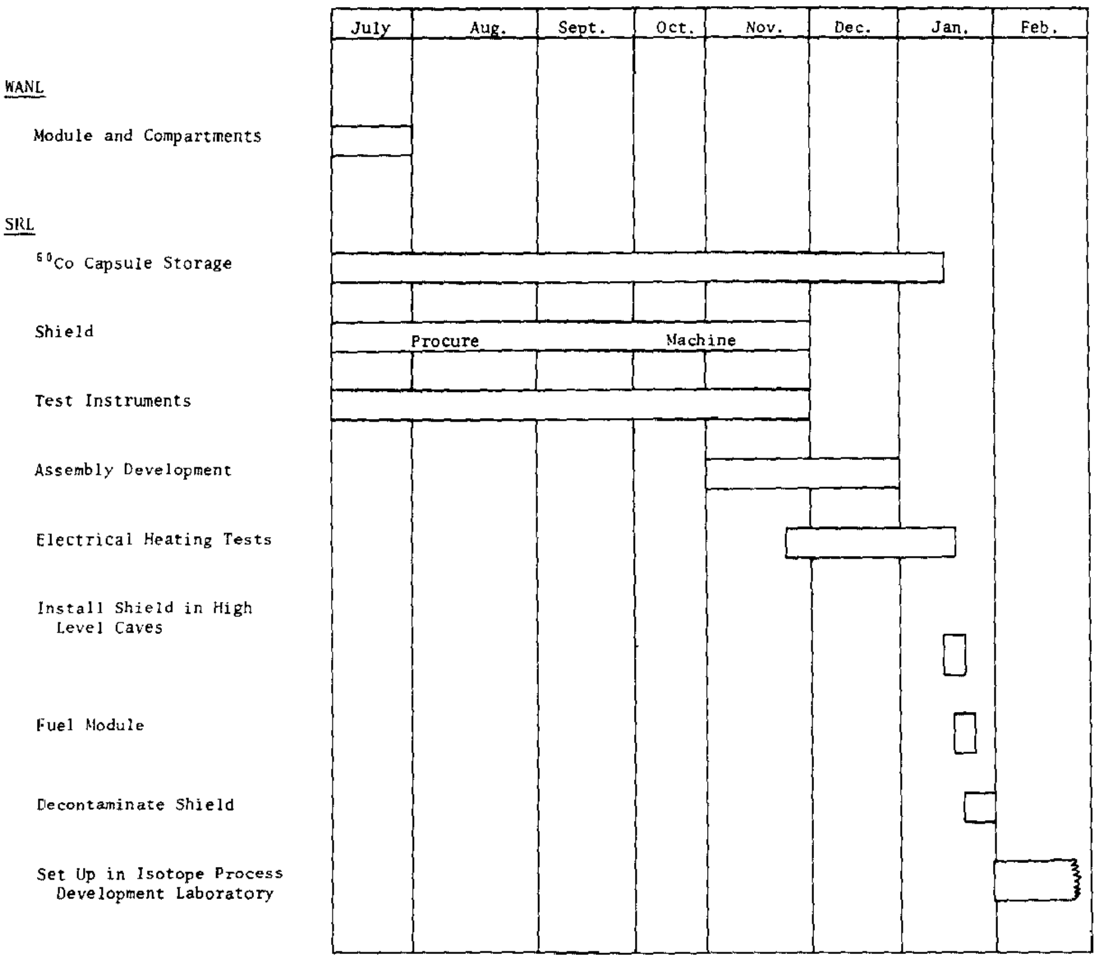


FIGURE 17. Schedule for ^{60}Co-Fueled Tubular Thermoelectric Demonstration (1970 - 1971)

PRODUCTION OF ^{60}Co IN CONTROL RODS OF ^{252}Cf CHARGES

Table IX summarizes the status of cobalt irradiations in control rods of Cf-I charges.

TABLE IX

ESTIMATED PRODUCTION OF HIGH ACTIVITY COBALT IN CALIFORNIUM-I CONTROL RODS

Metal Specimens 73 mils thick
Nickel-plated Ceramics 150 mils thick

	No. of Pieces	Wt of Co, g/Piece	Avg. Sp. Activity, Ci/g Co	Total Activity, MCi	Total Power, kw (t)	Date Available (Activity Calculated as of this Date)
Cobalt Metal						
Wafers 0.745 in. dia.	3080	4.5	500	6.93	108.0	6-30-70
	2660	4.5	350	4.18	65.1	12-31-70
	1860	4.5	250	2.09	32.5	6-30-70
	4560	4.5	200	4.10	63.8	12-31-70
Half-wafers, 1.00 in.	682	4.1	300	0.84	13.1	12-31-70
Half-wafers, 1.25 in.	434	6.4	300	0.83	12.9	12-31-70
Half-wafers, 1.49 in.	620	9.1	300	1.69	26.3	12-31-70
CoO wafers, 0.700 in.	120	4.0	500	0.24	3.7	9-30-70
$Co_{.5}Mg_{.5}O$ wafers, 0.700 in.	120	2.26	500	0.135	2.1	9-30-70
$CoAl_2O_4$ wafers, 0.700 in.	120	1.27	500	0.075	1.2	9-30-70
Total				21.11	328.7	

^{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 this material. About 10 MCi (150 kw) of ^{60}Co at over 350 Ci/g of Co and another 10 MCi at over 200 Ci/g will be 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 amounts of ^{60}Co at lower activities can be obtained commercially.

SAVANNAH RIVER LABORATORY ^{60}Co PUBLICATIONS

QUARTERLY PROGRESS REPORTS

"Savannah River Laboratory Isotopic 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

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).

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