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REPORT NO. RN-S-0398

TO

AEC-NASA SPACE NUCLEAR PROPULSION OFFICE

FINAL REPORT ON GTR-18 TEST TO DETERMINE
HIGH-TEMPERATURE RADIATION EFFECTS ON
STRUCTURAL MATERIALS

JULY 1967

NERVA PROGRAM

CONTRACT SNP-1

MASTER

NUCLEAR PRODUCTS AND SERVICES GROUP

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FINAL REPORT ON GTR-18 TEST TO DETERMINE
HIGH-TEMPERATURE RADIATION EFFECTS ON
STRUCTURAL MATERIALS

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ABSTRACT

This report summarizes the results of Test 37/R105 to determine radiation effects on structural materials containing boron. The test, performed in reactor run GTR-18 at General Dynamics, Fort Worth, during July 1966, was conducted in support of the NERVA program under the auspices of the Space Nuclear Propulsion Office, Cleveland, under Contract SNP-1.

Specimens of Hastelloy X, AISI 347 stainless steel, and Inconel 625 - all in the forged, welded, and thin sheet form - were irradiated in the water pool of the ground-test reactor to thermal-neutron fluences that ranged from 6×10^{17} to 1×10^{19} nvt. The specimens were tested at temperatures that ranged from 780 to 1540°F. Data on tensile properties and hardness were obtained and evaluated to determine the combined effects of radiation and temperature on the materials in their various forms.

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I. INTRODUCTION

GTR-18 irradiation was performed in July 1966 with the ground-test reactor at General Dynamics, Fort Worth. Six individual radiation-effects tests were performed under the auspices of the Space Nuclear Propulsion Office, Cleveland, in conjunction with the GTR-18 radiation run; three were sponsored by Aerojet-General Corporation, two by Westinghouse Astronuclear Laboratory, and one by the Space Nuclear Propulsion Office, Cleveland. The three Aerojet-sponsored tests included: (1) 37R/105, radiation effects on structural materials containing boron; (2) 37R/106, radiation effects on bearing cage materials; and (3) 23/R104, radiation effects on resistance temperature transducers. The results of Test 37/R105 are presented herein; the results of Tests 37/R106 and 23/R104 are presented in AGC Reports RN-S-0420 and RN-S-0370, respectively. The WANL-sponsored tests included: (1) 37/W404, radiation effects on Inconel 718 tensile properties, and (2) 37/W403, radiation effects on beryllium mechanical properties. The SNPO-C-sponsored test was an investigation of ortho- and para-hydrogen conversion.

Test 37R/105 had three objectives: (1) to investigate the effects of radiation on the tensile properties of candidate NERVA nozzle materials at thermal-neutron fluences ranging from 10^{17} to 19^{19} nvt ($E < 0.48$ ev) and test temperatures ranging up to 1600°F, (2) to determine radiation exposures and operating temperatures at which property changes could be detected, and (3) to provide guidelines for the specification of maximum boron content in structural alloys for use in NERVA environments.

II. SUMMARY

Specimens of three candidate nozzle materials, Inconel 625, Hastelloy X, and AISI 347 stainless steel, in three different forms - thin sheet, forgings, and weldments - were irradiated at 100°F to three thermal-neutron fluences: 6×10^{17} , 4×10^{18} , and 1×10^{19} nvt ($E < 0.48$ ev). The specimens were subsequently tested at temperatures that ranged from 780 to 1540°F. Control specimens of the materials were tested at the same temperatures. The testing

provided data on yield, ultimate tensile, and fracture strengths; uniform elongation at break; reduction of area; hardness; and stress-strain relationships.

Evaluation of the results showed that ductility was the property most affected by irradiation. Tensile strengths were unaffected by irradiation, except in a few cases. Figures 1 through 4 summarize the combined effects of irradiation and test temperature in terms of percent change in elongation, reduction of area, ultimate strength, and yield strength. Decreases in ductility were observed at exposures and temperatures as low as 6×10^{17} nvt and 1040°F. Ductility decreases were greatest at the maximum exposure and test temperature, 1×10^{19} nvt and 1540°F; elongation decreased 60, 55, and 50% for Hastelloy X, Inconel 625, and the stainless steel, respectively.

III. TEST SPECIMENS AND ENVIRONMENT

A. MATERIALS

A total of 150 tensile specimens were prepared from Hastelloy X, Inconel 625, and AISI 347 stainless steel in the form of forgings (parent metal and welded) and in the form of sheet, 0.012 and 0.015 in. thick. Table 1 gives the details of specimen preparation. As noted, all completed specimens were successively heated and cooled to simulate brazing cycles used in nozzle fabrication. Table 2 gives the chemical specifications and analyses of the materials.

B. SPECIMEN DESIGN

Two types of specimens were used in this test. The specimens used for the forgings and weldments were round and were fabricated in accordance with Federal Test Methods Standard No. 151, Type R-3, with a modified grip area, as shown in Figure 5. The specimens used for the thin sheet material were fabricated in accordance with Federal Test Methods Standard No. 151, Type F-2, with a modified grip area to permit pin loading, as shown in Figure 6. Two doublers were spot-welded on each end to reinforce the pulling sections.

—●— DENOTES 90% CONFIDENCE BAND

Figure 1 - Change in High-Temperature Ultimate and Yield Strengths vs Thermal-Neutron Fluence for Sheet Materials

—●— DENOTES 90% CONFIDENCE BAND THERMAL NEUTRON FLUENCE $\approx 4 \times 10^{18}$ nvt ($E < 0.48$ ev)

Figure 2 - Change in High-Temperature Ultimate and Yield Strengths vs Thermal-Neutron Fluence for Forgings and Weldments

—●— DENOTES 90% CONFIDENCE BAND

Figure 3 - Change in High-Temperature Ductility vs Thermal-Neutron Fluence for Sheet Materials

—●— DENOTES 90% CONFIDENCE BAND

THERMAL NEUTRON FLUENCE = 4×10^{18} nvt (E < 0.48 ev)

Figure 4 - Change in High-Temperature Ductility vs Thermal-Neutron Fluence for Forgings and Weldments

TABLE I
SPECIMEN PREPARATION

FORGED OR ROLLED STOCK AS RECEIVED					SPECIMEN PROCESSING (1)				
Item	Material	Vendor	Form	Dimensions	Heat Treatment	Specification	Weldment	Anneal	Grain Size ASTM No.
1.	Hast X	Viking Forge & Steel Co.	Ring forging	20" O.D. x 17" I.D. x 6" high	2150°F 1-hr Water quench	AGC-90056	--- TIG welded heat X5-27 by weld wire AGC-90058	Original by forger 2080°F 45 min air cool	2-3 Dendrites
2.	Hast X	Stellite Division Union Carbide	Strip	0.012 - 0.15" thick	2150°F 1-hr in hydrogen	AGC-90057	---	Original by forger	5-6
3.	Inco 625	International Nickel Co.	Plate	12" x 7" x 1"	Annealed 1850°F	International Nickel Co. specification	--- TIG welded parent metal filler	Original by forger Re-annealed at 1850 °F	4-6 on flat surface 7 on transverse Dendrites
4.	Inco 625	ALLVAC Metals Co.	Strip	0.012" thick x 8" x 30"	Annealed 1850°F	AGC-90057	---	Original by forger	4-6 7 on surface
5.	347 S.S.	Ladish Co.	Forging (segment of nozzle skirt) P/N 1010176-3 S/N 0000027	39.1" I.D. x 1" high coupon	Annealed 1900°F for 1 hr furnace cool to 300°F A.C.	Forge per QQ-S-763	 TIG welded 349 filler heat Al615	Original Re-annealed at 1900°F 1 hr, furnace cool to 300°F A.C.	5 9
6.	347 S.S.	Rodney Metals Inc.	Strip P/N 707217-1	0.0155" thick x 4" wide	Cold rolled	MIL-S-6721B	---	None	

NOTE:

After fabrication, specimens were subjected to the following simulated brazing cycle: 1) 1830°F for 1 hour, furnace cool to 975°F; 2) 1800°F for 1 hour, furnace cool to 957°F; 3) 1775°F for 1 hour, furnace cool to 975°F.

TABLE 2

CHEMICAL ANALYSIS

Material		Ni	Mo	Cr	Fe	C	Mn	Si	W	Al	Ti	Zr	Cu	Co	P	S	B	Va	Cb
Hastelloy X	Specification Limits	Min	Bal	8 00	20 50	17 00	0 05	--	-	0 20	--	--	-	0 50	-	--	--	--	--
		Max		10 00	23 00	20 00	0 15	1 00	1 00	1 00	0 02	0 02	0 02	0 35	2 50	0 020	0 015	0 001	0 50
	Ring, Heat																		
	Form 261-5-4000		Bal	9 05	21 77	18 22	0 12	0 66	0 32	0 48	0 14	0 01	--	0 03	1 59	0 001	0 010	0 0007 ⁽¹⁾	0 01
	Strip, Heat		Bal	9 22	21 56	18 20	0 11	0 74	0 31	0 54	0 17	0 02		0 02	1 46	0 003	0 009	0 0002 ⁽¹⁾	0 01
Inconel 625	Filler, Heat		Bal	8 93	21 42	18 36	0 08	0 63	0 37	0 61	Al+Ti	0 23	--	0 03	1 93	0 012	0 002	0 0006 ⁽¹⁾	
	X5-2784																		
	Specification Limits	Min	Bal	8 00	20 00	--	-	--	--	--	--	--	-	--	--	--	--	--	3 15
		Max		10 00	23 00	5 00	0 10	0 50	0 50	0 50	0 02	0 02	0 02	0 35	1 00	0 015	0 015	0 001	4 15
	Plate, Heat																		
347 SS	Form NH 2172 (ORNL)		62 64	9 05	21 64	2 44	0 02	0 05	0 26	-	0 15	0 15		0 04	--	-	0 007	0 0008 ⁽¹⁾	-
	Strip Heat 5940		Bal	8 07	20 92	2 48	0 056	0 01	0 01	0 01	0 06	0 03	--	0 05	0 11	0 004	0 002	0 0015 ⁽²⁾	0 01
	Specification Limits	Min	9 00		17 00	Bal	--	-	--	--	--	--	-	--	-	-	-	-	-
		Max	13 00	--	19 00		0 08	2 00	1 00	-	--	--	-	-	0 045	0 030			-
	Forging, Heat																		
349 SS	Form 223-3904		11 1	-	18 1	Bal	0 071	1 43	0 45	-		-	--	-	0 012	0 008	0 0006 ⁽¹⁾		0 62
	Channel, Heat		11 22	0 26	17 42	Bal	0 046	1 53	0 67	--	-	--	0 18		0 015	0 010	0 0007 ⁽¹⁾	--	0 86
	830617																		
	Specification Limits	Min	8 0	--	19 0	Bal	--	--	--	1 00	-	--	--	--	--	--	-	-	1 00
		Max		0 75	--		0 12	2 00	1 00	2 00	--	--	--	-	0 030	0 030	--	--	--
349 SS	Filler, Heat																		
	Al615		9 18	0 56	19 60	Bal	0 100	1 35	0 35	1 50	--	0 20	-	0 11	-	0 015	0 006	--	1 30

NOTE

- (1) Ledoux Analysis
 (2) ORNL Analysis
 (3) Weld filler rod in Inconel 625 Weld specimen was machined from parent forging

Figure 5 - Round Tensile Specimen

Figure 6 - Sheet Tensile Specimen

C. IRRADIATION AND TESTING

The irradiation temperature of the specimens ranged between 70 and 140°F. Specimens were submerged in the reactor pool at three locations. The reactor was operated at 3 Mw for approximately 200 hr. The resulting thermal-neutron fluences attained at the different locations were 6.1×10^{17} nvt, ($E < 0.48$ ev), 4.2×10^{18} nvt ($E < 0.48$ ev), and 1×10^{19} nvt ($E < 0.48$ ev). The accuracy and precision of these values are estimated at $\pm 50\%$ and $\pm 5\%$, respectively.

Specimens were tested at 780, 1040, 1290, and 1540°F. The environmental test conditions for irradiated and control specimens are summarized in Table 3. The specimen temperature was controlled to within $\pm 10^\circ\text{F}$ during tensile testing.

TABLE 3
TEST SPECIMEN SCHEDULE

Neutron Fluence, nvt Fast (E>2.9 Mev) Thermal (E<0.48 ev)	6×10^{16} 6×10^{17}		4×10^{17} 4×10^{18}		1×10^{18} 1×10^{19}		Control	
Test Temperature	Material	Form	Material	Form	Material	Form	Material	Form
780°F			Hast. X Hast. X 347 347	F W F W			Hast. X Hast. X 347 347	F W F W
1040°F			Hast. X Hast. X Hast. X 347 347 347 Inco 625 Inco 625 Inco 625	F W S F W S F W S			Hast. X Hast. X Hast. X 347 347 347 Inco 625 Inco 625 Inco 625	F W S F W S F W S
1290°F	Hast. X 347 Inco 625	S S S	Hast. X 347 Inco 625	S S S	Hast. X 347 Inco 625	S S S	Hast. X 347 Inco 625	S S S
1540°F	Hast. X 347 Inco 625	S S S	Hast. X 347 Inco 625	S S S	Hast. X 347 Inco 625	S S S	Hast. X 347 Inco 625	S S S

NOTES:

(1) Material Forms:

F = Forging

W = Welded forging

S = Sheet

(2) Three specimens were provided for each condition

(3) Irradiation temperature, 70 - 140°F

IV. TEST PROCEDURES

A. TENSILE TESTING

Tensile testing was accomplished with a Model TT Instron testing machine. Special fixtures were provided to hold each type of specimen. Alignment of the pulling assembly for the round specimen was checked by using specimens instrumented with strain gages. The variation in strain from the average, as measured by the gages, was less than 20% and decreased to an insignificant value as stress approached the specimen yield point. The instrumented specimens were stressed to about 75% of their yield strengths. Misalignment of the flat specimen was negligible because of the nature of the pin loading.

A 2000-w temperature-controlled Marshall testing furnace was used to control specimen temperature. Each specimen was held at its test temperature for 30 min before the test was initiated. The Instron cross-head speed was held constant during each test to provide a nominal 0.002-in./in.-min strain rate.

B. ELONGATION AND HARDNESS MEASUREMENTS

Dimensional measurements for elongation and reduction of area were made with a toolmaker's microscope. Hardness of the round specimens was measured with a Model-3 JR Rockwell hardness tester. Hardness of the thin sheet specimens was measured with a Rockwell superficial-hardness tester.

V. TEST RESULTS

A. DATA

Results obtained are summarized in Tables 4 through 9, a separate table being provided for each material in sheet form and for each material in forged and weldment form. Values reported include ultimate and yield tensile strengths, elongation, reduction in area, uniform elongation, and fracture strength. "Elongation" is the elongation at break, as determined from bench measurements. "Uniform elongation" is the plastic elongation at ultimate tensile strength, as determined from Instron cross-head movement. Table 10 summarizes hardness data.

In the tensile tests, all of the sheet specimens broke within the gage length. Fracture locations for forgings and weldments are shown in Table 11.

Elongation, reduction of area, and yield strength are shown in Figures 7 through 21 as functions of test temperature and neutron fluence for the various materials.

Average stress-strain relationships for groups of specimens are shown in Figures 22 through 35. Strain is reported in terms of percent elongation and was calculated from Instron cross-head movement adjusted for the plastic strain outside of the gage section as determined from bench elongation-at-break measurements.

TABLE 4
HASTELLOY X SHEET
MECHANICAL PROPERTIES TEST DATA

Test Temperature, °F		1040		1290				1540			
Fluence, nvt (E<0.48 ev)		Control	4.2 x 10 ¹⁸	Control	6.1 x 10 ¹⁷	4.2 x 10 ¹⁸	1 x 10 ¹⁹	Control	6.1 x 10 ¹⁷	4.2 x 10 ¹⁸	1 x 10 ¹⁹
Ultimate Strength, ksi	Test Values	96.4	93.7	63.5	59.6	61.0	65.7	25.3	25.7	30.2	26.0
		95.6	95.1	62.4	63.1	60.4	59.5	26.6	24.4	30.0	25.9
		97.9	94.9	56.4	65.3	60.6	62.4	26.9	24.4	31.5	25.4
	Average	96.7	94.6	60.7	62.6	60.6	62.5	26.2	24.8	30.5	25.7
	Range	2.3	1.5	7.1	5.7	0.6	6.2	1.6	1.3	1.5	0.6
	Std. Dev.	1.20	0.73	3.72	2.98	0.31	3.25	0.84	0.68	0.79	0.31
0.2% Yield Strength, ksi	Test Values	40.3	39.8	(48.1)	37.0	35.3	38.5	21.9	21.9	27.4	23.2
		41.8	41.2	38.1	38.0	33.9	36.9	25.7	21.8	27.4	23.5
		42.2	41.7	34.4	37.5	36.2	36.6	24.4	22.3	29.9	24.2
	Average	41.4	40.9	36.2	37.5	35.1	37.3	24.0	22.0	28.2	23.6
	Range	1.9	1.9	3.7	1.0	2.3	1.9	3.8	0.5	2.5	1.0
	Std. Dev.	1.00	1.00	2.62	0.52	1.20	1.00	1.98	0.26	1.31	0.52
Fracture Strength, ksi	Test Values	95.0	90.0	0	41.0	50.0	52.0	0	0	0	0
		92.0	95.0	0	44.0	46.0	45.0	0	0	0	0
		96.0	95.0	0	53.0	47.0	47.0	0	0	0	0
	Average	94.3	93.3		46.0	47.7	48.0				
	Range	4.0	5.0		12.0	4.0	7.0				
	Std. Dev.	2.1	2.6		6.3	2.1	3.7				
% Uniform Elongation	Test Values	29.2	30.4	8.5	12.0	12.3	10.7	3.5	4.8	5.4	4.4
		31.7	25.6	7.4	10.8	12.4	8.4	6.6	4.0	(1.7)	3.0
		31.6	30.8	7.9	10.7	13.2	7.2	5.0	3.4	5.1	
	Average	30.8	28.9	7.9	11.2	12.6	8.8	5.0	4.1	5.2	3.7
	Range	2.5	5.2	1.1	1.2	0.9	3.5	3.1	1.4	0.3	1.4
	Std. Dev.	1.31	2.73	0.58	0.68	0.47	1.83	1.62	0.73	0.21	0.99
% Elongation	Test Values	36.4	31.7	40.3	36.9	31.0	22.1	48.2	30.3	23.6	20.0
		37.7	30.4	42.1	31.3	28.8	20.1	44.8	26.1	25.9	19.3
		42.7	34.8	42.4	32.6	26.7	24.0	51.5	29.7	28.7	19.7
	Average	38.9	32.3	41.6	33.6	28.8	22.1	48.1	28.7	26.1	19.7
	Range	6.3	4.4	2.1	5.6	4.3	3.9	6.7	4.2	5.1	0.7
	Std. Dev.	3.30	2.30	1.10	2.93	2.25	2.04	3.51	2.20	2.67	0.37
% Reduction In Area	Test Values	34.8	27.2	48.9	34.2	27.5	26.8	45.2	24.2	26.1	18.8
		41.2	31.7	49.2	30.5	31.1	30.8	41.1	(14.7)	23.5	21.2
		36.4	(9.2)	56.5	35.6	29.3	25.4	40.8	32.5	24.3	22.2
	Average	37.5	29.4	51.5	33.4	29.3	27.7	42.3	28.4	24.6	20.7
	Range	6.4	4.5	7.6	5.1	3.6	5.4	4.4	8.3	2.6	3.4
	Std. Dev.	3.35	3.19	4.00	2.67	1.88	2.83	2.30	5.89	1.36	1.78

NOTE: Values in parentheses were omitted from computations of average, range, and standard deviation.

TABLE 5

HASTELLOY X FORGINGS AND WELDMENTS
MECHANICAL PROPERTIES TEST DATA

Material Form		Forging				Weldment			
Test Temperature, °F		780		1040		780		1040	
Fluence, nvt ($E < 0.48$ ev)		Control	4.2×10^{18}	Control	4.2×10^{18}	Control	4.2×10^{18}	Control	4.2×10^{18}
Ultimate Strength, ksi	Test Values	74.5 78.7 76.0	83.6 81.0 81.0	82.4 77.7 79.0	74.3 68.9 76.4	82.0 89.5 83.8	82.3 83.9 81.5	76.2 78.8 80.5	77.9 78.2 77.8
	Average	76.4	81.9	79.7	73.2	85.1	82.6	78.4	77.9
	Range	4.2	2.6	4.7	7.5	7.5	2.4	4.3	0.4
	Std. Dev.	2.20	1.36	2.46	3.93	3.93	1.26	2.25	0.21
0.2% Yield Strength, ksi	Test Values	30.7 29.7 28.7	32.3 34.0 27.5	34.6 28.7 27.2	27.0 29.4 28.0	29.7 (51.2) 36.4	35.5 34.0 33.5	31.5 33.8 30.0	30.3 33.4 30.5
	Average	29.7	31.2	30.2	28.1	33.0	34.3	31.7	31.4
	Range	2.0	6.5	7.4	2.4	6.7	2.0	3.8	3.1
	Std. Dev.	1.05	3.40	3.87	1.26	4.75	1.05	1.99	1.62
Fracture Strength, ksi	Test Values	76.0 78.0 69.0	81.0 79.0 83.0	82.0 76.0 80.0	65.0 72.0	(96.0) 82.0 83.0	74.0 82.0 80.0	77.0 74.0 78.0	73.0 77.0
	Average	74.3	81.0	79.3	68.5	87.0	78.7	76.3	75.0
	Range	9.0	4.0	6.0	7.0	14.0	8.0	4.0	4.0
	Std. Dev.	4.7	2.1	3.1	5.0	7.3	4.2	2.1	2.1
% Uniform Elongation	Test Values	21.6 23.0 22.5	27.8 29.3 26.7	29.6 26.7 36.4	20.4 25.3	27.6 28.6 (21.1)	(19.3) 31.2 28.7	19.9 20.2 (33.1)	24.2 24.3
	Average	22.4	27.9	30.9	22.8	28.1	30.0	20.0	24.2
	Range	1.4	2.6	9.7	4.9	1.0	2.5	0.3	0.1
	Std. Dev.	0.73	1.36	5.08	3.48	0.70	1.77	0.21	0.07
% Elongation	Test Values	22.5 23.1 22.8	26.9 27.8 29.7	29.6 26.7 36.4	25.7 20.6 25.4	31.3 28.7 22.2	(20.0) 32.4 32.1	20.8 20.9 (33.9)	25.4 22.4 25.5
	Average	22.8	28.1	30.9	23.9	27.4	32.3	20.9	24.4
	Range	0.6	2.8	9.7	5.1	9.1	0.3	0.1	3.1
	Std. Dev.	0.31	1.46	5.08	2.67	4.76	0.21	0.07	1.62
% Reduction In Area	Test Values	24.8 17.7 20.3	27.2 26.4 27.4	29.5 25.1 28.9	(29.8) 19.5 19.5	32.5 30.0 32.4	24.7 (37.3) 30.3	33.9 30.5 35.2	32.3 31.6 31.0
	Average	20.9	27.0	27.8	19.5	31.6	27.5	33.2	31.6
	Range	7.1	1.0	4.4	0.0	2.5	5.6	4.7	1.3
	Std. Dev.	3.72	0.52	2.30	0.00	1.31	3.97	2.46	0.68

NOTE: Values in parentheses were omitted from computations of average, range, and standard deviation.

TABLE 6

AISI 347 STAINLESS-STEEL SHEET
MECHANICAL PROPERTIES TEST DATA

Test Temperature, °F		1040		1290				1540			
Fluence, nvt ($E < 0.48$ ev)		Control	4.2×10^{18}	Control	6.1×10^{17}	4.2×10^{18}	1×10^{19}	Control	6.1×10^{17}	4.2×10^{18}	1×10^{19}
Ultimate Strength, ksi	Test Values	55.6	57.5	34.4	37.9	35.3	34.9	11.1	12.1	13.9	11.6
		57.0	56.4	34.0	(35.6)	34.1	34.9	(15.5) ²	11.5	(13.3) ³	12.6
		56.5	(54.6) ¹	36.3	35.5	33.4	35.7	11.3	11.4	12.6	12.2
	Average	56.4	57.0	34.9	36.7	34.3	35.1	11.2	11.7	13.2	12.2
	Range	1.4	1.1	2.3	2.4	1.9	0.8	0.2	0.7	1.3	1.0
	Std. Dev.	0.73	0.78	1.20	1.70	1.00	0.42	0.14	0.37	0.92	0.52
0.2% Yield Strength, ksi	Test Values	25.8	27.0	23.3	22.8	22.6	22.8	10.0	11.0	11.2	9.5
		24.3	26.5	21.5	(31.4)	23.2	22.1	(12.5) ²	10.6	(12.9) ³	11.4
		24.7	(45.9)	22.9	24.4	22.9	22.6	10.3	10.5	12.2	11.2
	Average	24.9	26.8	22.3	23.6	22.9	22.5	10.2	10.8	11.7	10.7
	Range	1.5	0.5	1.8	1.6	0.6	0.7	0.3	0.5	1.0	1.9
	Std. Dev.	0.78	0.35	0.94	1.13	0.31	0.37	0.21	0.26	0.71	1.00
Fracture Strength, ksi	Test Values	54.0	48.0	0	0	0	0	0	0	0	0
		55.0	50.0	0	0	0	0	0	0	0	0
		52.0		0		0	0				0
	Average	53.7	49.0								
	Range	3.0	2.0								
	Std. Dev.	1.6	1.4								
% Uniform Elongation	Test Values	18.7	21.7	11.6	12.7	8.4	12.7	4.7	5.0	4.5	7.0
		21.4	22.3	(18.7)	15.2	12.5	13.3	2.6	3.7	4.0	3.2
		22.2		9.4		11.0	13.0				4.0
	Average	20.8	22.0	10.5	14.0	10.6	13.0	3.6	4.4	4.2	4.7
	Range	3.5	0.6	2.2	2.5	4.1	0.6	2.1	1.3	0.5	3.8
	Std. Dev.	1.83	0.43	1.56	1.77	2.15	0.31	1.49	0.92	0.35	1.99
% Elongation	Test Values	27.9	28.2	38.4	40.4	30.8	35.6	69.5	50.0	44.8	31.9
		26.8	28.0	41.5	(32.0)	33.5	36.9	(66.7) ²	(75.1)	(50.1) ³	38.7
		29.3 ⁴	(28.6)	37.2	39.9	30.7	25.7	68.4	62.7	55.5	30.6
	Average	28.0	28.1	39.0	40.2	31.7	32.7	69.0	56.4	50.1	33.7
	Range	2.5	0.2	4.3	0.5	2.8	11.2	1.1	12.7	10.7	8.1
	Std. Dev.	1.31	0.14	2.25	0.35	1.47	5.86	0.78	9.01	7.59	4.24
% Reduction In Area	Test Values	38.1	35.1	54.1	44.8	32.9	37.0	62.5	48.9	37.1	37.2
		33.1	34.6	55.9	(39.3)	41.2	33.4	(57.2) ²	59.5	(52.4) ³	34.6
		40.5	(34.4)	50.0	53.3	39.3	40.9	58.2	61.9	49.5	32.0
	Average	37.2	34.7	53.3	49.0	37.8	37.1	60.4	56.7	43.3	34.6
	Range	7.4	0.7	5.9	8.5	8.3	7.5	4.3	13.0	12.4	5.2
	Std. Dev.	3.87	0.50	3.09	6.03	4.34	3.93	3.05	6.81	8.79	2.72

NOTES: 1. Values in parentheses were omitted from computations of average, range, and standard deviation.
2. Instron chart data not usable.

3. Low temperature during yield.
4. Calculated from Instron chart.

TABLE 7

AISI 347 STAINLESS STEEL, FORGINGS AND WELDMENTS
MECHANICAL PROPERTIES TEST DATA

Material Form		Forging				Weldment			
Test Temperature, °F		780		1040		780		1040	
Fluence, nvt ($E < 0.48$ ev)		Control	4.2×10^{18}	Control	4.2×10^{18}	Control	4.2×10^{18}	Control	4.2×10^{18}
Ultimate Strength, ksi	Test Values	57.2 56.6 56.6	57.7 53.5 53.6	48.9 48.4	51.1 51.4 50.1	59.8 56.8 55.7	56.2 55.3 54.9	50.7 52.8 51.6	46.5 52.4 50.2
	Average	56.8	54.9	48.6	50.9	57.4	55.4	51.6	49.6
	Range	0.6	4.2	0.5	1.3	4.1	1.3	2.1	5.9
	Std. Dev.	0.31	2.20	0.35	0.68	2.15	0.68	1.10	3.09
0.2% Yield Strength, ksi	Test Values	16.6 16.0 20.9	18.2 18.5 18.1	(38.3) 17.6	17.5 21.5 18.3	29.2 22.9 22.7	23.9 23.6 21.2	26.2 26.0 23.1	20.0 27.8 22.1
	Average	17.8	18.2	17.6	19.1	24.9	22.8	25.0	23.3
	Range	4.9	0.4		4.0	6.5	2.7	3.1	7.8
	Std. Dev.	2.57	0.21		2.09	3.40	1.41	1.62	4.08
Fracture Strength, ksi	Test Values	45.0 46.0 46.0	38.0 34.0 40.0	31.0 28.0	36.0 37.0 32.0	25.0 34.0 (50.0)	34.0 31.0 30.0	36.0 44.0 (25.0)	(41.0) 24.0 20.0
	Average	45.7	37.3	29.5	35.0	29.5	31.7	40.0	22.0
	Range	1.0	6.0	3.0	5.0	9.0	4.0	8.0	4.0
	Std. Dev.	0.5	3.1	2.1	2.6	6.4	2.6	5.7	2.8
% Uniform Elongation	Test Values	24.6 25.0 25.7	26.0 27.5 28.2	23.8 23.5	23.7 23.6 22.5	14.5 17.0 16.2	18.2 17.0 16.6	14.1 14.6 12.5	16.2 13.7 18.7
	Average	25.1	27.2	23.6	23.3	15.9	17.3	13.7	16.2
	Range	1.1	2.2	0.3	1.2	2.5	1.6	2.1	5.0
	Std. Dev.	0.58	1.15	0.21	0.63	1.31	0.84	1.10	2.62
% Elongation	Test Values	34.9 35.0 34.4	34.0 38.0 37.0	39.8 35.3	35.1 35.3 36.3	22.0 25.8 26.4	25.5 27.2 26.9	23.3 22.5 20.7	28.3 22.3 29.9
	Average	34.7	36.3	37.5	35.6	24.7	26.5	22.2	26.8
	Range	0.6	4.0	4.5	1.2	4.4	1.7	2.6	7.6
	Std. Dev.	0.31	2.09	3.19	0.63	2.30	0.89	1.36	4.00
% Reduction In Area	Test Values	59.4 52.6 60.4	53.6 60.4 63.8	62.4 55.6	52.7 54.3 55.2	52.4 58.9 61.7	59.3 61.4 59.8	52.0 48.5 (66.8)	70.6 (34.3) 64.6
	Average	57.5	59.3	59.0	54.1	57.6	60.2	50.2	67.6
	Range	7.8	10.2	6.8	2.5	9.3	2.1	3.5	6.0
	Std. Dev.	4.08	5.34	4.82	1.31	4.87	1.10	2.48	4.26

NOTE: Values in parentheses were omitted from computations of average, range, and standard deviation.

TABLE 8
INCONEL 625 SHEET
MECHANICAL PROPERTIES TEST DATA

Test Temperature, °F		1040		1290				1540			
Fluence, nvt (E<0.48 ev)		Control	4.2 x 10 ¹⁸	Control	6.1 x 10 ¹⁷	4.2 x 10 ¹⁸	1 x 10 ¹⁹	Control	6.1 x 10 ¹⁷	4.2 x 10 ¹⁸	1 x 10 ¹⁹
Ultimate Strength, ksi	Test Values	108.7	97.6	77.7	80.2	79.9	76.2	36.7	(49.9) ¹	32.7	35.4
		107.3	106.7	77.8	75.7	74.5	65.5	45.5	32.7	31.3	35.4
		107.1	103.7	79.0	77.2	77.5	71.7	34.8	32.4	34.5	35.3
	Average	107.7	102.6	78.1	77.6	77.3	71.1	38.9	32.6	32.8	35.4
	Range	1.6	9.1	1.3	4.5	5.4	10.7	10.7	0.3	3.2	0.1
	Std. Dev.	0.84	4.76	0.68	2.36	2.83	5.60	5.60	0.21	1.68	0.05
0.2% Yield Strength, ksi	Test Values	40.9	42.8	47.0	39.8	40.0	39.0	35.9	(49.5) ¹	32.7	34.3
		41.1	43.4	40.2	38.8	37.7	34.2	(45.3)	32.6	30.9	34.0
		42.7	43.5	39.4	39.3	(52.3)	36.9	34.8	32.3	34.1	34.3
	Average	41.5	43.2	42.2	39.3	38.8	36.7	35.4	32.5	32.5	34.1
	Range	1.8	0.7	7.6	1.0	2.3	4.8	1.1	0.3	3.1	0.3
	Std. Dev.	0.94	0.37	3.98	0.52	1.63	2.51	0.78	0.21	1.62	0.15
Fracture Strength, ksi	Test Values	109.0	97.0	67.0	69.0	78.0	76.0	0	0	0	0
		107.0	107.0	67.0	68.0	73.0	64.0	0	0	0	0
		107.0	99.0	72.0	69.0	75.0	70.0	0	0	0	0
	Average	107.7	101.0	68.7	68.7	75.3	70.0				
	Range	2.0	10.0	5.0	1.0	5.0	12.0				
	Std. Dev.	1.0	5.2	2.6	0.5	2.6	6.3				
% Uniform Elongation	Test Values	43.8	31.4	24.2	21.0	21.0	18.2	0.4	0.4	0.5	0.6
		45.5	37.3	24.8	24.7	24.4	19.6	0.2	0.3	0.2	0.5
		40.6	33.0	26.3	23.8	21.0	16.5	0.5	0.2		
	Average	43.3	33.9	25.1	23.2	22.1	18.1	0.4	0.3	0.4	0.6
	Range	4.9	5.9	2.1	3.7	3.4	3.1	0.3	0.2	0.3	0.1
	Std. Dev.	2.50	3.09	1.10	1.94	1.78	1.62	0.16	0.10	0.21	0.07
% Elongation	Test Values	43.8	31.4	31.4	27.6	22.3	19.3	44.8	(27.7) ¹	16.5	15.6
		45.5	37.3	32.4	28.1	24.6	21.3	47.2	27.1	16.1	14.9
		40.6	33.2	35.6	28.5	23.0	18.0	44.2	27.6	19.1	15.2
	Average	43.3	34.0	33.1	28.1	23.3	19.5	45.3	27.4	17.2	15.2
	Range	4.9	5.9	4.2	0.9	2.3	3.3	3.0	0.5	3.0	0.7
	Std. Dev.	2.56	3.09	2.19	0.47	1.20	1.73	1.57	0.35	1.57	0.37
% Reduction In Area	Test Values	37.1	35.4	35.4	32.6	30.5	22.4	36.9	(32.5) ¹	21.1	17.7
		37.1	36.0	29.8	24.0	28.4	30.7	45.8	17.4	28.3	18.3
		36.2	30.3	33.0	24.6	32.6	19.4	41.8	21.4	21.3	17.4
	Average	36.8	33.9	32.7	27.1	30.5	24.2	41.5	19.4	23.6	17.8
	Range	0.9	5.7	5.6	8.6	4.2	11.3	8.9	4.0	7.2	0.9
	Std. Dev.	0.47	2.98	2.93	4.50	2.20	5.92	4.66	2.84	3.77	0.47

NOTE: Values in parentheses were omitted from computations of average, range, and standard deviation.

¹ Oven temperature varied beyond $\pm 10^\circ\text{F}$ limit.

TABLE 9

INCONEL 625 FORGINGS AND WELDMENTS
MECHANICAL PROPERTIES TEST DATA

Material Form		Forging		Weldment	
Test Temperature, °F		1040		1040	
Fluence, nvt (E<0.48 ev)		Control	4.2 x 10 ¹⁸	Control	4.2 x 10 ¹⁸
Ultimate Strength, ksi	Test Values	106.0	103.0	95.9	84.8
		107.4	102.5	101.1	85.5
		102.4	95.5	96.3	87.6
				99.6	
	Average	105.3	100.3	98.2	86.0
	Range	5.0	7.5	5.2	2.8
	Std. Dev.	2.62	3.93	2.32	1.47
0.2% Yield Strength, ksi	Test Values	40.1	41.9	39.7	44.4
		43.5	39.8	37.1	45.3
		40.1	39.7	39.9	43.6
				39.7	
	Average	41.2	40.5	39.1	44.4
	Range	3.4	2.3	2.8	1.7
	Std. Dev.	1.78	1.20	1.25	0.89
Fracture Strength, ksi	Test Values	100.0	97.0	96.0	79.0
		97.0	97.0	96.0	86.0
		106.0	87.0	90.0	88.0
				100.0	
	Average	101.0	93.7	95.5	84.3
	Range	9.0	10.0	10.0	9.0
	Std. Dev.	4.7	5.2	5.2	4.7
% Uniform Elongation	Test Values	38.0	36.4	33.3	30.4
		38.4	37.2	36.6	32.3
		36.9	(29.9)	36.8	36.0
				38.7	
	Average	37.8	36.8	36.1	32.9
	Range	1.5	0.8	5.4	5.6
	Std. Dev.	0.78	0.57	2.41	2.93
% Elongation	Test Values	39.0	37.6	38.4	31.4
		37.8	38.5	34.6	32.3
		38.9	31.5	39.2	36.5
				37.7	
	Average	38.8	35.9	37.5	33.4
	Range	1.2	7.0	4.6	5.1
	Std. Dev.	0.63	3.66	2.05	2.67
% Reduction In Area	Test Values	30.9	27.7	41.9	31.9
		33.6	31.0	40.8	42.3
		34.6	27.7	38.5	33.9
				36.1	
	Average	33.0	28.8	39.3	36.0
	Range	3.7	2.3	5.8	10.4
	Std. Dev.	1.94	1.73	2.59	5.45

NOTE: Values in parentheses were omitted from computations of average, range, and standard deviation.

TABLE 10
HARDNESS DATA

SHEET STOCK (ROCKWELL 15-T)										
Test Temperature, °F	1040		1290				1540			
Fluence nvt (E<0.48 ev)	Control	4.2 x 10 ¹⁸	Control	6.1 x 10 ¹⁷	4.2 x 10 ¹⁸	1 x 10 ¹⁹	Control	6.1 x 10 ¹⁷	4.2 x 10 ¹⁸	1 x 10 ¹⁹
<u>MATERIAL</u>										
Hastelloy X Strained	90.0	91.2	86.8	88.1	89.2	90.1	86.3	86.8	86.4	85.1
Hastelloy X Unstrained	84.8	88.6	86.4	90.1	87.0	90.0	89.1	90.5	87.4	88.5
347 SS Strained	93.2	94.4	86.8	91.1	87.5	90.0	81.2	85.1	84.2	84.1
347 SS Unstrained	86.0	88.4	83.0	87.6	87.1	85.7	81.6	86.3	86.2	86.7
Inconel 625 Strained	93.2	94.9	90.4	91.2	91.1	89.4	84.4	85.2	85.8	88.1
Inconel 625 Unstrained	86.1	90.0	85.4	88.4	86.6	87.5	87.1	88.7	88.1	87.7

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FORGINGS AND WELDMENTS (ROCKWELL B)								
FORGING					WELDMENT			
Test Temperature	780°F		1040°F		780°F		1040°F	
Fluence nvt (E<0.48 ev)	Control	4.2 x 10 ¹⁸	Control	4.2 x 10 ¹⁸	Control	4.2 x 10 ¹⁸	Control	4.2 x 10 ¹⁸
<u>MATERIAL</u>								
Hastelloy X Strained	98.6	100.3	100.9	98.0	100.6	100.6	101.3	92.4
Hastelloy X Unstrained	87.2	87.7	88.4	88.2	87.6	87.6	88.8	87.8
347 SS Strained	90.8	94.5	89.7	89.0	92.6	94.1	88.0	91.8
347 SS Unstrained	72.7	75.4	69.8	74.2	74.2	72.7	74.6	71.5
Inconel 625 Strained			104.9	105.5			103.0	101.3
Inconel 625 Unstrained			93.6	94.6			92.4	94.6

A Rockwell Superficial Hardness Tester was used to measure hardness of the sheet stock specimens.
A Rockwell Hardness Tester Model 3JR was used to measure hardness of the forgings and weldments.
All hardness measurements were made at room temperature

TABLE 11
LOCATION OF BREAKS

<u>Material</u>	<u>Form</u>	<u>Temperature, °F</u>	<u>Fracture Area*</u>	
			<u>Control</u>	<u>Irrad</u>
Hastelloy X	Forging	780	Outside of Gage Marks	3
			3	2
			2	2
		1040	Gage Mark	3
			1	3
	Weld	780	1	2
			Gage Mark	3
			3	3
		1040	3	2
			2	2
347 Stainless Steel	Forging	780	1	1
			1	1
			1	1
		1040	1	2
			1	1
	Weld	780	3	2
			3	2
			2	2
		1040	3	3
			3	3
Inconel 625	Forging	1040	Gage Mark	3
			Gage Mark	3
			Gage Mark	2
	Weld	1040	3	3
			1	2
			1	1
			1	-

*Fracture areas:

Figure 7 - Hastelloy X High-Temperature Ultimate Tensile Strength vs Thermal-Neutron Fluence

Figure 8 - Hastelloy X High-Temperature Elongation vs Thermal-Neutron Fluence

Figure 9 - Hastelloy X Elongation vs Test Temperature for Various Thermal-Neutron Fluences

Figure 10 - Hastelloy X High-Temperature Reduction of Area vs Thermal-Neutron Fluence

Figure 11 - Hastelloy X Reduction of Area vs Test Temperature for Various Thermal-Neutron Fluences

Figure 12 - AISI 347 Stainless-Steel High-Temperature Ultimate Tensile Strength vs Thermal-Neutron Fluence

Figure 13 -AISI 347 Stainless-Steel High-Temperature Elongation vs Thermal-Neutron Fluence

Figure 14 - AISI 347 Stainless-Steel Elongation vs Test Temperature for Various Thermal-Neutron Fluences

Figure 15 - AISI 347 Stainless-Steel High-Temperature Reduction of Area vs Thermal-Neutron Fluence

Figure 16 - AISI 347 Stainless-Steel Reduction of Area vs Test Temperature
for Various Thermal-Neutron Fluences

Figure 17 - Inconel 625 High-Temperature Ultimate Tensile Strength vs Thermal-Neutron Fluence

Figure 18 - Inconel 625 High-Temperature Elongation vs Thermal-Neutron Fluence

Figure 19 - Inconel 625 Elongation vs Test Temperature for Various Thermal-Neutron Fluences

Figure 20 - Inconel 625 High-Temperature Reduction of Area vs Thermal-Neutron Fluence

Figure 21 - Inconel 625 Reduction of Area vs Test Temperature for Various Thermal-Neutron Fluences

Figure 22 - Hastelloy X Average Stress-Strain Curves for Forgings and Weldments at 780°F

Figure 23 - Hastelloy X Average Stress-Strain Curves for Forgings and Weldments at 1040°F

Figure 24 - Hastelloy X Average Stress-Strain Curves for Sheet Materials at 1040°F

Figure 25 - Hastelloy X Average Stress-Strain Curves for Sheet Materials at 1290°F

Figure 26 - Hastelloy X Average Stress-Strain Curves for Sheet Materials at 1540°F

Figure 27 - AISI 347 Stainless-Steel Average Stress-Strain Curves for Forgings and Weldments at 780°F

Figure 28 - AISI 347 Stainless-Steel Average Stress-Strain Curves for Forgings and Weldments at 1040°F

Figure 29 - AISI 347 Stainless-Steel Average Stress-Strain Curves for Sheet Materials at 1040°F

Figure 30 - AISI 347 Stainless-Steel Average Stress-Strain Curves for Sheet Materials at 1290°F

Figure 31 - AISI 347 Stainless-Steel Average Stress-Strain Curves for Sheet Materials at 1540°F

Figure 32 - Inconel 625 Average Stress-Strain Curves for Forgings and Weldments at 1040°F

Figure 33 - Inconel 625 Average Stress-Strain Curves for Sheet Materials at 1040°F

Figure 34 - Inconel 625 Average Stress-Strain Curves for Sheet Materials at 1290°F

Figure 35 - Inconel 625 Average Stress-Strain Curves for Sheet Materials at 1540°F

B. DATA ANALYSIS

1. General

Extreme individual values were considered in initial calculation of the averages. If the extreme values were determined to be "outliers," as described below, they were eliminated from further consideration. Subsequent analysis was based on the range method. The significant level for decision was taken at 90% confidence.

2. Outliers

For each treatment combination, the individual values (replications) were tested by means of "Dixon's Criteria for Extreme Values*," as well as by cross-comparison. Any value that was determined to be an outlier was omitted from subsequent analysis. Outliers are included in the tabulated data in the report and are identified as such. If the cause for an outlier is known, the information appears in a footnote.

C. TENSILE STRENGTH

1. General

The results indicate that, with few exceptions, tensile strengths of the materials did not change significantly as a result of exposure to the radiation environments of the test. The exceptions and some anomalies and trends are covered in Sections 2 and 3, immediately following.

*W. J. Dixon, "Analysis of Extreme Values," Annals of Mathematical Statistics," Vol 21, 1960

2. Forging and Weldments

The ultimate and yield tensile strengths of Hastelloy X and AISI 347 stainless-steel forgings and weldments at 780 and 1040°F were not affected when these materials were irradiated. On the other hand, the ultimate tensile strength of Inconel 625 weldments and forgings at 1040°F decreased about 10%.

While the yield strength of the Inconel forgings at 1040°F was unaffected by irradiation, the data show that the yield strength of the Inconel weldments at 1040°F increased when irradiated. This increase in yield strength is questionable; it is not consistent with other results obtained for Inconel 625 in this test or those obtained for similar metals under comparable conditions. No explanation can be offered for this anomaly.

3. Sheet

Inconel 625 sheet material tended to decrease in strength with increasing neutron exposure. This effect was evident at both the 1290 and the 1540°F test temperatures. The maximum change in yield strength was shown by specimens irradiated to 1×10^{19} nvt ($E < 0.48$ ev) and tested at 1290°F. Their average yield strength decreased 15%.

The strength properties of Hastelloy X sheet were unaffected by irradiation, except at the intermediate exposure of 4×10^{18} nvt ($E < 0.48$ ev) and the test temperature of 1540°F. For these conditions, the ultimate and yield strengths increased an average of 15%. Additional data would be required before any significance could be attached to these results.

The stainless-steel sheet tended to increase in strength with irradiation.

D. DUCTILITY

1. General

High-temperature ductility was the mechanical property most affected by irradiation. Appreciable reductions in ductility resulted from irradiation, as evidenced by the changes in elongation at break and in the reduction in area. For example, elongation at 1540°F decreased about 60% for all materials irradiated to a fluence of 1×10^{19} nvt ($E < 0.48$ ev).

Significant changes occurred for Hastelloy X at fluences as low as 6×10^{17} nvt ($E < 0.48$ ev) and at test temperatures as low as 1040°F.

2. Materials

As noted above, Hastelloy X was the most susceptible to ductility changes in terms of test temperature and thermal-neutron fluence thresholds. At the intermediate and high test temperatures and irradiation levels, Hastelloy X and Inconel 625 showed about the same decreases in elongation and in reduction in area.

Changes in ductility for AISI 347 stainless steel were less than those for Hastelloy X and Inconel 625, except at the highest test temperatures and irradiation levels, where changes in percent elongation and area reduction were about the same for all materials.

At the 780°F test temperature, irradiation of Hastelloy X resulted in a significant increase in its ductility, as measured by percent elongation and area reduction. No radiation effects on ductility could be detected at the same temperature for AISI 347 stainless steel; however, irradiated weldments of this material tested at 1040°F showed significant increases in ductility. Effects of radiation on the ductility of Inconel 625 at 780°F were not determined.

3. Form

The ductility of Hastelloy X forgings at 1040°F decreased significantly as a result of irradiation, while that of Hastelloy X weldments did not.

4. Temperature Effects

The ductility of all unirradiated materials increased rapidly with temperature at temperatures of 1290°F and above. The ductility of irradiated Hastelloy X and Inconel 625 either decreased or did not change with temperature. The ductility of irradiated AISI 347 stainless steel increased less rapidly with temperature than the ductility of the unirradiated material.

E. HARDNESS

No significant effects of radiation on hardness could be detected, except in the case of AISI 347 stainless steel, as shown in Table 10. Hardness of this material in sheet and forged form, in the strained and unstrained condition, and under exposure to all test temperatures increased with irradiation.

All material specimens showed the effects of strain hardening except the specimens exposed to the 1540°F test temperature. AISI 347 stainless steel was the material most affected by strain hardening.

F. DISCUSSION

1. Tensile and Yield Strengths

Inconel 625 sheet tested at 1290°F after the maximum exposure showed significant decreases of 15 and 10% in yield and ultimate tensile strengths, respectively. The decrease in yield is anomalous; such changes are

rarely observed in high-temperature postirradiation testing*. However, the small decrease in tensile strength is a result of fracture prior to the completion of strain hardening, as is apparent from the 1290°F stress-strain curves in Figure 34. This explanation does not apply to possible decreases at 1540°F, because strain hardening does not occur at this temperature.

2. Ductility

Sufficient data were obtained to show the approximate thresholds of temperature and radiation damage for the three materials tested. These thresholds are apparent from inspection of Figures 1 through 4. Although the three materials had large reductions in high-temperature ductility when irradiated, they retained good ductility at the maximum temperature (1590°F) after irradiation to the maximum thermal-neutron fluence of 1×10^{19} nvt ($E < 0.48$ ev). For these conditions, elongation at break was 20% for Hastelloy X and Inconel 625 and was 35% for AISI 347 stainless steel.

Effects of radiation on high-temperature ductility were observed for materials with relatively low boron contents - 2 ppm for Hastelloy X, 15 ppm for Inconel 625, and 7 ppm for AISI stainless steel in the case of sheet material.

3. Damage Mechanisms

The results show that ductility losses did not begin to manifest themselves until a test temperature of 1040°F had been reached. This result is consistent with the results** of other investigators,

*W.R. Martin and J. R. Weir, Nuclear Applications, Vol 1/2, April 1965, p 160.

**P. C. L. Pfeil and D. R. Harries, Flow and Fracture of Metals and Alloys in Nuclear Environments, ASTM STP 380, ASTM, Philadelphia, 1965, p 202.

who place the temperature threshold for this phenomenon at about 1000°F. The losses increased with test temperature and thermal-neutron fluence.

The dominant cause of high-temperature embrittlement of irradiated metals is considered to be the presence of low concentrations of helium at grain boundaries*. The helium originates from the $n-\alpha$ reaction in which thermal neutrons react with traces of boron in a metal to yield Li^7 and alpha particles. Helium gas formed from the alpha particles will concentrate at the grain boundaries if test temperatures are high enough for helium diffusion to occur. Presence of helium at the grain boundaries acts to reduce grain-boundary sliding, thus decreasing elongation.

Test results indicate that the mechanism described above may be responsible for the observed effects on high-temperature ductility. Most outstanding were the effects of test-temperature increases described in Paragraph D.4 above. Evaluation of metallography will provide an increased understanding of the mechanisms involved.

*J. Moteff, F. C. Robertshaw, and F. D. Kingsbury; J. Nuclear Mats, Vol 17, 1965, p 245; and W. R. Martin and J. R. Weir, J. Nuclear Mats, Vol 18, 1966, p 18.