NUCLEAR DIVISION

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To AEC-NASA Space Nuclear Propulsion Office

FINAL REPORT

GTR-19 TEST

TO DETERMINE CRYOGENIC RADIATION EFFECTS
ON STRUCTURAL MATERIALS

NERVA Program

Contract SNP-1

September 1969

MASTER

NUCLEAR ROCKET OPERATIONS

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CONTRACT SNP-1

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SEPTEMBER 1969

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Sept. 3, 1969
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FINAL REPORT

GTR-19 TEST
TO DETERMINE CRYOGENIC RADIATION EFFECTS
ON STRUCTURAL MATERIALS *308*

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I. INTRODUCTION

A. GTR-19

The GTR-19 irradiation test was performed at the General Dynamics 10-Mw facility in Fort Worth. Alloys in various forms were irradiated at both cryogenic and ambient temperatures and subsequently tested for mechanical properties at temperatures that ranged from 36 to 1660°R. The tests were performed for Aerojet-General Corporation and the Westinghouse Astronuclear Laboratory in support of the NERVA Program directed by SNPO-C. The experimental work was completed in April 1968.

Test details and procedures are described in reports issued by General Dynamics, Fort Worth Division (References 1, 2, and 3). Reports evaluating the test data to date include two by Westinghouse on Ti 5Al 2.5Sn ELI and Al 2219 (References 4 and 5), and two by Aerojet-General on a comparison of the effects of irradiation in liquid hydrogen and liquid nitrogen (References 6 and 7).

B. TEST 37R006

This report summarizes the AGC test of cryogenic structural materials (Test 37R006), which was performed to: (1) screen prospective materials for NERVA applications; (2) provide preliminary data for determining design properties; and (3) evaluate the combined effects on tensile properties of radiation environment, temperature, material, and form.

In References 6 and 7, the effects of irradiation in liquid hydrogen and in liquid nitrogen are compared. Some of the results are discussed in this report.

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II. SUMMARY

Ten structural alloys in 23 different forms were irradiated and tested in liquid nitrogen to neutron fluences of approximately 10^{18} nvt $\sim$ 1.0 Mev.* In addition, seven structural alloys were irradiated and tested in liquid hydrogen and liquid nitrogen to neutron fluences of approximately 3×10^{17} nvt $\sim$ 1.0 Mev.

Summaries of properties determined for the control and the irradiated specimens of each material are given in Tables 1, 2, and 3. Figures 1, 2, and 3 show the effects on ultimate strength, yield strength, and elongation for the alloys irradiated to 10^{18} nvt.

The materials generally exhibited significant increases in yield strength and notched strength, minor increases in ultimate strength, and decreases in elongation that varied in significance. The performance of Ti 5Al 2.5Sn was an exception; the notch strength decreased significantly. In some cases, the magnitude of radiation effects was found to be significantly influenced by the form of the material.

The property changes detected after irradiation in liquid nitrogen and in liquid hydrogen were essentially the same when compared on the basis of percent change in the property from that of the unirradiated value. The most significant exception was the change in yield strength for Al 6061-T6; the percent change in yield strength was more than twice as great in liquid hydrogen as in liquid nitrogen.

*" $\sim$ 1.0 Mev" is equivalent to "energy $\sim$ 1.0 Mev." This convention will be used throughout the report.

TABLE 1

AVERAGE TENSILE PROPERTIES AT 140°R OF ALLOYS
BEFORE AND AFTER IRRADIATION AT 140°R

Alloy	Form	Fluence 10 ¹⁷ nvt >1 mev	Ultimate Strength, ksi		Yield Strength, ksi		Elongation %	
			Control	Irrad.	Control	Irrad.	Control	Irrad.
Al 6061-T6	1/4 inch plate	3	61.1	61.6	49.6	57.7*	20.8	16.5*
	Ring forging	11	64.1	65.8	51.6	62.4*	16.5	14.2*
	Welded ring forging	11	58.7	61.4*	47.9	59.1*	18.7	8.4*
	Pressure vessel forging	11	62.5	66.4*	53.5	64.3*	6.6	7.0
Al 7075-T73	Forging	9	91.1	93.0*	75.2	82.2*	13.4	12.2*
Al 7039-0	Forging	9	50.7	56.2*	23.4	46.5*	12.7	9.0
Ti 5Al- 2.5Sn ELI	5/16 inch plate	3	197.4	200.5	187.2	192.8	12.4	10.8*
	Forging	11	182.0	197.7*	174.2	188.0*	10.8	7.6*
	EB weldment	9	184.4	197.6*	175.4	189.6*	14.2	7.3
	TIG weldment	9	185.3	199.4*	178.2	194.3*	15.9	9.0*
	Pressure vessel forging	8	180.7	195.1*	175.6	191.8*	16.6	12.2*
A-286	Forging	3	197.3	199.6	131.5	136.3	31.7	33.4
	Forging	12	193.9	196.6	130.6	147.0*	28.8	28.7
AISI 347	1/4 inch plate	3	213.6	210.4	65.4	85.2*	32.3	33.1
	Welded plate	4	208.4	204.7	54.8	77.6*	27.1	28.1
Hastelloy X	Forging	3	142.7	148.1*	80.4	106.0*	45.4	40.5
	Forging	8	140.8	155.4*	77.1	112.6*	44.7	36.6*
	Weldment	8	135.3	144.4*	80.9	115.8*	26.0	15.5*
Inconel 625	Plate	11	154.1	166.1*	73.2	123.4*	56.8	46.0*
	TIG weldment	11	151.2	169.5*	88.7	125.5*	30.2	27.6
Waspaloy	Cold reduced	8	311.0	302.7	283.7	295.0	11.1	8.1*
Udimet 630	Forging	12	259.4	258.4	209.6	226.8*	21.0	18.1
	Cold reduced rod	8	334.6	335.0	332.9	332.2	5.7	5.5
Inconel 718	Forging	3	263.8	257.8	217.9	225.0*	21.4	20.7*
	Ring forging	9	252.1	252.4	199.4	225.7*	17.2	14.5*
	EB weldment	9	241.8	245.6*	199.8	223.0*	17.2	15.0
	TIG weldment	9	243.0	243.1	201.3	220.0*	14.7	10.4*
	All weld	9	239.9	249.0	205.2	222.6*	10.4	9.8
	Cold reduced rod	8	288.9	296.4*	277.0	289.4*	12.2	9.4*

*The difference between the control and irradiated values is statistically significant at the 90% confidence level.

TABLE 2

AVERAGE TENSILE PROPERTIES OF
ALLOYS AT 40°R BEFORE AND
AFTER IRRADIATION AT 40°R(1)

Alloy	Form	Ultimate Strength, ksi		Yield Strength, ksi		Elongation %	
		Control	Irrad.	Control	Irrad.	Control	Irrad.
Al 6061-T6	1/4 inch plate	73.7	76.6*	52.9	72.2*	26.4	18.1*
Ti 5Al 2.5Sn ELI	5/16 inch plate	234.8	243.8*	217.5	233.3*	9.6	10.3
A-286	Forging	208.5	204.4	146.8	156.5*	25.8	23.0*
AISI 347	1/4 inch plate	230.0	228.4	65.6	87.3*	27.2	26.2
	Welded 1/4 inch plate	203.8	208.3	67.1	90.0*	21.9	19.7
Hastelloy X	Forging	154.6	163.8*	98.5	121.8*	33.6	32.8
Inconel 718	Forging	265.6	269.7	219.7	234.4*	18.4	18.2
H Monel	Cast Plate	103.6	116.6*	58.9	98.3*	23.2	11.8*

(1) Specimens were irradiated to approximately 3×10^{17} nvt > 1 mev.

* The difference between the control and irradiated values is statistically significant at the 90% confidence level.

TABLE 3

AVERAGE NOTCH STRENGTH AND NOTCH STRENGTH
RATIO OF ALLOYS AT 140°R BEFORE AND
AFTER IRRADIATION AT 140°R

Alloy	Form	Fluence 10^{17} nvt >1 mev	K_T	Notch Strength		Notch	
				Value, ksi		Strength Ratio	
				Control	Irrad	Control	Irrad
Al 6061-T6	Ring forging	6	17	59.2	68.2*	0.92	1.04
	Welded ring forging	6	17	50.2	55.4	0.85	0.90
	Pressure vessel forging	11	6.3	85.6	89.1	1.37	1.34
Al 7075-T73	Forging	9	6.3	106.8	107.3	1.17	1.15
Ti 5Al 2.5Sn ELI	Forging	6	17	175.7	131.4*	0.96	0.67
	EB weldment	6	17	168.3	142.3*	0.91	0.72
	TIG weldment	17	17	148.2	167.2*	0.80	0.84
	Pressure vessel forging	8	6.3	252.8	222.7*	1.40	1.14
A-286	Forging	12	6.3	235.0	247.6*	1.21	1.26
Hastelloy X	Weldment	8	6.3	163.2	193.9*	1.21	1.34
Inconel 625	TIG weldment	6	17	116.8	137.4*	0.77	0.84
Udimet 630	Forging	12	6.3	269.8	342.2*	1.04	1.35
Inconel 718	Ring forging	6	17	223.7	242.7*	0.89	0.96
	TIG weldment	9	6.3	260.2	277.0	1.07	1.14
	TIG weldment	6	17	192.8	181.0	0.79	0.74
H Monel	Cast plate	3 ⁽¹⁾	6.3	100.8 ⁽¹⁾	122.4 ^{(1)*}	0.97	1.05

(1) Irradiated and tested at 40°R.

* The difference between the control and irradiated values is statistically significant at the 90% confidence level.

Figure 1 - Ultimate Strength of Alloys at 140°R Before and After
Irradiation to Approximately 1×10^{18} nvt > 1.0 Mev at 140°R

Figure 2 - Yield Strength of Alloys at 140°R Before and After
Irradiation to Approximately 1×10^{18} nvt > 1.0 Mev at 140°R

Figure 3 - Elongation of Alloys at 140°R Before and After Irradiation to Approximately 1×10^{18} nvt > 1.0 Mev at 140°R

III. TEST ITEMS, PROCEDURES, AND CONDITIONS

A. MATERIALS

Materials selected for testing were being considered for various structural applications in a cryogenic environment. The alloys and their forms, processing history, and specifications are shown in Table 4. Their chemistry is shown in Table 5. Their room-temperature properties, as determined in this test, are shown in Table 6.

B. SPECIMENS

Test specimens were the modified R-3 type. Their designs are shown in Figures A-1 through A-10 in the Appendix. All designs were influenced by requirements to minimize personnel exposure to radioactive material and to permit cryogenic testing after cryogenic irradiation without an intervening warmup period for the specimen. Designs in some cases were also constrained by stock dimensions. Fabrication of weldment specimens is shown schematically in Figure 4.

C. PROCEDURE

Specimens were irradiated at the General Dynamics, Fort Worth Division, Nuclear Aerospace Research Facility and were subsequently tested in a cryogenic environment at the same facility. Time-temperature histories of the tests are shown in Figure 5.

Irradiation was performed in both liquid nitrogen and liquid hydrogen, in three Dewars. Two (one for liquid-hydrogen service, the other for liquid-nitrogen service) were fitted with remotely operated pulling assemblies (called cryotensile testers or CTTs) and were used to compare the properties of alloys irradiated in liquid hydrogen and in liquid nitrogen.

TABLE 4
SPECIMEN PEDIGREE

Alloy	Form	Material Data					Specimen Preparation		
		Specification	Heat Treat	Dimensions or Descriptions	Vendor	Heat No.	Parent Metal or Welded	Heat Treat	Rockwell Hardness
A1 6061-T6	0.25 in. plate	QQ-A-327b	Commercial	1/4 in. x 36 in. x 48 in.	Reynolds Aluminum Sup. Co.	Commercial	Parent	None	
A1 6061-T6	Ring forging	QQ-A-367	MIL-H-6088	20 in. OD x 18 in. ID x 6 in.	Ladish Pacific	LA 6603	Parent	None	65B
A1 6061-T6	Ring forging	QQ-A-367	MIL-H-6088	20 in. OD x 18 in. ID x 6 in.	Ladish Pacific	LA 6603	Welded Alcoa Almig weld C809 filler	MIL-H-6066 to T-6	63B
A1 6061-T6	Forging	QQ-A-367	MIL-H-6088	Pressure vessel	Taylor Forge and Pipe Works	Alcoa CH-68612-C	Parent	None	99E
A1 7075-T73	Forging	MIL-A-22771	MIL-H-6088C	Impeller blank	Paragon Tool Die and Engr.		Parent	None	78B
A1 7039-0	Ring forging	ASTM B 209		5-1/2 in. x 1/2 in. x 35 in. (sector)	Alcoa Cleveland, ACFI		Parent	None	23B
Ti 5A1-2.5Sn ELI	Plate	MIL-T-9046E Type II	Commercial stock annealed	5/16 in. x 36 in. x 96 in.	Titanium Metals	D-9027	Parent	None	
Ti 5A1-2.5Sn ELI	Ring forging	MIL-T-9047C Type II	1500°F 1 hr, air cool	20-1/4 in. OD x 17-1/2 in. ID x 8-1/2 in.	Reisner Metals, Inc.	301635	Parent	None	29C
Ti 5A1-2.5Sn ELI	Ring forging	MIL-T-9047C Type II	1500°F 1 hr, air cool	20-1/4 in. OD x 17-1/2 in. ID x 8-1/2 in.	Reisner Metals, Inc.	301635	Electron beam weld	Anneal 1200°F, 3 hours	30C
Ti 5A1-2.5Sn ELI	Ring forging	MIL-T-9047C Type II	1500°F 1 hr, air cool	20-1/4 in. OD x 17-1/2 in. ID x 8-1/2 in.	Reisner Metals, Inc.	301635	TIG glove box weld. AMS 4953 wire from Abell Welding Supply Heat 222401	Anneal 1200°F, 3 hours	31C
Ti 5A1-2.5Sn ELI	Forging	MIL-T-9047 Class 2	1350°F 2 hr, air cooled	Pressure vessel	Wyman Gordon Co.		Parent	None	29C
A-286	Disc forging	AMS 5735	Solution annealed and aged	13 in. dia x 1 in.	Coulter Steel Forge Company	C5036K1	Parent	None	36C

TABLE 4 (cont.)

Alloy	Form	Material Data					Specimen Preparation		
		Specification	Heat Treat	Dimensions or Descriptions	Vendor	Heat No.	Parent Metal or Welded	Heat Treat	Rockwell Hardness
Inconel 718	Forging	AGC 44151	Solution annealed and aged per AGC 46604	8 in x 12 in. x 2-1/2 in	West Coast Forge	7049	Parent	None	
Inconel 718	Ring forging	AGC 44194A	Annealed at 1950°F 1 hr, Rapid air cool	23 in. OD x 21-1/2 in. ID x 4.7 in.	Reisner Metals, Inc.	8289	Parent	Aged per AGC 46604	43C
Inconel 718	Ring forging	AGC 44194A	Annealed at 1950°F 1 hr, Rapid air cool	23 in. OD x 21-1/2 in. ID x 4.7 in.	Reisner Metals, Inc.	8289	Electron beam weld.	Solution annealed and aged per AGC 46604	43C
Inconel 718	Ring	AGC 44194A	Annealed at 1950°F 1 hr, Rapid air cool	23 in. OD x 21-1/2 in. ID x 4.7 in.	Reisner Metals, Inc.	8289	TIG welded AGC 44131 filler wire. Techalloy Heat 4735E	Solution annealed and aged per AGC 46604	43C
Inconel 718	Filler wire	AGC 44131	-	-	Techalloy Co., Inc.	4735E	Specimen fabricated from weld fillet	Solution annealed and aged per AGC 46604	44C
Inconel 718	Rod		1950°F 1 hr, air cool Cold reduced 36 - 40%	1/2 in. dia x 3+ in.	Standard Pressed Steel Co.	B-347	Parent	1250°F, 8 hr, 1150°F, 10 hr, air cool Finish machining	45C
H Monel	Cast plate	QQ-N-288-Comp B	1600°F 1 hr, furnace cool to 1300°F 0.5 hr, air cool	1/4 in. thick	Dareron Alloy Foundry	Lot No. 6192	Parent	None	

TABLE 4 (cont.)

Alloy	Form	Material Data					Specimen Preparation		
		Specification	Heat Treat	Dimensions or Descriptions	Vendor	Heat No.	Parent Metal or Welded	Heat Treat	Rockwell Hardness
AISI 347	0.25 in. plate	AMS 5512	Commercial stock annealed	1/4 in. x 8 ft x 3 ft	Ducommun Metals Supply	Allegheny Ludlum 29001-6	Parent	None	
AISI 347	0.25 in. plate	AMS 5512	Commercial stock annealed	1/4 in. x 8 ft x 3 ft	Ducommun Metals Supply	Allegheny Ludlum 29001-6	TIG weld 349 SS weld wire, AMS 5782. McKay Heat A1615	Annealed	
Hastelloy X	Ring forging	AGC 90056	Annealed at 2150°F 1 hour air cool	20 in. OD x 18 in. ID x 6 in.	Viking Forge and Steel Co.	261-4-4000	Parent	2080°F, 45-min air cool	82B
Hastelloy X	Ring forging	AGC 90056	Annealed at 2150°F 1 hour air cool	20 in. OD x 18 in. ID x 5 in.	Viking Forge and Steel Co.	261-4-4000	Welded. Filler Heat X5-2784	Anneal 2150°F	-
Inconel 625	Forged plate	AGC 90057	As forged	1-1/2 in. x 12 in. x 36 in.	Alvac Metals Company	5942	Parent	2150°F, 30 min. Quenched in hydrogen from 2150°F to 1000°F in five minutes	87B
Inconel 625	Forged plate	AGC 90057	As forged	1-1/2 in. x 12 in. x 36 in.	Alvac Metals Company	5942	TIG weld. Filler wire made from stock	2150°F. Water quench	90B
Waspaloy	Rod		1875°F 4 hr, water quench Cold reduced 36 - 40%	1/2 in. dia x 3+ in.	Standard Pressed Steel Co.	5557	Parent	1375°F, 24 hr, air cool; 1225°F, 16 hr, air cool; finish machining	49C
Udimet 630	Disc forging	Special Metals, Inc. Report dated 12-16-64	As forged	12 in. dia x 1 in.	Reisner Metals, Inc.	7-1990	Parent	1875°F, 4 hr, air cool; 1400°F, 8 hr, air cool; 1200°F, 10 hr, air cool	45C
Udimet 630	Rod		1875°F 8 hr, air cool Cold reduced 36 - 40%	1/2 in. dia x 3+ in.	Standard Pressed Steel Co.	6-3596	Parent	1300°F, 8 hr, air cool; 1100°F, 10 hr, air cool; finish machining	52C

TABLE 5
CHEMICAL ANALYSIS OF ALLOYS

Alloy	Form	Element, Mass Percent																							
		Ni	Mo	Cr	Fe	C	Cb	Mn	Si	Al	Mg	Zn	Ti	Sn	W	V	Zr	Cu	Co	P	S	B	H	O	N
Al 6061	Plate	<0 02	--	0 22	0 41	--	--	0 07	0 62	Bal	0 98	<0 10	0 03	--	--	--	--	0 25	--	--	--	--	--	--	--
	Ring Forging	0 02	--	0 22	0 29	--	--	0 03	0 62	Bal	0 98	0 10	0 02	--	--	--	--	0 28	--	--	--	--	--	--	--
	Filler Wire	0 02	--	<0 02	--	0 27	--	0 03	4 14	Bal	0 20	0 10	--	--	--	--	--	<0 05	--	--	--	--	--	--	--
	Pressure Vessel Forging*	Min --	--	0 04	--	--	--	--	0 40	Bal	0 8	--	--	--	--	--	--	0 15	--	--	--	--	--	--	--
		Max --	--	0 35	0 7	--	--	0 15	0 80	Bal	1 2	0 25	0 15	--	--	--	--	0 40	--	--	--	--	--	--	--
Al 7075	Forging	0 02	--	0 22	0 14	--	--	0 03	0 10	Bal	2 2	5 3	0 08	--	--	--	--	1 4	--	--	--	--	--	--	--
Al 7039	Forging	--	--	0 20	0 18	--	--	0 19	0 15	Bal	2 54	3 94	0 022	--	--	--	--	0 068	--	--	--	--	--	--	--
Ti 5Al 2 5Sn ELI	Plate	--	--	--	0 14	0 026	--	--	--	5 1	--	--	Bal	2 4	--	--	--	--	--	--	--	--	0 007	0 10	0 016
	Ring Forging	--	--	--	0 18	0 02	--	0 01	--	5 5	--	--	Bal	2 6	--	--	--	--	--	--	--	--	0 013	0 074	0 005
	Filler Wire	--	--	--	0 065	0 014	--	0 019	--	5 58	--	--	Bal	2 6	--	--	--	--	--	--	--	--	0 0045	0 10	0 010
	Pressure Vessel Forging*	Min --	--	--	--	--	--	--	--	4 70	--	--	Bal	2 00	--	--	--	--	--	--	--	--	--	--	--
		Max --	--	--	0 25	0 08	--	--	--	5 60	--	--	Bal	3 00	--	--	--	--	--	--	--	--	0 125	0 12	0 07
A-286	Forging	25 20	1 38	14 36	Bal	0 053	--	1 27	0 49	0 23	--	--	2 30	--	--	0 23	--	--	--	0 022	0 004	0 004	--	--	--
AISI 347	Plate	9 82	--	17 72	Bal	0 056	--	1 65	0 60	--	--	--	--	--	--	--	--	--	--	0 018	0 008	--	--	--	--
AISI 349	Filler Wire	9 18	0 56	19 60	Bal	0 100	1 30	1 35	0 35	--	--	--	0 20	--	1 50	--	--	0 11	--	0 015	0 006	--	--	--	--
Hastelloy-X	Forging	Bal	9 05	21 77	18 22	0 12	--	0 66	0 32	0 14	0 01	--	0 01	--	0 48	0 01	--	0 03	1 59	0 001	0 010	0 0007	--	--	--
	Filler Wire	Bal	8 93	21 42	18 36	0 08	0 063	0 63	0 37	--	0 23	--	0 23	--	0 61	--	--	0 03	1 98	0 012	0 002	0 0006	--	--	--
Inconel 625	Forging	Bal	7 89	21 00	2 42	0 042	3 92	0 01	0 01	0 07	--	--	0 03	--	0 01	0 04	--	0 05	0 07	0 004	0 003	0 0008	--	--	--
	Filler Wire	Bal	7 89	21 00	2 42	0 042	3 92	0 01	0 01	0 07	--	--	0 03	--	0 01	0 04	--	0 05	0 07	0 004	0 003	0 0008	--	--	--
Waspaloy	Rod	Bal	4 33	18 95	0 51	0 081	--	0 03	0 09	1 46	--	--	2 98	--	--	--	0 07	0 02	13 7	0 005	0 003	0 007	--	--	--
Udimet 630	Forging	Bal	2 75	17 6	17 1	0 03	6 05	0 1	0 10	0 13	--	--	0 89	--	2 80	--	--	0 10	0 11	0 01	0 006	0 004	--	--	--
	Rod	Bal	2 90	17 5	17 2	0 04	6 20	0 21	0 10	0 61	--	--	1 05	--	2 75	--	--	0 10	0 10	0 01	0 004	0 004	--	--	--
Inconel 718	Forging (West Coast)	51 83	3 07	18 55	Bal	0 03	5 31	0 21	0 31	0 37	--	--	0 87	--	--	--	--	0 04	0 05	--	0 007	0 0018	--	---	--
	Forging (Reisner)	53 30	3 10	18 50	Bal	0 05	5 25	0 10	0 18	0 50	--	--	1 05	--	--	--	--	0 10	0 10	0 01	0 003	0 0046	--	--	--
	Filler Wire	53 68	3 20	18 21	17 2	0 05	5 48	0 26	0 24	0 56	1 02	--	1 02	--	--	--	--	0 06	--	0 007	--	--	--	--	--
	Rod	52 24	2 96	19 31	Bal	0 039	5 18	0 01	0 05	0 48	0 78	--	0 78	--	--	--	--	0 10	0 04	0 007	0 008	0 0046	--	--	--
H Mone1	Cast Plate	Bal	--	--	1 95	0 04	--	1 00	4 64	--	--	--	--	--	--	--	--	31 80	--	--	--	--	--	--	--

*Compositions of the Ti 5Al 2 5Sn pressure vessel forging and the Al 6061 pressure vessel forging met the requirements of MIL-T-9047D Type IIB and QQ-A-367g, respectively. Specification limits are shown.

TABLE 6

TENSILE PROPERTIES OF ALLOYS AT ROOM TEMPERATURE

Alloy	Form	Ultimate Strength, ksi	Yield Strength, ksi	Elongation %	Reduction of Area %	Notch Strength	
						K _T	Value, ksi
Al 6061-T6	1/4 inch plate	46.1	42.2	14.1	47.0	--	--
	Ring forging	47.5	41.9	14.8	28.2	17	67.4
	Welded ring forging	44.5	40.0	14.4	39.5	17	63.3
Al 7075-T73	Forging	70.2	60.7	12.9	36.6	6.3	91.8
Al 7039-T0	Forging	37.3	17.6	14.0	17.4	--	--
Ti 5Al 2.5Sn ELI	5/16 inch plate	120.8	112.2	12.7	32.0	--	--
	Forging	120.5	114.4	13.4	29.5	17	126.6
	EB weldment	120.5	115.4	13.3	13.1	17	129.8
	TIG weldment	119.1	112.5	12.3	35.6	17	123.7
A-286	Forging	150.8	112.9	24.3	34.4	6.3	199.3
AISI 347	1/4 inch plate	95.7	39.5	44.7	68.8	--	--
	Weldment	94.9	41.6	37.1	52.6	--	--
Hastelloy X	Forging	100.0	46.7	50.9	47.1	--	--
	Weldment	97.2	46.0	42.6	45.4	6.3	113.4
Inconel 625	Plate	112.0	47.0	51.6	48.0	--	--
	TIG weldment	114.6	60.6	39.4	38.0	17	84.3
Waspaloy	Cold reduced rod	254.6	249.7	6.2	25.8	--	--
Udimet 630	Forging	201.2	178.2	17.8	32.0	6.3	239.8
	Cold reduced rod	277.4	276.7	5.8	31.2	--	--
Inconel 718	Forging	196.2	176.2	19.4	43.6	--	--
	Ring forging	192.9	174.0	22.1	42.5	17	223.7
	EB weldment	194.2	176.3	13.1	29.2	--	--
	TIG weldment	198.8	179.6	12.6	14.7	17	165.0
	TIG weldment	--	--	--	--	6.3	227.6
	All weld	187.5	174.2	5.4	15.0	--	--
	Cold reduced rod	235.2	234.8	7.6	36.5	--	--
H Monel	Cast plate	85.2	44.0	29.0	31.0	6.3	74.4

Figure 4 - Preparation of Weldment Specimen (Schematic)

* During checkout, the temperature of the specimens to be irradiated was cycled between ambient temperature and irradiation temperature two or more times.

Figure 5 - Time-Temperature History of Test

The third (called static-test Dewar) was for liquid-nitrogen service and was used for the irradiation of most specimens.

Specimens in the CTT Dewars were tested in place in the irradiation cell. Specimens in the static Dewar were tested after they had been transferred in liquid nitrogen to a Dewar mounted in a conventional test machine. All specimens were tested without intervening warmup, except those used for annealing studies. During testing, both cross-head speed (in the case of the static specimens) and pulling-assembly pull-rod speeds (in the case of the CTT specimens) were maintained at 0.05 in./min. The resulting strain rate in the plastic region was a nominal 0.04 in./in./min.

Elongation and area-reduction data were determined from bench measurements of tested specimens by using a toolmaker's microscope. Elongation data obtained from test-machine charts were used to supplement the bench elongation data.

Specimens in all Dewars were scheduled to be irradiated to a fluence of approximately 1×10^{18} nvt > 1.0 Mev. Irradiation of the two CTT Dewars was interrupted because of a suspected hydrogen leak. The approximate fluences actually received by each Dewar were:

CTT Dewars - 2.2 to 3.5×10^{17} nvt > 1.0 Mev

Static Dewar - 8 to 12×10^{17} nvt > 1.0 Mev

A total of 250 irradiated and 200 control specimens was tested. Table 7, a summary by test condition and alloy, indicates the scope of the testing.

TABLE 7
SPECIMEN SUMMARY

Alloy and Form	Quantity of Cryogenic Specimens					
	CTT-LH ₂ Tests ²		CTT-LN ₂ Tests ²		Static-LN ₂ Tests ²	
	Control	Irrad ⁽¹⁾	Control	Irrad ⁽²⁾	Control	Irrad ⁽³⁾
Al 6061-T6 Plate Ring forging Welded ring forging Pressure vessel forging	4	6	4	4	8 8 7	8 8 5
Al 7075-T73 Forging					8	1
Al 7039-0 Forging					4	4
Ti 5Al 2.5Sn ELI Plate Forging EB welded forging TIG welded forging Pressure vessel forging	4	6	4	4	8 8 8 8	8 8 8 16
A-286 Forging	4	4	4	3	8	13
AISI 347 Plate Weldment	4 4	4 4	4 4	4 4		
Hastelloy-X Forging Weldment	4	5	4	3	4 8	13 12
Inconel 625 Plate Weldment					4 8	4 8
Waspaloy Cold reduced rod					4	4
Udimet 630 Forging Cold reduced rod					8 4	8 4
Inconel 718 Forging Ring forging EB welded ring forging TIG welded ring forging All weld Cold reduced rod	4	4	4	4	8 4 12 4 4	8 4 12 4 4
H Monel Cast plate	8	8				

- (1) Specimens in the CTT-LH₂ Dewar (40°R) were exposed to $2.2 - 3.5 \times 10^{17}$ nvt > 1.0 mev.
 (2) Specimens in the CTT-LN₂ Dewar (140°R) were exposed to $2.5 - 3.4 \times 10^{17}$ nvt > 1.0 mev.
 (3) Specimens in the static-LN₂ Dewar (140°R) were exposed to $8 - 12 \times 10^{17}$ nvt > 1.0 mev.

IV. TEST RESULTS

A. PROPERTY VALUES

Results obtained for each group of specimens are summarized in Tables 8 through 17, each covering a specific material. Mean values and standard deviations are given for ultimate and yield tensile strengths, elongation, reduction in area, notch strength, and fracture strength. The elongation reported is the elongation at break for a nominal 1-in. gage length.

Property values determined for individual specimens are given in Appendix Tables A-1 through A-12. These tables are based on data provided in Reference 1 that were refined after data evaluation by remeasurement or by reobservation and recalculation.* The mean values and standard deviations** reported in Tables 8 through 17 were derived from the individual values reported in Tables A-1 through A-12 after rejection of faulty data or outliers as determined by Dixon's criteria (Reference 8). The values reported for neutron fluences were estimated to have an uncertainty of less than 25%. Property values obtained for specimens tested in the CTT Dewars generally had significantly greater variances than those for specimens tested in the static Dewars. This difference was expected because of difficulties in obtaining optimum specimen alignment and limitations of the data-acquisition equipment associated with the remotely operated testing equipment.

*In the case of elongation results, test-machine chart data served to supplement bench measurement data. For example, where it was apparent that a bench measurement procedure had been faulty, chart data were used to derive the elongation value for a given specimen. This value was given equal weight with bench measurements made on other specimens in determining the mean value for a group. Those instances where values were derived from chart data are noted in Tables A-1 through A-12.

**The standard deviation was computed as:

$$\sqrt{\frac{\sum_{i=1}^n X_i^2 - \frac{(\sum_{i=1}^n X_i)^2}{n}}{n(n-1)}} .$$

TABLE 8
TENSILE PROPERTY SUMMARY
ALUMINUM ALLOYS

Material Form	Environment				Property		Sample Size
	Neutron Fluence nvt (E > 1.0 Mev)	Temp. °R		Mean Value	Std. Dev.		
		Irrad.	Test				
ULTIMATE STRENGTH, ksi							
6061-T6 Plate	none	-	40	73.7	1.85	4	
	3.0 x 10 ¹⁷	40	40	76.6	1.61	4	
	none	-	140	61.1	4.09	4	
	3.0 x 10 ¹⁷	140	140	61.6	0.60	4	
	none	-	540	46.1	0.53	4	
6061-T6 Ring Forging	2.2 x 10 ¹⁷	40	40 ⁽¹⁾	71.2	0.70	2	
	none	-	140	64.1	1.50	4	
	1.1 x 10 ¹⁸	140	140	65.8	1.72	4	
6061-T6 Welded Ring Forging	none	-	540	47.5	0.54	5	
	none	-	140	58.7	0.54	4	
	1.1 x 10 ¹⁸	140	140	61.4	1.07	4	
6061-T6 Pressure Vessel Forging	none	-	540	44.5	0.66	5	
	1.1 x 10 ¹⁸	-	140	62.5	1.38	3	
	1.1 x 10 ¹⁸	140	140 ⁽²⁾	66.4	1.70	4	
7039-0 Forging	1.1 x 10 ¹⁸	140	140 ⁽²⁾	64.1	1.54	3	
	none	-	140	50.7	1.05	4	
	9.0 x 10 ¹⁷	140	140	56.2	0.51	4	
7075-T73 Forging	none	-	540	37.3	0.46	4	
	9.0 x 10 ¹⁷	-	140	91.1	0.86	4	
	9.0 x 10 ¹⁷	140	140	93.0	0.43	4	
	9.0 x 10 ¹⁷	-	540 ⁽²⁾	70.2	1.23	4	
	9.0 x 10 ¹⁷	140	140 ⁽²⁾	89.9	2.40	2	
0.2% OFFSET YIELD STRENGTH, ksi							
6061-T6 Plate	none	-	40	52.9	1.40	4	
	3.0 x 10 ¹⁷	40	40	72.2	2.54	4	
	none	-	140	49.6	4.90	4	
	3.0 x 10 ¹⁷	140	140	57.7	0.24	4	
	none	-	540	42.2	0.57	4	
6061-T6 Ring Forging	2.2 x 10 ¹⁷	40	40 ⁽¹⁾	63.1	0.14	2	
	none	-	140	51.6	1.72	4	
	1.1 x 10 ¹⁸	140	140	62.4	1.55	4	
	none	-	540	41.9	0.58	5	

TABLE 8 (Cont.)
TENSILE PROPERTY SUMMARY
ALUMINUM ALLOYS

Material Form	Environment			Property		Sample Size
	Neutron Fluence nvt (E > 1.0 Mev)	Temp., °R		Mean Value	Std. Dev.	
		Irrad.	Test			
0.2% OFFSET YIELD STRENGTH, ksi (cont.)						
6061-T6 Welded Ring Forging	none	-	140	47.9	0.97	4
	1.1 x 10 ¹⁸	140	140	59.1	1.14	3
	none	-	540	40.0	0.88	5
6061-T6 Pressure Vessel Forging	none	-	140	53.3	0.98	4
	1.1 x 10 ¹⁸	140	140	64.3	2.90	4
	1.1 x 10 ¹⁸	140	140 ⁽²⁾	61.0	4.38	3
7039-0 Forging	none	-	140	23.4	0.57	4
	9.0 x 10 ¹⁷	140	140	46.5	0.90	3
	none	-	540	17.6	0.24	4
7075-T73 Forging	none	-	140	75.2	1.04	4
	9.0 x 10 ¹⁷	140	140	82.2	0.25	3
	none	-	540	60.7	1.51	4
	9.0 x 10 ¹⁷	140	140 ⁽²⁾	77.2	5.51	2
ELONGATION, %						
6061-T6 Plate	none	-	40	26.4	0.28	4
	3.0 x 10 ¹⁷	40	40	18.1	1.46	4
	none	-	140	20.8	0.57	4
	3.0 x 10 ¹⁷	140	140	16.5	0.78	4
	none	-	540	14.1	0.72	4
	2.2 x 10 ¹⁷	40	40 ⁽¹⁾	22.4	0.20	2
6061-T6 Ring Forging	none	-	140	16.5	0.60	3
	1.1 x 10 ¹⁸	140	140	14.2	1.54	4
	none	-	540	14.8	1.39	5
6061-T6 Welded Ring Forging	none	-	140	18.7	1.15	3
	1.1 x 10 ¹⁸	140	140	8.4	2.88	3
	none	-	540	14.4	2.49	4
6061-T6 Pressure Vessel Forging	none	-	140	6.6	1.47	3
	1.1 x 10 ¹⁸	140	140	7.0	1.78	3
	1.1 x 10 ¹⁸	140	140 ⁽²⁾	10.8	3.71	4

TABLE 8 (Cont.)

TENSILE PROPERTY SUMMARY
ALUMINUM ALLOYS

Material Form	Environment			Property		Sample Size
	Neutron Fluence nvt (E > 1.0 Mev)	Temp., °R		Mean Value	Std. Dev.	
		Irrad.	Test			
ELONGATION, % (cont.)						
7039-0 Forging	none	-	140	12.7	1.36	4
	9.0 x 10 ¹⁷	140	140	9.0	1.21	3
	none	-	540	14.0	2.33	4
7075-T73 Forging	none	-	140	13.4	1.76	4
	9.0 x 10 ¹⁷	140	140	12.2	1.84	4
	none	-	540	12.9	0.37	4
	9.0 x 10 ¹⁷	140	140 ⁽²⁾	11.6	1.41	2
REDUCTION IN AREA, %						
6061-T6 Plate	none	-	40	33.8	2.27	4
	3.0 x 10 ¹⁷	40	40	32.6	3.26	3
	none	-	140	36.1	3.01	4
	3.0 x 10 ¹⁷	140	140	34.6	2.06	4
	none	-	540	47.0	3.88	4
6061-T6 Ring Forging	2.2 x 10 ¹⁷	40	40 ⁽¹⁾	33.8	3.46	2
	none	-	140	25.0	4.20	3
	1.1 x 10 ¹⁸	140	140	23.9	4.94	4
	none	-	540	28.2	5.69	5
	6061-T6 Welded Ring Forging	none	-	140	40.3	1.15
1.1 x 10 ¹⁸		140	140	16.7	0.0	3
none		-	540	39.5	3.84	4
6061-T6 Pressure Vessel Forging	none	-	140	11.8	4.31	3
	1.1 x 10 ¹⁸	140	140	7.8	2.59	4
	1.1 x 10 ¹⁸	140	140 ⁽²⁾	19.8	4.94	4
7039-0 Forging	none	-	140	14.7	1.88	4
	9.0 x 10 ¹⁷	140	140	13.8	1.09	4
	none	-	540	17.4	3.51	4
7075-T73 Forging	none	-	140	19.1	1.42	4
	9.0 x 10 ¹⁷	140	140	17.7	4.99	4
	none	-	540	36.6	2.73	4
	9.0 x 10 ¹⁷	140	140 ⁽²⁾	21.0	3.32	2

TABLE 8 (Cont.)

TENSILE PROPERTY SUMMARY
ALUMINUM ALLOYS

Material Form	Environment			Property		Sample Size
	Neutron Fluence nvt (E > 1.0 Mev)	Temp., °R		Mean Value	Std. Dev.	
		Irrad.	Test			
NOTCH TENSILE STRENGTH, ksi ⁽³⁾						
6061-T6	none	-	140	59.2	3.16	4
Ring	5.7 x 10 ¹⁷	140	140	68.2	2.51	4
Forging	none	-	540	67.4	0.41	4
6061-T6	none	-	140	50.2	1.70	4
Welded	5.7 x 10 ¹⁷	140	140	55.4	8.68	4
Ring	none	-	540	63.3	3.11	4
Forging						
6061-T6	none	-	140	85.6	1.24	4
Pressure	1.1 x 10 ¹⁸	140	140	89.1	4.37	4
Vessel	1.1 x 10 ¹⁸	140	140 ⁽²⁾	77.8	8.54	4
Forging						
7075-T73	none	-	140	106.8	1.17	4
Forging	9.0 x 10 ¹⁷	140	140	107.3	5.76	4
	none	-	540	91.8	1.26	4
NOTCHED/UNNOTCHED RATIO						
6061-T6		-	140	0.92		
Ring		140	140	1.04		
Forging		-	540	1.42		
6061-T6		-	140	0.85		
Welded		140	140	0.90		
Ring		-	540	1.42		
Forging						
6061-T6		-	140	1.37		
Pressure		140	140	1.34		
Vessel		140	140 ⁽²⁾	1.23		
Forging						
7075-T73		-	140	1.17		
Forging		140	140	1.15		
		-	540	1.31		

TABLE 8 (Cont.)

TENSILE PROPERTY SUMMARY
ALUMINUM ALLOYS

Material Form	Environment			Property		Sample Size
	Neutron Fluence nvt (E > 1.0 Mev)	Temp., °R		Mean Value	Std. Dev.	
		Irrad.	Test			
FRACTURE STRENGTH, ksi						
6061-T6 Plate	none	-	40	72.2	1.18	4
	3.0 x 10 ¹⁷	40	40	73.5	2.54	4
	none	-	140	54.7	3.81	4
	3.0 x 10 ¹⁷	140	140	55.2	0.40	4
	none	-	540	39.1	0.42	4
6061-T6 Ring Forging	2.2 x 10 ¹⁷	40	40 ⁽¹⁾	67.5	0.77	2
	none	-	140	61.6	2.14	4
	1.1 x 10 ¹⁸	140	140	61.8	2.58	4
	none	-	540	42.9	2.01	5
	none	-	140	50.9	1.14	3
6061-T6 Welded Ring Forging	1.1 x 10 ¹⁸	140	140	59.5	2.06	4
	none	-	540	38.7	2.56	5
	none	-	140	62.5	1.38	3
	1.1 x 10 ¹⁸	140	140	67.0	0.80	3
	1.1 x 10 ¹⁸	140	140 ⁽²⁾	62.9	1.30	4
7039-0 Forging	none	-	140	50.6	1.01	4
	9.0 x 10 ¹⁷	140	140	56.2	0.51	4
	none	-	540	36.0	0.64	4
7075-T73 Forging	none	-	140	88.4	1.18	4
	9.0 x 10 ¹⁷	140	140	89.0	2.70	4
	none	-	540	57.4	1.19	4
	9.0 x 10 ¹⁷	140	140 ⁽²⁾	85.8	1.20	2

(1) These specimens were annealed at 140°R prior to testing at 40°R.

(2) These specimens were annealed at 540°R prior to testing at 140°R.

(3) The stress concentration factors (K_T) for the 6061-T6 pressure vessel forging and 7075-T73 forging are 6.3. All other K_T 's are 17.

TABLE 9
TENSILE PROPERTY SUMMARY
TITANIUM 5A1 2.5Sn ELI

Material Form	Environment			Property		Sample Size
	Neutron Fluence nvt (E > 1.0 Mev)	Temp., °R		Mean Value	Std. Dev.	
		Irrad.	Test			
ULTIMATE STRENGTH, ksi						
Plate	none	-	40	234.8	2.62	3
	3.0 x 10 ¹⁷	40	40	243.8	1.70	2
	none	-	140	197.4	6.98	4
	3.0 x 10 ¹⁷	140	140	200.5	5.80	4
	none	-	540	120.8	0.83	4
Forging	2.4 x 10 ¹⁷	40	40 ⁽¹⁾	--	--	0
	none	-	140	182.0	0.87	4
	1.1 x 10 ¹⁸	140	140	197.7	0.84	4
	none	-	540	120.5	1.70	4
	TIG	-	140	185.3	1.64	4
Welded Forging	9.0 x 10 ¹⁷	140	140	199.4	1.30	4
	none	-	540	119.1	1.46	4
EB Welded Forging	9.0 x 10 ¹⁷	140	140	184.4	0.63	4
	none	-	540	197.6	1.66	4
Pressure Vessel Forging	7.9 x 10 ¹⁷	140	140 ⁽²⁾	120.5	3.41	4
	7.9 x 10 ¹⁷	140	140	180.7	0.70	4
0.2% OFFSET YIELD STRENGTH, ksi						
Plate	none	-	40	217.5	5.74	4
	3.0 x 10 ¹⁷	40	40	233.3	6.10	3
	none	-	140	187.2	5.25	4
	3.0 x 10 ¹⁷	140	140	192.8	4.99	4
	none	-	540	112.2	0.90	4
Forging	2.4 x 10 ¹⁷	40	40 ⁽²⁾	218.0	5.65	2
	none	-	140	174.2	1.38	4
	1.1 x 10 ¹⁸	140	140	188.0	2.68	4
	none	-	540	114.4	1.58	4
	TIG	-	140	178.2	3.59	4
Welded Forging	9.0 x 10 ¹⁷	140	140	194.3	1.50	4
	none	-	540	112.5	2.05	4

TABLE 9 (Cont.)

TENSILE PROPERTY SUMMARY
TITANIUM 5Al 2.5Sn ELI

Material Form	Environment			Property		Sample Size
	Neutron Fluence nvt (E > 1.0 Mev)	Temp., °R		Mean Value	Std. Dev.	
		Irrad.	Test			
0.2% OFFSET YIELD STRENGTH, ksi (cont.)						
EB	none	-	140	175.4	0.90	4
Welded	9.0 x 10 ¹⁷	140	140	189.6	2.01	4
Forging	none	-	540	115.4	2.42	4
Pressure	none	-	140	175.6	0.63	3
Vessel	7.9 x 10 ¹⁷	140	140	191.8	2.29	4
Forging	7.9 x 10 ¹⁷	140	140 ⁽²⁾	186.7	2.70	4
ELONGATION, %						
Plate	none	-	40	9.6	0.48	2
	3.0 x 10 ¹⁷	40	40	10.3	0.77	2
	none	-	140	12.4	1.30	4
	3.0 x 10 ¹⁷	140	140	10.8	1.16	4
	none	-	540	12.7	0.46	4
Forging	2.4 x 10 ¹⁷	40	40 ⁽¹⁾	Not avail.		
	none	-	140	10.8	0.79	4
	1.1 x 10 ¹⁸	140	140	7.6	0.72	4
	none	-	540	13.4	1.10	4
	TIG	none	-	140	15.9	1.02
Welded	9.0 x 10 ¹⁷	140	140	9.0	1.71	4
Forging	none	-	540	12.3	0.80	4
EB	none	-	140	14.2	1.83	4
Welded	9.0 x 10 ¹⁷	140	140	7.3	1.06	4
Forging	none	-	540	13.3	1.15	4
Pressure	none	-	140	16.6	1.46	4
Vessel	7.9 x 10 ¹⁷	140	140	12.2	0.20	4
Forging	7.9 x 10 ¹⁷	140	140 ⁽²⁾	12.8	1.38	4
REDUCTION IN AREA, %						
Plate	none	-	40	12.5	1.47	3
	3.0 x 10 ¹⁷	40	40	19.8	5.58	2
	none	-	140	27.8	2.30	4
	3.0 x 10 ¹⁷	140	140	30.4	3.14	4
	none	-	540	32.0	2.21	4
	2.4 x 10 ¹⁷	40	40 ⁽¹⁾	16.0	0.28	2

TABLE 9 (Cont.)
TENSILE PROPERTY SUMMARY
TITANIUM 5A1 2.5Sn ELI

Material Form	Environment			Property		Sample Size
	Neutron Fluence nvt (E > 1.0 Mev)	Temp., °R		Mean Value	Std. Dev.	
		Irrad.	Test			
REDUCTION IN AREA, % (cont.)						
Forging	none	-	140	19.5	1.28	4
	1.1×10^{18}	140	140	17.2	3.55	4
	none	-	540	29.5	3.01	4
TIG	none	-	140	28.4	0.84	4
Welded	9.0×10^{17}	140	140	21.9	6.00	4
Forging	none	-	540	35.6	1.44	4
EB	none	-	140	23.5	1.04	4
Welded	9.0×10^{17}	140	140	17.2	1.04	4
Forging	none	-	540	31.1	2.56	4
Pressure	none	-	140	29.2	2.04	3
Vessel	7.9×10^{17}	140	140	29.2	5.13	4
Forging	7.9×10^{17}	140	140 ⁽²⁾	27.6	4.61	4
NOTCH TENSILE STRENGTH, ksi ⁽³⁾						
Forging	none	-	140	175.1	1.04	3
	5.7×10^{17}	140	140	131.4	1.29	3
	none	-	540	126.6	2.18	4
TIG	none	-	140	148.2	7.54	4
Welded	5.7×10^{17}	140	140	167.2	3.42	4
Forging	none	-	540	123.7	1.04	4
EB	none	-	140	168.3	5.13	4
Welded	5.7×10^{17}	140	140	142.3	1.30	3
Forging	none	-	540	129.8	1.87	4
Pressure	none	-	140	252.8	3.64	4
Vessel	7.9×10^{17}	140	140	222.7	10.48	4
Forging	7.9×10^{17}	140	140 ⁽²⁾	226.3	5.21	4
NOTCHED/UNNOTCHED RATIO						
Forging	none	-	140	0.96		
	5.7×10^{17}	140	140	0.67		
	none	-	540	1.05		

TABLE 9 (Cont.)
TENSILE PROPERTY SUMMARY
TITANIUM 5Al 2.5Sn ELI

Material Form	Environment			Property		
	Neutron Fluence nvt (E > 1.0 Mev)	Temp., °R		Mean Value	Std. Dev.	Sample Size
		Irrad.	Test			
NOTCHED/UNNOTCHED RATIO (cont.)						
TIG	none	-	140	0.80		
Welded	5.7 x 10 ¹⁷	140	140	0.84		
Forging	none	-	540	1.04		
EB	none	-	140	0.91		
Welded	5.7 x 10 ¹⁷	140	140	0.72		
Forging	none	-	540	1.08		
Pressure	none	-	140	1.40		
Vessel	7.9 x 10 ¹⁷	140	140	1.14		
Forging	7.9 x 10 ¹⁷	140	140 ⁽²⁾	1.19		
FRACTURE STRENGTH, ksi						
Plate	none	-	40	234.3	2.97	3
	3.0 x 10 ¹⁷	40	40	243.8	1.70	2
	none	-	140	189.0	6.86	4
	3.0 x 10 ¹⁷	140	140	186.6	5.51	4
	none	-	540	109.0	2.42	4
Forging	2.4 x 10 ¹⁷	40	40 ⁽¹⁾	--	--	0
	none	-	140	181.5	1.05	4
	1.1 x 10 ¹⁸	140	140	193.1	1.24	4
	none	-	540	110.6	3.26	4
	none	-	140	177.8	2.31	4
TIG	none	-	140	177.8	2.31	4
Welded	9.0 x 10 ¹⁷	140	140	191.4	4.67	4
Forging	none	-	540	101.0	2.21	4
EB	none	-	140	183.1	1.50	4
Welded	9.0 x 10 ¹⁷	140	140	194.3	1.84	4
Forging	none	-	540	109.8	4.83	4
Pressure	none	-	140	172.1	1.93	4
Vessel	7.9 x 10 ¹⁷	140	140	180.5	5.43	4
Forging	7.9 x 10 ¹⁷	140	140 ⁽²⁾	177.9	1.27	4

(1) These specimens were annealed at 140°R prior to testing at 40°R.

(2) These specimens were annealed at 540°R prior to testing at 140°R.

(3) The stress concentration factors (K_T) for the pressure vessel forging are 6.3. All other K_T 's are 17.

TABLE 10
TENSILE PROPERTY SUMMARY
A286

Material Form	Environment			Property		Sample Size
	Neutron Fluence nvt (E > 1.0 Mev)	Temp., °R		Mean Value	Std. Dev.	
		Irrad.	Test			
ULTIMATE STRENGTH, ksi						
Forging	none	-	40	208.5	5.58	4
	3.2 x 10 ¹⁷	40	40	204.4	8.86	4
	none	-	140	197.3	3.44	4
	3.5 x 10 ¹⁷	140	140	199.6	1.58	3
	none	-	140	193.9	3.23	4
	1.2 x 10 ¹⁸	140	140	196.5	2.42	5
	none	-	540	150.8	1.73	5
1.2 x 10 ¹⁸	140	140 ⁽¹⁾	190.0	5.46	4	
0.2% OFFSET YIELD STRENGTH, ksi						
Forging	none	-	40	146.8	2.87	4
	3.2 x 10 ¹⁷	40	40	156.5	6.95	4
	none	-	140	131.5	6.80	4
	3.5 x 10 ¹⁷	140	140	136.3	7.50	3
	none	-	140	130.6	1.34	4
	1.2 x 10 ¹⁸	140	140	147.0	3.76	5
	none	-	540	112.9	4.88	5
1.2 x 10 ¹⁸	140	140 ⁽¹⁾	141.6	2.75	4	
ELONGATION, %						
Forging	none	-	40	25.8	1.33	4
	3.2 x 10 ¹⁷	40	40	23.0	1.74	4
	none	-	140	31.7	2.32	3
	3.5 x 10 ¹⁷	140	140	33.4	1.24	3
	none	-	140	28.8	1.76	4
	1.2 x 10 ¹⁸	140	140	28.7	2.60	5
	none	-	540	24.3	1.00	5
1.2 x 10 ¹⁸	140	140 ⁽¹⁾	31.0	1.25	4	
REDUCTION IN AREA, %						
Forging	none	-	40	27.7	3.50	4
	3.2 x 10 ¹⁷	40	40	24.7	2.27	4
	none	-	140	30.5	2.48	3
	3.5 x 10 ¹⁷	140	140	34.1	4.24	3
	none	-	140	28.4	1.00	4
	1.2 x 10 ¹⁸	140	140	30.4	6.44	5
	none	-	540	34.4	1.17	5
1.2 x 10 ¹⁸	140	140 ⁽¹⁾	29.6	2.47	4	

TABLE 10 (Cont.)

TENSILE PROPERTY SUMMARY
A286

Material Form	Environment			Property		Sample Size
	Neutron Fluence nvt (E > 1.0 Mev)	Temp., °R		Mean Value	Std. Dev.	
		Irrad.	Test			
NOTCH TENSILE STRENGTH, ksi (K _T = 6.3)						
Forging	none	-	140	235.0	4.67	4
	1.2 x 10 ¹⁸	140	140	247.6	7.71	4
	none	-	540	199.3	3.40	4
NOTCHED/UNNOTCHED RATIO						
Forging	none	-	140	1.21	-	-
	1.2 x 10 ¹⁸	140	140	1.26	-	-
	none	-	540	1.32	-	-
FRACTURE STRENGTH, ksi						
Forging	none	-	40	208.5	5.58	4
	3.2 x 10 ¹⁷	40	40	204.4	8.91	4
	none	-	140	196.8	3.44	4
	3.5 x 10 ¹⁷	140	140	197.8	2.35	3
	none	-	140	193.4	4.25	4
	1.2 x 10 ¹⁸	140	140	195.9	1.86	5
	none	-	540	142.3	2.64	5
	1.2 x 10 ¹⁸	140	140 ⁽¹⁾	189.1	5.06	4

(1) These specimens were annealed at 540°R prior to testing at 140°R.

TABLE 11
TENSILE PROPERTY SUMMARY
347 STAINLESS STEEL

Material Form	Environment			Property		Sample Size
	Neutron Fluence nvt (E > 1.0 Mev)	Temp., Irrad.	°R Test	Mean Value	Std. Dev.	
ULTIMATE STRENGTH, ksi						
Plate	none	-	40	230.0	9.70	4
	3.0 x 10 ¹⁷	40	40	228.4	11.61	4
	none	-	140	213.6	6.02	4
	3.0 x 10 ¹⁷	140	140	210.4	4.03	4
Weldment	none	-	540	95.7	1.36	4
	none	-	40	203.8	5.65	4
	3.0 x 10 ¹⁷	40	40	208.3	16.23	4
	none	-	140	208.4	3.92	4
	3.9 x 10 ¹⁷	140	140	204.7	3.99	3
	none	-	540	94.9	0.80	4
0.2% OFFSET YIELD STRENGTH, ksi						
Plate	none	-	40	65.6	13.80	4
	3.0 x 10 ¹⁷	40	40	87.3	6.19	4
	none	-	140	65.4	13.17	4
	3.0 x 10 ¹⁷	140	140	85.2	11.70	4
Weldment	none	-	540	39.5	0.61	4
	none	-	40	67.1	15.35	4
	3.0 x 10 ¹⁷	40	40	90.0	4.00	4
	none	-	140	54.8	9.58	4
	3.9 x 10 ¹⁷	140	140	77.6	3.36	3
	none	-	540	41.6	0.20	4
ELONGATION, %						
Plate	none	-	40	27.2	1.42	4
	3.0 x 10 ¹⁷	40	40	26.2	2.45	4
	none	-	140	32.3	1.56	4
	3.0 x 10 ¹⁷	140	140	33.1	2.10	4
Weldment	none	-	540	44.7	1.61	4
	none	-	40	21.9	0.80	4
	3.0 x 10 ¹⁷	40	40	19.7	4.02	4
	none	-	140	27.1	1.35	4
	3.9 x 10 ¹⁷	140	140	28.1	0.54	3
	none	-	540	37.1	3.03	4

TABLE 11 (Cont.)

TENSILE PROPERTY SUMMARY
347 STAINLESS STEEL

Material Form	Environment			Property		Sample Size
	Neutron Fluence nvt (E > 1.0 Mev)	Temp., °R		Mean Value	Std. Dev.	
		Irrad.	Test			
REDUCTION IN AREA, %						
Plate	none	-	40	29.1	10.24	4
	3.0 x 10 ¹⁷	40	40	38.5	7.10	4
	none	-	140	48.5	3.20	4
	3.0 x 10 ¹⁷	140	140	42.6	3.22	4
	none	-	540	68.8	1.50	4
Weldment	none	-	40	21.2	1.96	4
	3.0 x 10 ¹⁷	40	40	23.2	2.40	4
	none	-	140	32.0	3.40	4
	3.9 x 10 ¹⁷	140	140	33.6	4.10	3
	none	-	540	52.6	5.04	4
FRACTURE STRENGTH, ksi						
Plate	none	-	40	230.0	9.70	4
	3.0 x 10 ¹⁷	40	40	226.8	14.54	4
	none	-	140	200.7	6.68	4
	3.0 x 10 ¹⁷	140	140	198.2	6.78	4
	none	-	540	72.7	0.34	4
Weldment	none	-	40	203.8	5.65	4
	3.0 x 10 ¹⁷	40	40	208.3	16.23	4
	none	-	140	205.7	4.46	4
	3.0 x 10 ¹⁷	140	140	201.7	1.12	3
	none	-	540	84.1	1.25	4

TABLE 12
TENSILE PROPERTY SUMMARY
HASTELLOY X

Material Form	Environment			Property		Sample Size	
	Neutron Fluence nvt (E > 1.0 Mev)	Temp., °R		Mean Value	Std. Dev.		
		Irrad.	Test				
ULTIMATE STRENGTH, ksi							
Forging	none	-	40	154.6	6.15	2	
	2.9 x 10 ¹⁷	40	40	163.8	1.03	3	
	none	-	140	142.7	1.74	4	
	3.5 x 10 ¹⁷	140	140	148.1	4.44	3	
	none	-	140	140.8	1.24	4	
	8.0 x 10 ¹⁷	140	140	155.4	3.79	5	
	none	-	540	100.0	0.88	4	
	2.2 x 10 ¹⁷	40	40 ⁽¹⁾	164.3	-	1	
Weldment	8.0 x 10 ¹⁷	140	140 ⁽²⁾	154.5	1.89	3	
	none	-	140	135.3	4.16	4	
	8.0 x 10 ¹⁷	140	140	144.4	4.50	3	
	none	-	540	97.2	1.55	2	
	8.0 x 10 ¹⁷	140	140 ⁽²⁾	142.5	1.13	2	
	0.2% OFFSET YIELD STRENGTH, ksi						
	Forging	none	-	40	98.5	7.77	2
		2.9 x 10 ¹⁷	40	40	121.8	2.21	4
none		-	140	80.4	3.10	4	
3.5 x 10 ¹⁷		140	140	106.0	3.46	3	
none		-	140	77.1	0.80	4	
8.0 x 10 ¹⁷		140	140	112.6	3.44	5	
none		-	540	46.7	1.80	4	
2.2 x 10 ¹⁷		40	40 ⁽¹⁾	103.0	-	1	
Weldment	8.0 x 10 ¹⁷	140	140 ⁽²⁾	111.0	11.40	2	
	none	-	140	80.9	2.98	3	
	8.0 x 10 ¹⁷	140	140	115.8	1.00	4	
	none	-	540	46.0	0.28	2	
	8.0 x 10 ¹⁷	140	140 ⁽²⁾	111.0	7.98	2	

TABLE 12 (Cont.)
TENSILE PROPERTY SUMMARY
HASTELLOY X

Material Form	Environment			Property		Sample Size	
	Neutron Fluence nvt (E > 1.0 Mev)	Temp., °R		Mean Value	Std. Dev.		
		Irrad.	Test				
ELONGATION, %							
Forging	none	-	40	33.6	2.90	4	
	2.9 x 10 ¹⁷	40	40	32.8	2.78	4	
	none	-	140	45.2	4.10	4	
	3.5 x 10 ¹⁷	140	140	40.5	4.24	2	
	none	-	140	44.7	1.95	4	
	8.0 x 10 ¹⁷	140	140	36.6	2.71	4	
	none	-	540	50.9	2.82	4	
	2.2 x 10 ¹⁷	40	40 ⁽¹⁾	43.3	-	1	
Weldment	8.0 x 10 ¹⁷	140	140 ⁽²⁾	39.8	3.48	3	
	none	-	140	26.0	2.98	4	
	8.0 x 10 ¹⁷	140	140	15.5	2.32	3	
	none	-	540	42.6	3.11	2	
	8.0 x 10 ¹⁷	140	140 ⁽²⁾	16.2	2.75	2	
	REDUCTION IN AREA, %						
	Forging	none	-	40	28.2	2.59	4
		2.9 x 10 ¹⁷	40	40	28.7	2.64	4
none		-	140	34.9	2.46	4	
3.5 x 10 ¹⁷		140	140	33.0	1.48	2	
none		-	140	34.6	0.87	4	
8.0 x 10 ¹⁷		140	140	27.8	1.22	5	
none		-	540	47.1	5.24	4	
2.2 x 10 ¹⁷		40	40 ⁽¹⁾	33.4	-	1	
Weldment	8.0 x 10 ¹⁷	140	140 ⁽²⁾	31.9	1.27	3	
	none	-	140	27.8	2.70	4	
	8.0 x 10 ¹⁷	140	140	19.4	2.08	3	
	none	-	540	45.4	3.60	2	
	8.0 x 10 ¹⁷	140	140 ⁽²⁾	19.4	7.21	2	

TABLE 12 (Cont.)
TENSILE PROPERTY SUMMARY
HASTELLOY X

Material Form	Environment			Property		Sample Size
	Neutron Fluence nvt (E > 1.0 Mev)	Temp., °R		Mean Value	Std. Dev.	
		Irrad.	Test			
NOTCH TENSILE STRENGTH, ksi (K _T = 6.3)						
Weldment	none	-	140	163.2	1.86	4
	8.0 x 10 ¹⁷	140	140	193.9	2.10	4
	none	-	540	113.4	4.21	4
NOTCHED/UNNOTCHED RATIO						
Weldment	none	-	140	1.21	-	-
	8.0 x 10 ¹⁷	140	140	1.34	-	-
	none	-	540	1.17	-	-
FRACTURE STRENGTH, ksi						
Forging	none	-	40	154.6	6.15	2
	2.9 x 10 ¹⁷	40	40	163.8	1.03	3
	none	-	140	142.7	1.74	4
	3.5 x 10 ¹⁷	140	140	148.1	4.44	3
	none	-	140	140.8	1.24	4
	8.0 x 10 ¹⁷	140	140	155.4	3.79	5
	none	-	540	92.6	2.97	4
	2.2 x 10 ¹⁷	40	40 ⁽¹⁾	164.3	-	1
Weldment	8.0 x 10 ¹⁷	140	140 ⁽²⁾	154.5	1.89	3
	none	-	140	135.3	4.16	4
	8.0 x 10 ¹⁷	140	140	144.4	4.50	3
	none	-	540	92.0	1.27	2
	8.0 x 10 ¹⁷	140	140 ⁽²⁾	142.5	1.13	2
	none	-	140	135.3	4.16	4
	8.0 x 10 ¹⁷	140	140	144.4	4.50	3
	none	-	540	92.0	1.27	2

(1) These specimens were annealed at 140°R prior to testing at 40°R.

(2) These specimens were annealed at 540°R prior to testing at 140°R.

TABLE 13
TENSILE PROPERTY SUMMARY
INCONEL 625

Material Form	Environment			Property		Sample Size
	Neutron Fluence nvt (E > 1.0 Mev)	Temp., °R		Mean Value	Std. Dev.	
		Irrad.	Test			
ULTIMATE STRENGTH, ksi						
Plate	none	-	140	154.1	1.82	4
	1.1 x 10 ¹⁸	140	140	166.1	1.51	4
	none	-	540	112.0	0.60	4
Weldment	none	-	140	151.2	3.45	4
	1.1 x 10 ¹⁸	140	140	169.5	2.00	4
	none	-	540	114.6	2.13	3
0.2% OFFSET YIELD STRENGTH, ksi						
Plate	none	-	140	73.2	0.78	4
	1.1 x 10 ¹⁸	140	140	123.4	2.35	4
	none	-	540	47.0	0.82	4
Weldment	none	-	140	88.7	1.10	4
	1.1 x 10 ¹⁸	140	140	125.5	1.78	4
	none	-	540	60.6	1.38	3
ELONGATION, %						
Plate	none	-	140	56.8	3.88	4
	1.1 x 10 ¹⁸	140	140	46.0	5.34	4
	none	-	540	51.6	3.81	4
Weldment	none	-	140	30.2	3.80	4
	1.1 x 10 ¹⁸	140	140	27.6	1.31	4
	none	-	540	39.4	8.88	3
REDUCTION IN AREA, %						
Plate	none	-	140	39.9	1.35	4
	1.1 x 10 ¹⁸	140	140	31.7	3.57	4
	none	-	540	48.0	1.67	4
Weldment	none	-	140	27.2	2.08	4
	1.1 x 10 ¹⁸	140	140	31.4	3.91	4
	none	-	540	38.0	3.15	3

TABLE 13 (Cont.)

TENSILE PROPERTY SUMMARY
INCONEL 625

Material Form	Environment			Property		Sample Size
	Neutron Fluence nvt (E > 1.0 Mev)	Temp., °R		Mean Value	Std. Dev.	
		Irrad.	Test			
NOTCH TENSILE STRENGTH, ksi ($K_T = 17$)						
Weldment	none	-	140	116.8	3.30	3
	1.1×10^{18}	140	140	137.4	9.64	2
	none	-	540	84.3	3.72	4
NOTCHED/UNNOTCHED RATIO						
Weldment	none	-	140	0.77	-	-
	1.1×10^{18}	140	140	0.84	-	-
	none	-	540	0.74	-	-
FRACTURE STRENGTH, ksi						
Plate	none	-	140	153.7	2.00	4
	1.1×10^{18}	140	140	166.0	1.70	4
	none	-	540	107.3	0.77	4
Weldment	none	-	140	151.2	3.45	4
	1.1×10^{18}	140	140	169.5	2.00	4
	none	-	540	113.5	0.64	3

TABLE 14
TENSILE PROPERTY SUMMARY
WASPALLOY

Material Form	Environment			Property		Sample Size
	Neutron Fluence nvt (E > 1.0 Mev)	Temp., °R		Mean Value	Std. Dev.	
		Irrad.	Test			
ULTIMATE STRENGTH, ksi						
Cold	none	-	140	311.0	5.84	4
Reduced	7.8 x 10 ¹⁷	140	140	302.7	9.40	4
Rod	none	-	540	254.6	4.10	2
0.2% OFFSET YIELD STRENGTH, ksi						
Cold	none	-	140	283.7	9.48	3
Reduced	7.8 x 10 ¹⁷	140	140	295.0	12.30	4
Rod	none	-	540	249.7	4.94	2
ELONGATION, %						
Cold	none	-	140	11.1	1.50	4
Reduced	7.8 x 10 ¹⁷	140	140	8.1	2.62	4
Rod	none	-	540	6.2	0.70	2
REDUCTION IN AREA, %						
Cold	none	-	140	26.4	2.85	4
Reduced	7.8 x 10 ¹⁷	140	140	22.2	4.35	4
Rod	none	-	540	25.8	4.52	2
FRACTURE STRENGTH, ksi						
Cold	none	-	140	301.2	7.67	4
Reduced	7.8 x 10 ¹⁷	140	140	293.1	9.47	4
Rod	none	-	540	240.2	4.66	2

TABLE 15

TENSILE PROPERTY SUMMARY
UDIMET 630

Material Form	Environment			Property		Sample Size
	Neutron Fluence nvt (E > 1.0 Mev)	Temp., °R		Mean Value	Std. Dev.	
		Irrad.	Test			
ULTIMATE STRENGTH, ksi						
Forging	none	-	140	259.4	3.20	4
	1.2×10^{18}	140	140	258.4	2.50	4
	none	-	540	201.2	1.72	4
Cold Reduced Rod	none	-	140	334.6	7.64	4
	7.8×10^{17}	140	140	335.0	2.43	4
	none	-	540	277.4	2.61	2
0.2% OFFSET YIELD STRENGTH, ksi						
Forging	none	-	140	209.6	5.67	4
	1.2×10^{18}	140	140	226.8	2.88	4
	none	-	540	178.2	4.48	4
Cold Reduced Rod	none	-	140	332.9	7.09	4
	7.8×10^{17}	140	140	332.2	3.22	4
	none	-	540	276.7	1.55	2
ELONGATION, %						
Forging	none	-	140	21.0	3.72	4
	1.2×10^{18}	140	140	18.1	3.08	4
	none	-	540	17.8	2.17	4
Cold Reduced Rod	none	-	140	5.7	0.67	4
	7.8×10^{17}	140	140	5.5	0.10	4
	none	-	540	5.8	0.42	2
REDUCTION IN AREA, %						
Forging	none	-	140	28.3	8.24	4
	1.2×10^{18}	140	140	25.8	7.44	4
	none	-	540	32.0	70.33	4
Cold Reduced Rod	none	-	140	26.0	3.01	4
	7.8×10^{17}	140	140	24.6	1.90	4
	none	-	540	31.2	0	2

TABLE 15 (Cont.)

TENSILE PROPERTY SUMMARY
UDIMET 630

Material Form	Environment			Property		Sample Size
	Neutron Fluence nvt (E > 1.0 Mev)	Temp., °R		Mean Value	Std. Dev.	
		Irrad.	Test			
NOTCH TENSILE STRENGTH, ksi (K _T = 6.3)						
Forging	none	-	140	269.8	3.29	3
	1.2 x 10 ¹⁸	140	140	342.2	2.00	3
	none	-	540	239.8	3.53	3
NOTCH/UNNOTCHED RATIO						
Forging	none	-	140	1.04		
	1.2 x 10 ¹⁸	140	140	1.35		
	none	-	540	1.19		
FRACTURE STRENGTH, ksi						
Forging	none	-	140	256.6	4.70	4
	1.2 x 10 ¹⁸	140	140	253.6	7.55	4
	none	-	540	191.4	7.98	4
Cold Reduced Rod	none	-	140	321.0	10.23	4
	7.8 x 10 ¹⁷	140	140	310.9	1.08	4
	none	-	540	277.4	2.61	2

TABLE 16
TENSILE PROPERTY SUMMARY
INCONEL 718

Material Form	Environment			Property		Sample Size
	Neutron Fluence nvt (E > 1.0 Mev)	Temp., °R		Mean Value	Std. Dev.	
		Irrad.	Test			
ULTIMATE STRENGTH, ksi						
Forging	none	-	40	265.6	1.60	3
	3.2 x 10 ¹⁷	40	40	269.7	4.11	3
	none	-	140	263.8	4.64	3
	3.5 x 10 ¹⁷	140	140	257.8	7.07	4
	none	-	540	196.2	5.42	3
Ring Forging	none	-	140	252.1	1.07	3
	9.0 x 10 ¹⁷	140	140	252.4	2.59	4
	none	-	540	192.9	0.20	3
TIG Welded Ring Forging	none	-	140	243.0	1.13	2
	9.0 x 10 ¹⁷	140	140	243.1	3.81	3
	none	-	540	198.8	3.40	3
EB Welded Ring Forging	none	-	140	241.8	0.56	4
	9.0 x 10 ¹⁷	140	140	245.6	3.82	4
	none	-	540	194.2	1.17	4
All Weld	none	-	140	239.9	8.48	2
	9.0 x 10 ¹⁷	140	140	249.0	4.87	2
	none	-	540	187.5	3.21	5
Cold Reduced Rod	none	-	140	288.9	2.17	4
	7.8 x 10 ¹⁷	140	140	296.4	3.30	4
	none	-	540	235.2	3.81	2
0.2% OFFSET YIELD STRENGTH, ksi						
Forging	none	-	40	219.7	2.75	3
	3.2 x 10 ¹⁷	40	40	234.4	2.98	4
	none	-	140	217.9	3.58	4
	3.5 x 10 ¹⁷	140	140	225.0	3.55	4
	none	-	540	176.2	2.81	3
Ring Forging	none	-	140	199.4	6.00	4
	9.0 x 10 ¹⁷	140	140	225.7	3.29	4
	none	-	540	174.0	0.70	2
TIG Welded Ring Forging	none	-	140	201.3	2.21	4
	9.0 x 10 ¹⁷	140	140	220.0	1.03	3
	none	-	540	179.6	8.62	2

TABLE 16 (Cont.)

TENSILE PROPERTY SUMMARY
INCONEL 718

Material Form	Environment			Property		Sample Size
	Neutron Fluence nvt (E > 1.0 Mev)	Temp., °R		Mean Value	Std. Dev.	
		Irrad.	Test			
0.2% OFFSET YIELD STRENGTH, ksi (cont.)						
EB Welded Ring Forging	none	-	140	199.8	0.74	4
	9.0 x 10 ¹⁷	140	140	223.0	1.55	4
	none	-	540	176.3	0.58	4
All Weld	none	-	140	205.2	0.28	2
	9.0 x 10 ¹⁷	140	140	222.6	0.48	2
	none	-	540	174.2	1.29	5
Cold Reduced Rod	none	-	140	277.0	0.36	4
	7.8 x 10 ¹⁷	140	140	289.4	0.70	4
	none	-	540	234.8	5.86	2
ELONGATION, %						
Forging	none	-	40	18.4	3.03	4
	3.2 x 10 ¹⁷	40	40	18.2	1.20	3
	none	-	140	21.7	3.13	3
	3.5 x 10 ¹⁷	140	140	20.7	1.24	4
	none	-	540	19.4	1.62	3
Ring Forging	none	-	140	17.2	3.47	3
	9.0 x 10 ¹⁷	140	140	14.5	2.10	4
	none	-	540	22.1	0.10	3
TIG Welded Ring Forging	none	-	140	14.7	0.28	2
	9.0 x 10 ¹⁷	140	140	10.4	2.68	2
	none	-	540	12.6	0.40	3
EB Welded Ring Forging	none	-	140	17.2	0.72	4
	9.0 x 10 ¹⁷	140	140	15.0	1.83	3
	none	-	540	13.1	2.23	4
All Weld	none	-	140	10.4	0.42	2
	9.0 x 10 ¹⁷	140	140	9.8	2.04	2
		-	540	5.4	2.88	5
Cold Reduced Rod	none	-	140	12.2	0.78	4
	7.8 x 10 ¹⁷	140	140	9.4	0.58	4
	none	-	540	7.6	0.63	2

TABLE 16 (Cont.)

TENSILE PROPERTY SUMMARY
INCONEL 718

Material Form	Environment			Property		Sample Size
	Neutron Fluence nvt (E > 1.0 Mev)	Temp., °R		Mean Value	Std. Dev.	
		Irrad.	Test			
REDUCTION IN AREA, %						
Forging	none	-	40	29.9	6.65	4
	3.2 x 10 ¹⁷	40	40	23.6	1.84	3
	none	-	140	29.0	5.60	3
	3.5 x 10 ¹⁷	140	140	36.3	7.17	4
	none	-	540	43.6	-	2
Ring Forging	none	-	140	26.5	2.19	2
	9.0 x 10 ¹⁷	140	140	21.0	5.57	4
	none	-	540	42.5	0.92	3
TIG Welded Ring Forging	none	-	140	14.0	2.19	2
	9.0 x 10 ¹⁷	140	140	17.7	3.57	3
	none	-	540	14.7	1.55	3
EB Welded Ring Forging	none	-	140	30.0	3.70	4
	9.0 x 10 ¹⁷	140	140	26.9	3.69	3
	none	-	540	29.2	3.67	4
All Weld	none	-	140	15.6	-	1
	9.0 x 10 ¹⁷	140	140	12.5	4.38	2
	none	-	540	15.0	1.38	5
Cold Reduced Rod	none	-	140	35.8	1.24	4
	7.8 x 10 ¹⁷	140	140	31.2	2.57	4
	none	-	540	36.5	1.55	2
NOTCH TENSILE STRENGTH, ksi ⁽¹⁾						
Ring Forging	none	-	140	190.6	2.32	4
	9.0 x 10 ¹⁷	140	140	242.7	2.22	4
	none	-	540	223.7	2.96	4
TIG Welded Ring Forging	none	-	140	192.8	17.95	4
	9.0 x 10 ¹⁷	140	140	181.0	5.47	4
	none	-	540	165.0	9.13	4
TIG Welded Ring Forging	none	-	140	260.2	13.09	4
	9.0 x 10 ¹⁷	140	140	277.0	14.26	3
	none	-	540	227.6	13.52	4

TABLE 16 (Cont.)

TENSILE PROPERTY SUMMARY
INCONEL 718

Material Form	Environment			Property		Sample Size
	Neutron Fluence nvt (E > 1.0 Mev)	Temp., °R		Mean Value	Std. Dev.	
		Irrad.	Test			
NOTCHED/UNNOTCHED RATIO						
Ring Forging	none	-	140	0.76	-	-
	9.0 x 10 ¹⁷	140	140	0.96	-	-
	none	-	540	0.99	-	-
TIG Welded Ring Forging	none	-	140	0.79	-	-
	9.0 x 10 ¹⁷	140	140	0.74	-	-
	none	-	540	0.83	-	-
TIG Welded Ring Forging	none	-	140	1.07	-	-
	9.0 x 10 ¹⁷	140	140	1.14	-	-
	none	-	540	1.11	-	-
FRACTURE STRENGTH, ksi						
Forging	none	-	40	265.6	1.60	3
	3.2 x 10 ¹⁷	40	40	267.2	7.42	2
	none	-	140	259.9	1.81	3
	3.5 x 10 ¹⁷	140	140	256.5	9.43	4
	none	-	540	181.9	12.40	3
Ring Forging	none	-	140	250.7	0.65	3
	9.0 x 10 ¹⁷	140	140	252.4	2.59	4
	none	-	540	170.3	1.01	3
TIG Welded Ring Forging	none	-	140	243.0	1.13	2
	9.0 x 10 ¹⁷	140	140	243.1	3.81	3
	none	-	540	198.2	2.35	3
EB Welded Ring Forging	none	-	140	239.0	2.66	4
	9.0 x 10 ¹⁷	140	140	244.0	3.97	4
	none	-	540	189.7	4.53	4
All Weld	none	-	140	239.9	8.48	2
	9.0 x 10 ¹⁷	140	140	249.0	4.87	2
	none	-	540	187.5	3.21	5
Cold Reduced Rod	none	-	140	263.6	1.56	4
	9.0 x 10 ¹⁷	140	140	269.4	5.37	4
	none	-	540	202.1	5.23	2

(1) The stress concentration factors (K_T) for the second group of TIG welds are 6.3. All other K_T 's are 17.

TABLE 17

TENSILE PROPERTY SUMMARY
H MONEL

Material Form	Environment			Property ⁽¹⁾		Sample Size
	Neutron Fluence nvt (E > 1.0 Mev)	Temp., °R		Mean Value	Std. Dev.	
		Irrad.	Test			
ULTIMATE STRENGTH, ksi						
Cast Plate	none	-	40	103.6	4.10	4
	2.2 x 10 ¹⁷	40	40	116.6	4.95	4
	none	-	540	85.2	8.08	4
0.2% OFFSET YIELD STRENGTH, ksi						
Cast Plate	none	-	40	58.9	2.14	4
	2.2 x 10 ¹⁷	40	40	98.3	5.26	4
	none	-	540	44.0	9.76	4
ELONGATION, %						
Cast Plate	none	-	40	23.2	5.67	4
	2.2 x 10 ¹⁷	40	40	11.8	2.76	4
	none	-	540	29.0	1.35	4
REDUCTION IN AREA, %						
Cast Plate	none	-	40	28.1	3.45	4
	2.2 x 10 ¹⁷	40	40	22.7	4.91	4
	none	-	540	31.0	2.89	4
NOTCH TENSILE STRENGTH, ksi (K _T = 6.3)						
Cast Plate	none	-	40	100.8	6.50	4
	2.2 x 10 ¹⁷	40	40	122.4	7.75	4
	none	-	540	74.4	7.37	4
NOTCHED/UNNOTCHED RATIO						
Cast Plate	none	-	40	0.97	-	-
	2.2 x 10 ¹⁷	40	40	1.05	-	-
	none	-	540	0.88	-	-

TABLE 17 (Cont.)

TENSILE PROPERTY SUMMARY
H MONEL

Material Form	Environment			Property ⁽¹⁾		Sample Size
	Neutron Fluence nvt (E > 1.0 Mev)	Temp., °R		Mean Value	Std. Dev.	
		Irrad.	Test			
FRACTURE STRENGTH, ksi						
Cast Plate	none	-	40	103.6	4.10	4
	2.2 x 10 ¹⁷	40	40	116.6	4.95	4
	none	-	540	85.2	8.09	4

(1) Control data was obtained from Control Specimen Data for Structural Material Irradiation Test Program, Aerojet-General Report RN-S-0128, 12 November 1964.

B. STRESS-STRAIN CURVES

Typical stress-strain curves for control and irradiated specimens of Al 6061-T6, Hastelloy X, and Ti 5Al 2.5Sn ELI are shown in Figures 6, 7, and 8. Each curve was derived from a test chart of load vs cross-head travel adjusted for deflection outside the specimen gage section. Values of Young's modulus from the literature (Reference 8) were used to construct the elastic portion of the curve.

C. NERVA APPLICATION

For NERVA use, these data will be combined with other test results and further evaluated, including analysis of variance, for incorporation into appropriate NERVA engineering documents. As a part of these evaluations, the results of this test will be used as a basis for material evaluation, prediction of material behavior, planning of future tests, and design and reliability purposes.

Typical NERVA applications would include the determination of: (1) whether ductile or brittle design criteria are required in the use of a given material and (2) whether fracture-toughness test data will be necessary for proper design. In each case, the decision would be based on an estimate of the elongation of the irradiated material. The required estimate can be computed and expressed as an interval within which the average elongation is expected to lie (i.e., the confidence interval), or as a boundary above which a specified proportion of individual values are estimated to lie (i.e., the tolerance limits). For example, by using data pertaining exclusively to the Al 6061-T6 ring forging and assuming random, normal distribution, estimates concerning elongation could be expressed as follows:

The 95% confidence interval is 16.2 to 12.2%

There is a 95% probability that the elongation
of 99% of the population will be greater than 5.4%

In actual practice, evaluated data from several tests would be used for the estimate.

Figure 6 - Typical Engineering Stress-Strain Relationships for Al6061-T6
Ring Forging at 140°R Before and After Irradiation to
 1.1×10^{18} nvt > 1.0 Mev at 140°R

Figure 7 - Typical Engineering Stress-Strain Relationships for Hastelloy X
Forging at 140°R Before and After Irradiation to
 8.0×10^{17} nvt ~ 1.0 Mev at 140°R

Figure 8 - Typical Engineering Stress-Strain Relationships for Ti 5Al 2.5 Sn Ring Forging at 140°R Before and After Irradiation to 1.1×10^{18} nvt > 1.0 Mev at 140°R

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V. EVALUATION OF RESULTS

A. RADIATION EFFECTS ON PROPERTIES

Behavior of alloy properties as a result of irradiation was generally typical of that observed by other investigators (References 10, 11, and 12). Yield strength increased appreciably, whereas ultimate strength increased slightly or remained constant. The titanium alloys were an exception; increases in both ultimate and yield strengths were of the same magnitude.

Notch strengths of the alloys either increased or remained constant, except for Ti 5Al-2.5Sn, which had a 25% decrease. Similar results were observed for the notch-strength ratios. Ductility, as measured by elongation, decreased or remained the same in most cases. Where increases were noted, they were not statistically significant.

The stress-strain characteristics for all materials except the titanium alloys were significantly changed. The stress-strain curves for Al 6061-T6 and Hastelloy X are representative of the effects (see Figures 6 and 7).

B. COMPARISON OF RADIATION EFFECTS ON ALLOYS

Figures 9 through 12 summarize effects of irradiation on yield strengths and elongations of the alloys, the properties most influenced by radiation. The effects are presented in terms of absolute change and in terms of percent change from the unirradiated value, with 90%-confidence bands shown.

—●— Denotes 90% Confidence Interval

Figure 9 - Absolute Change in Yield Strength and Elongation Caused by Irradiation at 140°R

—●— Denotes 90% Confidence Interval

Figure 10 - Percent Change in Yield Strength and Elongation Caused by Irradiation at 140°R

—●— Denotes 90% Confidence Interval

Material and Form	Fluence 10 ¹⁷ nvt >1.0 Mev	Change in Yield Strength (ksi)										Change in Elongation (%)									
		-					+					-					+				
		40	30	20	10	0	10	20	30	40	40	30	20	10	0	10	20	30	40		
Al 6061-T6 Plate	3																				
Ti 5Al-2.5 Sn ELI Plate	3																				
A-286 Forging	3.2																				
AISI 347 Plate Weldment	3 3																				
Hastelloy X Forging	2.9																				
Inconel 718 Forging	3																				
H Monel Cast Plate	2.2																				

Figure 11 - Absolute Change in Yield Strength and Elongation Caused by Irradiation at 40°R

—●— Denotes 90% Confidence Interval

Material and Form	Fluence 10 ¹⁷ nvt >1.0 Mev	Percent Change in Yield Strength										Percent Change in Elongation									
		-					+					-					+				
		80	60	40	20	0	20	40	60	80	80	60	40	20	0	20	40	60	80		
Al 6061-T6 Plate	3																				
Ti 5Al-2.5 Sn ELI Plate	3																				
A-286 Forging	3.2																				
AISI 347 Plate Weldment	3 3																				
Hastelloy X Forging	2.9																				
Inconel 718 Forging	3																				
H Monel Cast Plate	2.2																				

Figure 12 - Percent Change in Yield Strength and Elongation Caused by Irradiation at 40°R

Tables 18 through 21 rank the alloys irradiated to 1×10^{18} nvt in the order of absolute change and percent change of yield strength and percent elongation.

Aluminum and H-Monel were the alloys most affected by radiation. The reactions of H-Monel and Al7039-0 (the softest alloy studied) were pronounced, the elongation of H-Monel decreasing 50% and the yield strength of Al7039-0 increasing 100%. The effects of radiation generally decreased with increasing strength and decreasing ductility.

The solution-hardened alloys (Ti 5Al 2.5Sn ELI, Hastelloy X, 347 stainless steel, and Inconel 625) were significantly more affected by radiation than the precipitation-hardened alloys (Udimet 630, Inconel 718, and Waspaloy).

Similarity of behavior of alloys in the same class was noted; i.e., the effects on Inconel 718 were comparable to those on Udimet 630, and the effects on Hastelloy X were comparable to those on Inconel 625. On the other hand, behavior among the various aluminum alloys was significantly different, apparently because of differences in formulation (e.g., Al 7075 vs Al 6061) as well as in temper and form.

As indicated previously, the behavior of the Ti 5Al 2.5Sn ELI alloys was distinctly different from that of the other alloys. The notch tensile strength and the ratio of notch strength to ultimate strength for the titanium alloys decreased with irradiation. Westinghouse reported no change in notch-tensile strength as a result of irradiation in GTR-19 tests (Reference 4); however, Westinghouse observed a decrease in notch tensile strength in the earlier work of GTR-16 (Reference 13). Ti 5Al 2.5Sn also had an appreciable decrease in elongation.

The results with titanium are of significance in design, because the unirradiated properties show that the alloy has relatively low initial ductility. For similar but less compelling reasons, the performance of

Inconel 718 and the aluminums is of significance in design. Because titanium, aluminum, and Inconel 718 in various forms are potentially key materials of construction in the NERVA engine, it is evident that further evaluation and testing of these materials are required to select optimum alloys and forms and to determine design properties and limits.

C. RADIATION EFFECTS VS FORM

In some instances, the effect of varying the form or processing of an alloy on its response to radiation could be detected (see Figures 9 through 12). Causes for differences in behavior in most cases, however, cannot be readily explained. Detailed studies of the influence of micro-structure and chemistry of each alloy class would be required to determine the explanation, and such studies are beyond the scope of this report.

For Al 6061-T6, the plate and the ring forging had comparable decreases in elongation; but the elongation of the pressure-vessel forging was not affected. (The unirradiated elongation of the pressure vessel forging was only 7%.)

The two titanium forgings behaved in a similar manner. However, the titanium plate appeared to be less affected by irradiation than the forgings, with allowance made for the differences in radiation levels. Westinghouse observed similar differences between forgings and sheet (Reference 7). Additional testing would be required to demonstrate a significant difference in forged and plate material.

High-strength alloys in the cold-worked and aged condition were significantly less affected than alloys in the as-forged condition. This difference indicates that the process-induced crystalline disorder tended to dwarf the effect of radiation-induced disorder.

TABLE 18

ABSOLUTE CHANGE IN YIELD STRENGTH OF
ALLOYS IRRADIATED TO APPROXIMATELY
 1×10^{18} nvt > 1.0 Mev

Rank	Material and Form	Unirradiated Yield Strength, ksi	Change, ksi*
1	Inconel 625 Plate	73.2	+50
2	Inconel 625 Welded Plate	88.7	+37
3	Hastelloy X Forging	77	+36
4	Hastelloy X Welded Forging	81	+35
5	Inconel 718 Ring Forging	199.	+26
6	Al 7039-0 Forging	22.4	+23
7	Inconel 718 EB Welded Ring Forging	200	+23
8	Inconel 718 TIG Welded Ring Forging	201	+19
9	Udimet 630 Forging	210	+17
10	Inconel 718 All Weld	205	+17
11	Waspaloy Cold-Reduced Rod	285	+17
12	A-286 Forging	131.	+16
13	Ti 5Al 2.5Sn ELI Pressure Vessel Forging	176.	+16
14	Ti 5Al 2.5Sn ELI TIG Welded Forging	178.	+16
15	Ti 5Al 2.5Sn ELI EB Welded Forging	175	+14
16	Ti 5Al 2.5Sn ELI Forging	174	+14
17	Inconel 718 Cold-Reduced Rod	277	+12
18	Al 6061-T6 Welded Ring Forging	47.9	+11
19	Al 6061-T6 Ring Forging	51.6	+11
20	Al 6061-T6 Pressure Vessel Forging	53.3	+11
21	Al 7075-T73 Forging	75.2	+7
22	Udimet 630 Cold-Reduced Rod	333	0

*Each change was statistically significant at the 90% confidence level
except that for Udimet 630 cold-reduced rod.

TABLE 19

PERCENT CHANGE IN YIELD STRENGTH OF
ALLOYS IRRADIATED TO APPROXIMATELY
 1×10^{18} nvt > 1.0 Mev

Rank	Material and Form	Unirradiated Yield Strength, ksi	% Change*
1	Al 7039-0 Forging	23.4	+99
2	Inconel 625 Plate	73.2	+69
3	Hastelloy X Forging	77.1	+46
4	Hastelloy X Welded Forging	80.9	+43
5	Inconel 625 Welded Plate	88.7	+42
6	Al 6061-T6 Welded Ring Forging	47.9	+23
7	Al 6061-T6 Ring Forging	51.6	+21
8	Al 6061-T6 Pressure Vessel Forging	53.3	+21
9	Inconel 718 Ring Forging	199.	+13
10	A-286 Forging	131	+13
11	Inconel 718 EB Welded Ring Forging	200	+12
12	Inconel 718 TIG Welded Ring Forging	201	+10
13	Inconel 718 All Weld	205	+9
14	Ti 5Al 2.5Sn ELI Pressure Vessel Forging	176	+9
15	Ti 5Al 2.5Sn TIG Welded Forging	178	+9
16	Al 7075-T73 Forging	75.2	+9
17	Ti 5Al 2.5Sn ELI EB Welded Forging	175	+8
18	Ti 5Al 2.5Sn ELI Forging	174	+8
19	Udimet 630 Forging	210	+8
20	Waspaloy Cold-Reduced Rod	284	+6
21	Inconel 718 Cold-Reduced Rod	277	+4
22	Udimet 630 Cold-Reduced Rod	333	0

*Each change was statistically significant at the 90% confidence level
except that for Udimet 630 cold-reduced rod.

TABLE 20

ABSOLUTE CHANGE IN ELONGATION OF
ALLOYS IRRADIATED TO APPROXIMATELY
 1×10^{18} nvt > 1.0 Mev

Rank	Material and Form	Unirradiated Elongation, %	Change, %
1	Inconel 625 Plate	56.8	-10.8*
2	Hastelloy X Forging - Weldment	26.0	-10.5*
3	Al 6061-T6 Ring Forging Weldment	18.7	-10.3*
4	Hastelloy X Forging	44.7	- 8.1*
5	Ti 5Al 2.5Sn ELI EB Welded Forging	14.2	- 6.9*
6	Ti 5Al 2.5Sn ELI TIG Welded Forging	15.9	- 6.9*
7	Ti 5Al 2.5Sn ELI Pressure Vessel Forging	16.6	- 4.4*
8	Inconel 718 Ring TIG Welded Forging	14.7	- 4.3*
9	Al 7039-0 Forging	12.7	- 3.7*
10	Ti 5Al 2.5Sn ELI Forging	10.8	- 3.2*
11	Udimet 630 Forging	21.0	- 2.9
12	Inconel 718 Cold-Reduced Rod	12.2	- 2.8*
13	Inconel 718 Ring Forging	17.2	- 2.7
14	Inconel 625 Welded Plate	30.2	- 2.6
15	Al 6061-T6 Ring Forging	16.5	- 2.3*
16	Inconel 718 EB Welded Ring Forging	17.2	- 2.2*
17	Waspaloy Cold-Reduced Rod	11.1	- 2.2
18	Al 7075-T73 Forging	13.4	- 1.2
19	Inconel 718 All Weld	10.4	- 0.6
20	Udimet 630 Cold-Reduced Rod	5.7	- 0.2
21	A-286 Forging	28.8	- 0.1
22	Al 6061-T6 Pressure Vessel Forging	6.6	+ 0.4

*Statistically significant change at the 90 percent confidence level

TABLE 21

PERCENT CHANGE IN ELONGATION OF
ALLOYS IRRADIATED TO APPROXIMATELY
 1×10^{18} nvt > 1.0 Mev

Rank	Material and Form	Unirradiated Elongation, %	% Change
1	Al 6061-T6 Ring Forging Weldment	18.7	-55*
2	Ti 5Al 2.5Sn ELI EB Welded Forging	14.2	-49*
3	Ti 5Al 2.5Sn ELI TIG Welded Forging	15.9	-43*
4	Hastelloy X Welded Forging	26.0	-40*
5	Ti 5Al 2.5Sn ELI Forging	10.8	-30*
6	Inconel 718 TIG Welded Ring Forging	14.7	-29*
7	Al 7039-0 Forging	12.7	-29*
8	Ti 5Al 2.5Sn ELI Pressure Vessel Forging	16.6	-26*
9	Inconel 718 Cold-Reduced Rod	12.2	-23*
10	Waspaloy Cold-Reduced Rod	11.0	-20
11	Inconel 625 Forged Plate	56.8	-19*
12	Hastelloy X Forging	44.7	-18*
13	Inconel 718 Ring Forging	17.2	-16
14	Udimet 630 Forging	21.0	-14
15	Al 6061-T6 Ring Forging	16.5	-14*
16	Inconel 718 EB Welded Ring Forging	17.2	-13*
17	Al 7075-T73 Forging	13.4	-9
18	Inconel 625 Welded Plate	30.2	-9
19	Inconel 718 All Weld	10.4	-6
20	Udimet 630 Cold-Reduced Rod	5.7	-3
21	A-286 Forging	28.8	0
22	Al 6061-T6 Pressure Vessel Forging	6.6	+6

*Statistically significant change at the 90 percent confidence level.

Comparisons between TIG weldments and electron-beam weldments of titanium and Inconel 718 revealed no differences in radiation effects. However, there may have been differences in the properties of the two types of weldments; but these considerations are beyond the scope of this report.

D. PARENT METAL VS WELDMENTS

Radiation effects on parent metal and weldments were compared for Al 6061-T6, Ti 5Al 2.5Sn, 347 stainless steel, Hastelloy X, Inconel 625, and Inconel 718. In general, where differences in the radiation effects on parent metal and weldments could be detected, the effects were greater on weldments. The properties for which differences in behavior could be detected between parent metal and weldments were generally elongation and notch strength, both potential indicators of ductility changes (see Figures 9 and 10 and Table 3).*

Al 6061-T6 weldments were significantly more embrittled by irradiation than the parent material, as indicated by the changes in elongation. The weldments were also more affected with respect to the changes in reduction of area and in fracture strength (see Table 8). Irradiated weldment specimens broke in the weld-affected zone, whereas control weldment specimens broke outside the weld-affected zone. The behavior of the irradiated Al 6061-T6 weldments would be of major concern to design.

Titanium weldments were also significantly more embrittled by irradiation than the parent metal, as seen by comparing the changes in elongation. As noted previously, the notch strength of titanium decreased with irradiation, with one exception: the notch strength of the titanium electron-beam weldment increased. No explanation can be offered for this exception.

*For all materials except Ti 5Al 2.5Sn, the pre- and postirradiation values of ultimate strength and elongation were lower for weldments than for parent material.

No differences were detected in the effects of radiation on parent metal and weldments of 347 stainless steel.

Differences in the effects of radiation on fracture strength (see Table 12) and elongation of Hastelloy X in the weldments and in the parent material were significant, whereas those for Inconel 625 were not. The results with Hastelloy X indicate that embrittlement as a result of irradiation was significantly greater in the weldments than in the parent material.

Weldments of Inconel 718 appeared to be more embrittled by irradiation than the parent metal, although the elongation data (because of scatter and small sample size) are not conclusive. The notch strength of Inconel 718 weldments was not significantly affected by irradiation, whereas that of the parent metal increased (see Table 3). Both the pre- and post-irradiation elongations for the weldment specimens and the "all-weld" specimens (a value of only 10%) were sufficiently low to be of engineering significance.

E. EFFECTS OF FLUENCE

Hastelloy X and A-286 were subjected to two or more fluence levels during testing. These differences in neutron exposure afforded an opportunity to observe the way properties vary with fluence. The yield strengths of these two materials and the percent change in these values are plotted as functions of fluence in Figure 13. Testing and data evaluation now in process will provide more definitive studies of the manner in which properties vary with neutron irradiation.

F. LIQUID-HYDROGEN VS LIQUID-NITROGEN IRRADIATION

Earlier reports have compared the effects of irradiation in liquid hydrogen and in liquid nitrogen (References 6 and 7). The results showed that differences were caused mainly by the effects of temperature on the material property, as shown in Figures 14 and 15. There were the following exceptions,

Figure 13 - 140°R Yield Strength and Percent Change in 140°R Yield Strength for A-286 and Hastelloy X as Functions of Fluence

however: the radiation effects in liquid hydrogen were appreciably greater than in liquid nitrogen for (1) the yield strength and elongation of Al 6061-T6, (2) the yield strength of Inconel 718, and (3) the elongation of A-286. The results obtained with Al 6061-T6 are shown in detail in Figure 16.

References 6 and 7 furnish approaches whereby the properties of materials irradiated in liquid hydrogen can be approximated from data on unirradiated properties in liquid hydrogen and liquid nitrogen and irradiated properties in liquid nitrogen. The data included in this report should be used in making these approximations. The results are based on relatively low fluences, and, for that reason, the relationships have limited application. (Irradiation was stopped for safety reasons as noted in Section III.)

Performance comparison between alloys irradiated in liquid hydrogen and those irradiated in liquid nitrogen indicates there is cause for concern in design where an alloy has marginal ductility when irradiated in liquid nitrogen. More costly testing in liquid hydrogen may be required in such cases. The nature and scope of this testing will depend on the specific application of the alloy, as well as the expected operating temperature and radiation environment.

G. EFFECTS OF ANNEALING

Annealing studies were performed to investigate the dependence of radiation effects on temperature for selected alloys and to provide background information on the effects temperature cycling may have during NERVA missions requiring restart capabilities. Table 22 summarizes the results of the studies; Figures 17 and 18 show the results for yield strength.

Annealing at ambient temperature substantially restored the properties of aluminum irradiated at 140°R. Annealing appreciably affected the properties of irradiated titanium and A-286, but the effects were less than those for aluminum. The effects for titanium were comparable to those

—●— Denotes 90% Confidence Interval

Figure 14 - Absolute Change in Yield Strength and Elongation Due to Irradiation to 3×10^{17} nvt > 1.0 Mev at 40°R and 140°R

—●— Denotes 90% Confidence Interval

Figure 15 - Percent Change in Yield Strength and Elongation Due to Irradiation to 3×10^{17} nvt > 1.0 Mev at 40°R and 140°R

$\Phi = \pm 1$ STD DEV(4 SPECIMENS) O = ANNEALED 1 HR @ 140°R (2 SPECIMENS)

Figure 16 - Tensile Properties of Al 6061-T6 Plate Before and After Irradiation to 3×10^{17} nvt > 1.0 Mev in Liquid Hydrogen and Liquid Nitrogen

TABLE 22
SUMMARY OF ANNEALING STUDIES

Alloy and Form	Fluence 10 ¹⁷ nvt >1 Mev	Ultimate Strength, ksi			Yield Strength, ksi			Elongation %			Temperature °R		
		Control	Irrad.	Anneal	Control	Irrad.	Anneal	Control	Irrad.	Anneal	Irrad.	Anneal	Test
Al 6061-T6 Plate Pressure Vessel Forging	2	73.7	76.6*	71.2 ⁽³⁾	52.9*	72.2*	63.1 ⁽³⁾	26.4*	18.1*	22.4 ⁽³⁾	40	140	40
	11	62.5	66.4*	64.1	53.3*	64.3	61.0	6.6	7.0	10.8	140	RT	140
Al 7075-T73 Forging	9	91.1	93.0*	89.9	75.2	82.2	77.2	13.4	12.2	11.6	140	RT	140
Ti 5Al 2.5Sn ELI Plate Pressure Vessel Forging	3	234.8	244.4	(1)	217.5	233.3*	218.0 ⁽³⁾	9.6	10.3	(1)	40	140	40
	8	180.7*	195.1*	190.8	175.6*	191.8*	186.7	16.6*	12.2	12.8	140	RT	140
A-286 Forging	12	193.9	196.5*	190.0	130.6*	147.0*	141.6	28.8*	28.7	31.0	140	RT	140
Hastelloy X Forging Forging Weldment	3	154.6 ⁽³⁾	163.8	164.3 ⁽⁴⁾	98.5 ⁽³⁾	121.8*	103.0 ⁽⁴⁾	33.6*	32.8*	43.3 ⁽⁴⁾	40	140	40
	8	140.8*	155.4	154.5	77.1*	112.1	114.9	44.7*	36.6	39.8	140	RT	140
	8	135.3*	144.4	142.5 ⁽³⁾	80.9*	115.8	111.0 ⁽³⁾	26.0*	15.5	16.2 ⁽³⁾	140	RT	140

NOTES:

- (1) Not available
- (2) Average fluence received by specimens
- (3) Value based on sample size of two
- (4) Value based on sample size of one
- (5) Values based on sample size of three or four except as noted
- * Statistically significant difference at 90% confidence level between indicated value and annealed value

Figure 17 - Effects of Irradiation at 140°R and Subsequent Annealing at 540°R on the 140°R Yield Strength of Alloys

Material	Number of Specimens		
	Control	Irrad	Anneal
Hastelloy X	2	4	1
Ti 5Al 2.5Sn ELI	4	3	2
Al 6061-T6	4	4	2

Figure 18 - Effects of Irradiation at 40°R and Subsequent Annealing at 140°R on the 40°R Yield Strength of Alloys

reported by Westinghouse (Reference 4). Annealing produced no appreciable change in the properties of irradiated Hastelloy X. Annealing studies of Hastelloy X and similar alloys should be continued, as these results indicate that damage of design significance remains after annealing at ambient temperature.

The few annealing studies with specimens irradiated at 40°R indicate that Ti 5Al 2.5Sn fully recovered and Al 6061 recovered 50% after annealing at 140°R. These results are consistent with the results of comparisons between the effects of irradiation in liquid nitrogen and liquid hydrogen; i.e., aluminum was significantly more affected by irradiation in liquid hydrogen than in liquid nitrogen, whereas the difference in effects was insignificant for titanium. (Conclusions regarding the effects of annealing on Ti 5Al 2.5Sn are based on a relatively small number of specimens.)

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TABLE A-1
TEST RESULTS INDIVIDUAL SPECIMENS, A1 6061-T6

PLATE - CTT TESTS													
CONTROL SPECIMENS ⁽¹⁾							IRRADIATED SPECIMENS ⁽¹⁾						
Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA %	Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA % Fluence 10 ¹⁷ nvt > 1 mev
LN ₂	520518	60.7	54.2	49.5	21.0	40.4	LN ₂	520517	61.8	55.6	57.5	16.6	36.2
	520306	66.4	59.6	55.5	21.2	36.1		520505	61.0	55.6	57.9	16.3	31.9
	520520	61.0	54.8	49.8	19.9	34.0		520519	62.3	54.9	58.0	17.5	36.2
	520508	56.4	50.3	43.5	20.9	34.0		520507	61.1	54.9	57.5	15.6	34.0
	$\bar{X}$	61.1	54.7	49.6	20.8	36.1		$\bar{X}$	61.6	55.2	57.7	16.5	34.6
LH ₂	520514	70.9	70.5	51.2	26.4	35.4	LH ₂	520513	75.2	71.5	70.0	19.8	29.8
	520502	74.7	72.8	52.5	26.5	36.2		520501	75.2	71.5	70.0	18.9	36.2
	520516	74.7	72.2	54.0	26.1	31.9		520515	78.0	74.3	74.3	17.0	31.9
	520503	74.4	73.2	54.2	26.8	31.9		520504	78.0	76.8	74.5	16.8	(51.0)
	$\bar{X}$	73.7	72.2	52.9	26.4	33.8		$\bar{X}$	76.6	73.5	72.2	18.1	32.6
							(5)	520524	70.68	67.0	63.0	22.3	36.2
								520523	71.68	68.1	63.2	22.6	31.3
								$\bar{X}$	71.2	67.5	63.1	22.4	33.8

RING FORGING - STATIC TESTS													
CONTROL SPECIMENS ⁽²⁾							IRRADIATED SPECIMENS ⁽²⁾						
Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA %	Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA % Fluence 10 ¹⁷ nvt > 1 mev
LN ₂	121302	63.6	62.8	52.2	17.2	25.0	LN ₂	121301	66.7	62.1	62.1	14.7	20.8
	121304	62.2	58.5	49.0	(11.4)	29.2		121303	64.2	61.0	60.9	14.6	22.9
	121306	65.4	63.2	52.2	16.1	(70.2)		121305	64.4	59.0	62.1	15.6	31.2
	121308	65.2	62.1	52.8	16.2	20.8		121307	67.7	65.2	64.6	12.0	20.8
	$\bar{X}$	64.1	61.6	51.6	16.5	25.0		$\bar{X}$	65.8	61.8	62.4	14.2	23.9
LN ₂	421402	60.6					LN ₂	421401	64.9				5.7
	421404	55.6						421403	67.6				5.7
	421406	62.8						421405	70.6				5.7
	421408	57.7						421407	69.6				5.7
	(4) $\bar{X}$	59.2						$\bar{X}$	68.2				

RING FORGING WELDMENT - STATIC TESTS													
CONTROL SPECIMENS ⁽³⁾							IRRADIATED SPECIMENS ⁽³⁾						
Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA %	Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA % Fluence 10 ¹⁷ nvt > 1 mev
LN ₂	121502W	59.4	52.0	47.6	18.1	39.6	LN ₂	121501W	61.6	61.1	59.1	7.0	16.7
	121504W	58.2	50.9	48.7	17.9	39.6		121503W	62.6	56.5	60.2	12.3	(35.4)
	121506W	58.3	(58.3)	46.6	(13.0)	(18.7)		121505W	60.0	59.8	(50.4)	8.6	16.7
	121508W	58.8	49.7	48.6	20.0	41.6		121507W	61.1	60.6	57.9	5.6	16.7
	$\bar{X}$	58.7	50.9	47.9	18.7	40.3		$\bar{X}$	61.4	59.5	59.1	8.4	16.7
LN ₂	421602W	52.7					LN ₂	421601W	59.5				5.7
	421604W	49.9						421603W	51.0				5.7
	421606W	49.0						421605W	45.8				5.7
	421608W	49.2						421607W	65.3				5.7
	(4) $\bar{X}$	50.2						$\bar{X}$	55.4				

TABLE A-1 (cont.)

PRESSURE VESSEL FORGING - STATIC TESTS													
CONTROL SPECIMENS ⁽³⁾							IRRADIATED SPECIMENS ⁽³⁾						
Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA %	Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Flong. %	RA % Fluence 10 ¹⁷ nvt > 1 mev
LN ₂	124302	60.9	60.9	52.6	5.5	10.4	LN ₂	124301	66.2	66.2	63.8	8.0 +	4.2
	124304	63.2	63.2	52.8	8.3	16.6		124303	64.2	(58.0)	60.5	(22.1) ⁺	8.3
	124306	63.4	63.4	54.4	6.1	8.3		124305	66.9	66.9	65.6	4.9 +	8.3
	X	62.5	62.5	53.3	6.6	11.8		124307	68.3	67.8	67.3	8.0 +	10.4
								X	66.4	67.0	64.3	7.0	7.8
LN ₂ (4)	224514	87.3					(6)	124308	(60.2)	(59.6)	(53.8)	13.7 +	20.8
	224516	85.3						124309	64.2	64.2	62.2	7.1 +	22.9
	224518	84.3						124312	65.7	65.2	64.6	14.2 +	22.9
	224520	85.7						124311	62.6	62.6	56.1	8.0 +	12.5
	X	85.6						X	64.1	62.9	61.0	10.8	19.8
							LN ₂ (4)	224513	83.1				11.0
								224515	92.9				11.0
								224517	92.1				11.0
								224519	88.4				11.0
								X	39.1				
(4)							(4)	224521	83.9				11.0
								224522	77.1				11.0
								224523	84.3				11.0
								224524	66.0				11.0
								X	77.8				

NOTES:

- (1) Specimen part number was 1117677.
- (2) Unnotched and notched specimen part numbers were 1116229 and 1116286 respectively.
- (3) Unnotched and notched specimen part numbers were 1116229 and 1116230 respectively.
- (4) Notched specimens.
- (5) LH₂ irradiated, LN₂ annealed, LH₂ tested.
- (6) LN₂ irradiated, ambient annealed, LN₂ tested.
- () Indicates data were not used in computing means and standard deviations.
- + Value derived from chart data

TABLE A-2

TEST RESULTS INDIVIDUAL SPECIMENS, A1 7075-T73

Forging - Static Tests															
CONTROL SPECIMENS ⁽¹⁾							IRRADIATED SPECIMENS ⁽¹⁾								
Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA %	Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA %	Fluence 10 ¹⁷ nvt > 1 mev	
LN ₂	123602	92.0	90.0	76.4	15.6	18.7	LN ₂	123601	93.1	92.9	82.5	9.5	14.3	9.0	
	123604	90.0	87.3	75.0	11.5	19.5		123603	92.6	86.6	82.2	13.2	21.7	9.0	
	123606	90.9	87.7	73.9	13.9	17.4		123605	92.6	88.2	82.0	12.3	22.2	9.0	
	123608	91.5	88.4	75.6	12.7	20.8		123607	93.5	88.4	(77.9)	13.6	12.5	9.0	
	X	91.1	88.4	75.2	13.4	19.1		X	93.0	89.0	82.2	12.2	17.7		
LN ₂ (3)	223702	107.1					(2)	123609	91.6	84.9	81.1	12.6	23.4	9.0	
	223704	108.0						123611	88.2	86.6	73.3	10.6	18.7	9.0	
	223706	107.1						X	89.9	85.8	77.2	11.6	21.0		
	(3)	223708	105.2					LN ₂ (3)	223701	98.8					9.0
		X	106.8						223703	111.3					9.0
									223705	110.4					9.0
									223707	108.7					9.0
									X	107.3					

NOTES:

- (1) Unnotched and notched specimen part numbers were 1116229 and 1116230 respectively.
 (2) LN₂ irradiated, ambient annealed, LN₂ tested
 (3) Notched specimens
 () Indicates data were not used in computing means and standard deviations

TABLE A-3

TEST RESULTS INDIVIDUAL SPECIMENS, A1 7039-0

Forging - Static Tests														
CONTROL SPECIMENS ⁽¹⁾							IRRADIATED SPECIMENS ⁽¹⁾							
Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA %	Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA %	Fluence 10 ¹⁷ nvt > 1 mev
LN ₂	122102	50.7	50.7	24.0	11.6	12.2	LN ₂	122101	56.6	56.6	45.6	10.4	14.3	9.0
	122104	49.2	49.2	22.6	11.4	16.0		122103	55.5	55.5	46.4	8.2	12.2	9.0
	122106	51.5	51.3	23.4	13.7	14.3		122105	56.1	56.1	47.4	8.4	14.3	9.0
	122108	51.4	51.4	23.4	14.0	16.3		122107	56.6	56.6	(56.1)	(10.4)	14.3	9.0
	X	50.7	50.6	23.4	12.7	14.7		X	56.2	56.2	46.5	9.0	13.8	

NOTES:

- (1)- Specimen part number was 1117853
 ()- Indicates data were not used in computing means and standard deviations.

TABLE A-4
TEST RESULTS INDIVIDUAL SPECIMENS, Ti 5Al 2.5Sn ELI

PLATE - CTT TESTS													
CONTROL SPECIMENS ⁽¹⁾							IRRADIATED SPECIMENS ⁽¹⁾						
Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA %	Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA % Fluence 10 ¹⁷ nvt > 1 mev
LN ₂	560618	201.6	195.0	190.0	11.4	24.3	LN ₂	560617	204.2	191.2	197.0	12.5	28.9
	560606	230.9	194.1	192.0	13.0	28.9		560605	205.9	190.1	196.0	11.6	34.2
	560620	196.0	186.7	186.7	14.0	28.9		560619	193.1	179.0	186.0	10.2	31.6
	560608	188.2	180.4	180.0	11.3	28.9		560607	198.6	186.1	192.0	9.9	27.0
	X	197.4	189.0	187.2	12.4	27.8		X	200.5	186.6	192.8	10.8	30.4
LH ₂	560614	(219.4)	(219.4)	210.0	(2.3)	(3.3)	LH ₂	560613	(216.2)	(216.2)	(4)	(5)	(23.7)
	560602	232.7	232.7	216.0	(4.5)	13.2		560609	(245.5)	(245.5)	240.0	(5)	(13.5)
	560616	234.2	232.6	222.0	9.2	10.8		560615	242.6	242.6	228.0	10.9	23.7
	560604	237.8	237.8	222.0	9.9	13.5		560603	245.0	245.0	232.0	9.8	15.8
	X	234.8	234.3	217.5	9.6	12.5		X	243.8	243.8	233.3	10.3	19.8
							(7)	560624	(228.2)	(225.1)	222.0	(5)	16.2
								560623	(224.5)	(224.5)	214.0	(5)	15.8
								X			218.0		16.0

FORGING - STATIC TESTS													
CONTROL SPECIMENS ⁽²⁾							IRRADIATED SPECIMENS ⁽²⁾						
Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA %	Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA % Fluence 10 ¹⁷ nvt > 1 mev
LN ₂	161702	181.7	181.1	174.5	10.8	20.4	LN ₂	161701	198.3	194.1	190.0	6.8	16.7
	161704	182.8	182.8	175.4	11.8	18.4		161703	197.3	192.1	187.9	7.8	18.8
	161706	182.6	181.8	174.7	10.5	20.8		161705	196.7	191.9	184.3	8.5	12.5
	161708	180.9	180.3	172.2	9.9	18.4		161707	198.5	194.2	190.0	7.3	20.8
	X	182.0	181.5	174.2	10.8	19.5		X	197.7	193.1	188.0	7.6	17.2
LN ₂ (6)	461802	174.5					LN ₂ (6)	461801	130.5				5.7
	461804	174.5						461803	130.9				5.7
	461806	176.3						461805	(118.4)				5.7
	461808	(161.4)						461807	132.9				5.7
	X	175.1						X	131.4				

EB WELDED FORGING - STATIC TESTS													
CONTROL SPECIMENS ⁽²⁾							IRRADIATED SPECIMENS ⁽²⁾						
Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA %	Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA % Fluence 10 ¹⁷ nvt > 1 mev
LN ₂	161902W	184.6	183.8	176.0	13.7	24.4	LN ₂	161901W	197.7	194.0	190.5	7.4	16.7
	161904W	184.7	182.6	176.0	13.6	22.8		161903W	195.3	192.2	186.8	7.3	18.8
	161906W	183.3	181.3	174.1	12.7	24.4		161905W	198.3	194.2	191.5	5.9	16.7
	161914W	184.8	184.8	175.6	16.9	22.4		161907W	199.2	196.7	189.5	8.5	16.7
	X	184.4	183.1	175.4	14.2	23.5		X	197.6	194.3	189.6	7.3	17.2
LN ₂ (6)	462002W	170.6					LN ₂ (6)	462001W	142.7				5.7
	462004W	172.8						462003W	(121.6)				5.7
	462006W	168.9						462005W	143.3				5.7
	462008W	161.0						462007W	140.8				5.7
	X	168.3						X	142.3				

TABLE A-4 (cont.)

TIG WELDED FORGING - STATIC TESTS														
CONTROL SPECIMENS ⁽²⁾							IRRADIATED SPECIMENS ⁽²⁾							
Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA %	Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA %	Fluence 10 ¹⁷ nvt > 1 mev
LN ₂	1620A02W	183.8	179.3	173.5	15.4	28.6	LN ₂	1620A01W	198.6	187.4	194.6	11.1	27.1	9.0
	1620A04W	184.0	174.5	177.6	16.9	28.6		1620A13W	199.6	187.6	192.1	9.6	27.1	9.0
	1620A06W	186.3	178.1	181.7	14.7	29.2		1620A05W	198.3	193.1	195.6	7.3	16.7	9.0
	1620A08W	187.1	179.5	180.2	16.6	27.2		1620A07W	201.2	197.3	194.8	7.9	16.7	9.0
	X	185.3	177.8	178.2	15.9	28.4		X	199.4	191.4	194.3	9.0	21.9	
LN ₂ (6)	4620B02W	151.0					LN ₂ (6)	4620B01W	167.1					5.7
	4620B04W	154.9						4620B03W	163.7					5.7
	4620B06W	137.4						4620B05W	166.3					5.7
	4620B08W	149.4						4620B07W	171.9					5.7
	X	148.2						X	167.2					5.7

PRESSURE VESSEL FORGING - STATIC TESTS															
CONTROL SPECIMENS ⁽³⁾							IRRADIATED SPECIMENS ⁽³⁾								
Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA %	Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA %	Fluence 10 ¹⁷ nvt > 1 mev	
LN ₂	164426	180.8	170.8	(5)	16.7	(41.7)	LN ₂	164425	195.7	182.2	192.5	12.3 ₊	25.0	7.9	
	164428	181.8	170.8	176.0	17.9	31.2		164427	197.5	186.3	194.6	12.3 ₊	25.0	7.9	
	164430	180.3	174.9	176.0	14.5	27.1		164429	194.6	180.1	189.4	12.3 ₊	35.5	7.9	
	164438	180.3	171.8	174.9	17.2	29.2		164437	192.5	173.3	190.5	11.9	31.2	7.9	
	X	180.7	172.1	175.6	16.6	29.2		X	195.1	180.5	191.8	12.2	29.2		
LN ₂ (6)	264632	256.4					(7)	164439	191.5	177.0	188.4	14.1	33.3	7.9	
	264634	248.2						164440	191.5	179.7	189.2	13.9 ₊	29.2	7.9	
	264636	255.0						164441	190.0	177.0	183.2	11.7 ₊	22.9	7.9	
	264644	251.8						164442	190.0	178.1	185.9	11.5	25.0	7.9	
	X	252.8						X	190.8	177.9	186.7	12.8	27.6		
	(6,7)	264631	217.9					(6,7)	264631	217.9					7.9
		264633	210.1						264633	210.1					7.9
		264635	234.6						264635	234.6					7.9
		264643	228.1						264643	228.1					7.9
		X	222.7						X	222.7					
264645		225.5					264645		225.5					7.9	
264646		226.6					264646		226.6					7.9	
264647	232.9					264647	232.9					7.9			
264648	220.2					264648	220.2					7.9			
X	226.3					X	226.3								

NOTES

- (1) Specimen number part number was 1117677.
- (2) Unnotched and notched specimen part numbers were 1116229 and 1116286 respectively.
- (3) Unnotched and notched specimen part numbers were 1116229 and 1116230 respectively.
- (4) Yield did not reach 0.2%.
- (5) No data are available.
- (6) Notched specimens.
- (7) LN₂ irradiated, ambient annealed, LN₂ tested.
- + Value derived from chart data.
- () Indicates data were not used in computing means and standard deviations.

TABLE A-5
TEST RESULTS INDIVIDUAL SPECIMENS, A-286

FORGING - STATIC TESTS															
CONTROL SPECIMENS(1)							IRRADIATED SPECIMENS(1)								
Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA %	Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA %	Fluence 10 ¹⁷ nvt 1 mev	
LN ₂	112802	196.6	196.6	129.3	29.6	28.2	LN ₂	110415	197.5	196.6	151.3	29.8	39.6	11.0	
	112804	194.5	194.5	130.5	27.6	29.2		112801	196.6	196.6	150.9	26.8	26.1	12.0	
	112806	195.2	195.2	132.5	27.1	27.1		112803	199.2	197.1	143.3	32.9	34.7	12.0	
	112803	189.2	187.1	130.2	30.9	29.2		112805	192.6	192.6	144.8	27.1	25.0	12.0	
	X	193.9	193.4	130.6	28.8	28.4		112807	196.7	196.7	144.9	27.2	26.5	12.0	
								X	196.5	195.9	147.0	28.7	30.4		
								112809	196.1	196.1	144.7	29.3	28.6	12.0	
								112810	185.0	185.0	138.6	32.3	26.5	12.0	
								(3)	112811	193.1	189.5	140.1	31.3	31.9	12.0
								112812	185.8	185.8	143.0	31.3	31.2	12.0	
LN ₂ (2) ⁺							X	190.0	189.1	141.6	31.0	29.6			
	212914	237.7						212901	241.7					12.0	
	212904	236.1						212903	250.9					12.0	
	212906	238.1					LN ₂	212905	256.9					12.0	
	212908	228.1					(2)	212907	240.8					12.0	
	X	235.0					X	247.6							

FORGING - CTT TESTS														
CONTROL SPECIMENS(1)							IRRADIATED SPECIMENS(1)							
Test Cond	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA %	Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA %	Fluence 10 ¹⁷ nvt 1 mev
LN ₂	110416	195.3	195.3	138.0	33.5	27.6	LN ₂	110413	200.0	200.0	132.0	32.6	29.8	3.5
	110414	194.0	194.0	134.0	(21.9)	(21.3)		110411	201.0	198.0	145.0	34.8	38.3	3.5
	110412	201.8	201.8	132.0	29.1	31.9		110409	197.9	195.3	132.0	32.7	34.1	3.5
	110410	198.0	196.0	122.0	32.6	31.9		X	196.6	197.8	136.3	33.4	34.1	
	X	197.3	196.8	131.5	31.7	30.5								
LN ₂	110406	206.0	206.0	145.0	24.9	23.4	LN ₂	110401	213.0	213.0	163.0	22.1	22.9	3.2
	110408	202.0	202.0	145.0	24.9	27.7		110403	196.0	196.0	147.0	21.0	25.5	3.2
	110402	214.4	114.4	146.0	27.7	27.7		110405	211.2	211.2	160.0	25.0	22.9	3.2
	110404	211.7	211.7	151.0	25.5	32.0		110407	197.5	197.5	156.0	23.6	27.6	3.2
	X	208.5	208.5	146.8	25.8	27.7		X	204.4	204.4	156.5	23.0	24.7	

NOTES

- (1) Unnotched and notched specimen part numbers were 1116229 and 1116230 respectively.
(2) Notched specimens
(3) LN₂ irradiated, ambient annealed, LN₂ tested.
() Indicates data were not used in computing means and standard deviations.

TABLE A-6
TEST RESULTS INDIVIDUAL SPECIMENS, AISI 347

PLATE - CTT TESTS													
CONTROL SPECIMENS ⁽¹⁾							IRRADIATED SPECIMENS ⁽¹⁾						
Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA %	Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA % Fluence 10 ¹⁷ nvt > 1 mev
LN ₂	590212	217.0	207.2	78.0	31.5	48.6	LN ₂	590217	214.0	197.6	92.0	31.1	40.5 2.5
	590206	216.4	203.4	54.0	32.0	50.0		590205	209.7	200.1	73.0	32.6	42.1 2.5
	590220	204.6	191.5	75.5	31.4	44.0		590219	205.3	189.3	98.0	32.8	40.5 3.4
	590208	216.5	200.6	54.0	34.6	51.4		590207	213.5	205.6	78.0	35.9	47.3 3.4
	X	213.6	200.7	65.4	32.4	48.5		X	210.6	198.2	85.2	33.1	42.6
LH ₂	590214	229.0	229.0	80.8	28.0	29.8	LH ₂	590221	232.5	232.5	96.5	23.6	48.6 2.6
	590202	230.7	230.7	63.0	26.7	21.6		590201	227.9	227.9	85.0	27.3	37.8 2.6
	590216	242.0	242.0	70.5	28.6	21.6		590215	240.4	240.4	84.7	29.0	35.1 3.5
	590204	218.3	218.3	48.0	25.4	43.3		590203	212.8	206.4	83.0	24.7	32.4 3.5
	X	230.0	230.0	65.6	27.2	29.1		X	228.4	226.8	87.3	26.2	38.5

WELDMENT - CTT TESTS													
CONTROL SPECIMENS ⁽¹⁾							IRRADIATED SPECIMENS ⁽¹⁾						
Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA %	Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA % Fluence 10 ¹⁷ nvt > 1 mev
LN ₂	590318W	214.1	210.9	46.4	25.8	29.7	LN ₂	590317W	204.0	201.0	76.0	28.1	35.1 2.5
	590320W	207.3	205.7	68.0	26.2	29.7		590321W	209.0	203.0	81.5	28.6	36.8 3.4
	590306W	207.1	206.3	49.3	27.8	31.6		590305W	201.1	201.1	75.4	27.5	29.0 4.4
	590311W	205.1	200.0	55.5	28.7	36.9		590307W	(123.5)	(123.5)	(72.2)	(14.9)	(18.4) 4.4
	X	208.4	205.7	54.8	27.1	32.0		X	204.7	201.7	77.6	28.1	33.6
LH ₂	590314W	203.6	203.6	86.0	22.0	21.0	LH ₂	590313W	207.8	207.8	96.0	17.3	23.7 2.6
	590302W	198.4	198.4	60.0	22.2	23.7		590301W	190.0	190.0	88.0	15.6	21.0 2.6
	590316W	201.4	201.4	50.5	20.8	18.9		590315W	205.8	205.8	88.0	21.4	21.6 3.5
	590304W	211.6	211.6	72.0	22.7	21.0		590303W	229.5	229.5	88.0	24.5	26.3 3.5
	X	203.8	203.8	67.1	21.9	21.2		X	208.3	208.3	90.0	19.7	23.2

NOTES

(1) Specimen part number was 1117677.

() Indicates data were not used in computing means and standard deviations.

TABLE A-7
TEST RESULTS INDIVIDUAL SPECIMENS, HASTELLOY X

FORGING - CTT TESTS													
CONTROL SPECIMENS ⁽¹⁾							IRRADIATED SPECIMENS ⁽¹⁾						
Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong %	RA %	Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA % Fluence 10 ¹⁷ nvt > 1 mev
LN ₂	130116	144.2	144.2	83.0	45.3	31.9	LN ₂	130113	143.0	143.0	108.0	(28.5)	(21.2) 3.5
	130114	144.2	144.2	76.0	50.8	37.5		130111	150.7	150.7	102.0	37.5	31.9 3.5
	130120	140.9	140.9	82.0	41.7	34.0		130109	150.7	150.7	108.0	43.5	34.0 3.5
	130110	141.5	141.3	80.8	43.0	36.2		X	148.1	148.1	106.0	40.5	33.0
	X	142.7	142.7	80.4	45.2	34.9							
LH ₂	130102	150.3	150.3	93.0	29.6 ⁽⁴⁾	29.2	LH ₂	130101	165.0	165.0	121.0	29.6	29.2 2.6
	130108	(3)	(3)	(3)	34.8 ⁽⁴⁾	27.1		130103	163.5	163.5	119.0	33.5	31.3 2.6
	130106	(3)	(3)	(3)	36.4 ⁽⁴⁾	31.2		130105	163.0	163.0	123.0	31.8	29.2 3.5
	030104	159.0	159.0	104.0	33.7	25.2		130117	(197.0)	(197.0)	124.0	36.2	25.0 3.5
	X	154.6	154.6	98.5	33.6	28.2		X	163.8	163.8	121.8	32.8	28.7
							(5)	130119	164.3	164.3	103.0	43.3	33.4 2.2

FORGING - STATIC TESTS													
CONTROL SPECIMENS ⁽¹⁾							IRRADIATED SPECIMENS ⁽¹⁾						
Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong %	RA %	Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA % Fluence 10 ¹⁷ nvt > 1 mev
LN ₂	130902	139.2	139.1	76.6	42.0	33.4	LN ₂	130115	160.8	160.8	117.7	36.7	29.2 11.0
	130904	141.8	141.8	78.3	44.9	35.5		130901	150.7	150.7	110.6	(28.7)	27.1 8.0
	130906	140.7	140.7	76.6	46.7	34.8		130903	154.5	154.5	108.7	37.8	29.1 8.0
	130908	141.7	141.7	77.0	45.1	34.7		130905	157.1	157.1	113.9	32.8	27.1 8.0
	X	140.8	140.8	77.1	44.7	34.6		130907	153.8	153.8	111.9	39.1	26.6 8.0
								X	155.4	155.4	112.6	36.6	27.8
								130909	(138.7)	(138.7)	99.2	(25.3)	(25.0) 8.0
								130911	156.1	156.1	126.3	36.1	31.2 8.0
							(6)	130913	154.9	154.9	106.7	40.3	33.4 8.0
								130915	152.4	152.4	111.7	43.0	31.2 8.0
								X	154.5	154.5	111.0	39.8	31.9
								130910	134.9	134.9	80.5	(36.6)	32.6 13.0
								130912	138.6	138.6	79.3	49.7	35.4 23.0
							(7)	130914	141.6	141.6	79.1	45.6	37.5 13.0
								130916	145.1	145.1	79.5	45.8	37.5 54.0
								X	140.1	140.1	79.6	47.0	35.8

TABLE A-7 (cont.)

WELDMENT - STATIC TESTS													
CONTROL SPECIMENS ⁽²⁾							IRRADIATED SPECIMENS ⁽²⁾						
Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA %	Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA % Fluence 10 ¹⁷ nvt > 1 mev
LN ₂	131002W	141.5	141.5	78.7	29.9	26.7	LN ₂	131001W	(131.4)	(131.4)	115.0	(6.8)	(12.2) 8.0
	131004W	133.7	133.7	79.7	26.7	30.6		131003W	145.5	145.5	115.5	16.4	17.0 8.0
	131006W	133.7	133.7	84.3	23.6	29.2		131005W	139.4	139.4	115.6	12.9	20.4 8.0
	131008W	132.4	132.4	3	23.7	24.5		131007W	148.2	148.2	117.3	17.3	20.8 8.0
	X	135.3	135.3	80.9	26.0	27.8		X	144.4	144.4	115.8	15.5	19.4
LN ₂ (5)	231102W	162.0					LN ₂ (8)	231101W	191.8				8.0
	231104W	165.9						231103W	196.4				8.0
	231106W	162.0						231105W	194.9				8.0
	231108W	162.7						231107W	192.6				8.0
	X	163.2						X	193.9				
(6)							(7)	131009W	141.7	141.7	105.3	18.1	14.3 8.0
								131011W	143.3	143.3	116.6	14.2 ⁽⁴⁾	24.5 8.0
								X	142.5	142.5	111.0	16.2	19.4
								131013W	135.9	135.9	79.5	31.8	23.0 22.0
								131014W	129.8	129.8	78.7	26.3	29.2 54.0
								X	132.8	132.8	79.1	29.0	26.1

NOTES

- (1) Specimen part number was 1116229.
- (2) Unnotched and notched specimen numbers were 1116229 and 1116230 respectively.
- (3) No data are available.
- (4) Value derived from test chart.
- (5) LH₂ irradiated, LN₂ annealed, LH₂ tested.
- (6) LN₂ irradiated, ambient annealed, LN₂ tested.
- (7) Ambient irradiated, LN₂ tested; test conditions precluded obtaining irradiation test temperature. For this reason, data is not included in body of report.
- (8) Notched specimens.
- () Indicates data were not used in computing means and standard deviations.

TABLE A-8
TEST RESULTS INDIVIDUAL SPECIMENS, INCONEL 625

PLATE - STATIC TESTS													
CONTROL SPECIMENS ⁽¹⁾							IRRADIATED SPECIMENS ⁽¹⁾						
Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA %	Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA % Fluence 10 ¹⁷ nvt < 1 mev
LN ₂	141202	155.4	155.4	74.3	56.8	38.3		141201	163.9	163.5	122.3	40.2	31.2 11.0
	141204	151.4	150.8	73.1	52.2	39.6		141203	167.0	167.0	124.8	49.4	27.0 11.0
	141206	154.7	154.0	72.4	56.4	40.0	LN ₂	141205	166.3	166.3	125.9	51.5	33.2 11.0
	141208	154.9	154.5	73.1	61.7	41.6		141207	167.2	167.2	120.7	42.8	35.4 11.0
	X	154.1	153.7	73.2	56.8	39.9		X	166.1	166.0	123.4	46.0	31.7

WFLDMFNT - STATIC TESTS													
CONTROL SPECIMENS ⁽²⁾							IRRADIATED SPECIMENS ⁽²⁾						
Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA %	Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA % Fluence 10 ¹⁷ nvt > 1 mev
LN ₂	1412A02W	152.0	152.0	87.1	31.7	24.5		1412A01W	166.7	166.7	124.2	26.5	34.0 11.0
	1412A04W	147.2	147.2	89.2	26.7	28.5		1412A03W	169.8	169.8	124.2	29.2	35.4 11.0
	1412A06W	155.5	155.5	89.6	34.9	29.1	LN ₂	1412A05W	171.4	171.4	125.5	28.4	27.1 11.0
	1412A08W	150.3	150.3	89.0	27.6	26.5		1412A07W	170.2	170.2	128.0	26.7	29.2 11.0
	X	151.2	151.2	88.7	30.2	27.2		X	169.5	169.5	125.5	27.6	31.4
LN ₂ (2)	1412B02W	116.7						1412B01W	141.6				5.7
	1412B04W	113.6						1412B03W	126.4				5.7
	1412B06W	(4)					LN ₂	1412B05W	(3)				5.7
	1412B08W	120.2					(2)	1412B07W	144.3				5.7
	X	116.8						X	137.4				

NOTES

- (1) Specimen part number was 1117853 modified to 0.3 inch head thickness.
 (2) Unnotched and notched specimen part numbers were 1117853 and 1116286 respectively.
 (3) No data are available.

TABLE A-9
TEST RESULTS INDIVIDUAL SPECIMENS, WASPALOY

COLD REDUCED ROD-STATIC TESTS													
CONTROL SPECIMENS ⁽¹⁾							IRRADIATED SPECIMENS ⁽¹⁾						
Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA %	Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA % Fluence 10 ¹⁷ nvt > 1 mev
LN ₂	-84026	308.7	297.4	(2)	10.8	29.0		-84027	304.9	295.4	295.1	7.1 ⁺	23.3 7.8
	-84028	318.5	310.5	291.4	10.8	22.6		-84029	303.9	293.5	298.7	6.4	26.6 7.8
	-84030	304.7	293.0	273.1	13.2	28.1	LN ₂	-84031	289.8	280.3	278.7	12.0 ⁺	22.6 7.8
	-84032	312.1	304.1	286.6	9.6	25.8		-84033	312.3	303.1	307.7	6.9 ⁺	16.2 7.8
	X	311.0	301.2	283.7	11.1	26.4		X	302.7	293.1	295.0	8.1	22.2

NOTES

- (1) Specimen part number was 1118388.
 (2) Data are not available.
 + Value derived from chart data.

TABLE A-10
TEST RESULTS INDIVIDUAL SPECIMENS, UDIMET 630

FORGING STATIC TESTS													
CONTROL SPECIMENS ⁽¹⁾							IRRADIATED SPECIMENS ⁽¹⁾						
Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA %	Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA % Fluence 10 ¹⁷ nvt >1 mev
LN ₂	173202	263.7	263.7	202.2	15.7	16.1		173201	260.5	260.5	225.1	17.6 ⁺	19.3 12.0
	173204	259.6	254.3	215.0	24.3	34.4		173203	254.8	248.0	226.8	21.5	32.2 12.0
	173206	256.2	254.3	208.2	21.8	31.3	LN ₂	173205	258.7	246.1	230.9	19.0	32.2 12.0
	173208	258.0	254.3	212.9	22.4	31.3		173207	259.6	259.6	224.5	14.1	19.3 12.0
	X	259.4	256.6	209.6	21.0	28.3		X	258.4	253.6	226.8	18.1	25.8
LN ₂ 3	273302	269.2						273301	340.2				12.0
	273304	273.4						273303	(275.1)				12.0
	273306	(246.2)					LN ₂ (3)	273305	342.1				12.0
	273308	266.9						273307	344.2				12.0
	X	269.8						X	342.2				

COLD REDUCED ROD - STATIC TESTS													
CONTROL SPECIMENS ⁽²⁾							IRRADIATED SPECIMENS ⁽²⁾						
Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA %	Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA % Fluence 10 ¹⁷ nvt >1 mev
LN ₂	-739A52	334.4	318.5	(4)	5.9	25.8		-739A51	337.6	310.8	328.8	5.3	25.8 7.8
	-739A54	324.6	308.4	324.7	6.1	29.0		-739A53	332.5	309.4	331.2	5.5	25.8 7.8
	-739A56	336.4	324.2	336.4	6.1	27.2	LN ₂	-739A55	333.3	311.7	333.3	5.5	25.0 7.8
	-739A58	343.1	332.8	337.5	4.7	21.9		-739A57	336.4	311.7	336.4	5.6	21.8 7.8
	X	334.6	321.0	332.9	5.2	26.0		X	335.0	310.9	332.2	5.5	24.6

NOTES:

- (1) Unnotched and notched specimen part numbers were 1117845 and 1116230 respectively.
- (2) Specimen part number was 1118388.
- (3) Notched specimens.
- (4) No data are available.
- () Indicates data were not used in computing means and standard deviations.
- + Value derived from chart data.

TABLE A-11
TEST RESULTS INDIVIDUAL SPECIMENS, INCONEL 718

FORGING - CTT TESTS													
CONTROL SPECIMENS ⁽¹⁾							IRRADIATED SPECIMENS ⁽¹⁾						
Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA %	Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA % Fluence 10 ¹⁷ nvt > 1 mev
LN ₂	150710	269.0	262.0	216.0	25.3	35.5	LN ₂	150709	253.8	252.3	223.0	18.5	25.8 3.4
	150714	260.0	259.2	222.0	19.6	25.8		150715	264.3	264.3	228.0	20.4	38.7 3.5
	150712	(241.0)	(241.0)	219.6	(14.4)	(9.8)		150713	264.3	264.3	228.0	19.9	42.0 3.5
	150721	262.5	258.6	214.0	20.2	25.8		150711	249.0	245.2	221.0	21.5	38.7 3.5
	X	263.8	259.9	217.9	21.7	29.0		X	257.8	256.5	225.0	20.1	36.3
LN ₂	150708	(4)	(4)	218.5	19.0	25.8	LN ₂	150701	(4)	(4)	236.5	(7.9)	(9.7) 3.2
	150706	365.1	265.1	(203.0)	20.6	35.5		150703	265.0	262.0	235.0	19.6	22.6 3.2
	150704	264.3	264.3	218.0	13.9	22.6		150705	271.7	(241.9)	230.0	17.8	22.6 3.2
	150702	267.4	267.4	223.0	19.9	35.5		150707	272.5	272.5	236.0	17.3	25.8 3.2
	X	265.5	265.6	219.7	18.4	29.9		X	269.7	267.2	234.4	18.2	23.6

RING FORGING - STATIC TESTS													
CONTROL SPECIMENS ⁽²⁾							IRRADIATED SPECIMENS ⁽²⁾						
Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA %	Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA % Fluence 10 ¹⁷ nvt > 1 mev
LN ₂	152402	251.3	251.3	207.0	18.5	25.0	LN ₂	152401	251.6	251.6	226.1	15.1	19.4 9.0
	152404	251.6	250.0	200.6	19.9	28.1		152403	251.6	251.6	226.1	13.4	16.1 9.0
	152406	(251.0)	(241.1)	197.4	(9.9)	(15.6)		152405	256.1	256.1	229.3	17.2	29.0 9.0
	152408	253.3	250.8	192.7	13.3	6.3		152407	250.1	250.1	221.3	12.4	19.4 9.0
	X	252.1	250.7	199.4	17.2	26.1		X	252.4	252.4	225.7	14.5	21.0
LN ₂ (5) ²	452502	(4)					LN ₂ (5) ²	452501	244.3				5.7
	452504	(4)						452503	244.1				5.7
	452506	225.8						452505	243.0				5.7
	452508	221.6						452507	239.5				5.7
	X	223.7						X	242.7				

EB WELDMENT - STATIC TESTS													
CONTROL SPECIMENS ⁽²⁾							IRRADIATED SPECIMENS ⁽²⁾						
Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA %	Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA % Fluence 10 ¹⁷ nvt > 1 mev
LN ₂	1534A02W	241.4	240.4	200.6	17.0	28.1	LN ₂	1534A01W	240.6	238.7	222.9	(8.1)	(19.4) 9.0
	1534A04W	241.9	235.6	199.4	18.2	25.5		1534A03W	248.3	248.3	222.9	14.6	29.0 9.0
	1534A06W	241.4	238.3	199.0	16.9	28.1		1534A05W	244.8	244.8	221.3	13.4	22.6 9.0
	1534A08W	242.6	241.7	200.3	16.5	28.1		1534A07W	248.9	244.4	225.1	17.0	29.0 9.0
	X	241.8	239.0	199.8	17.2	30.0		X	245.6	244.0	223.0	15.0	26.9

TIG WELDMENT - STATIC TESTS													
CONTROL SPECIMENS ⁽²⁾							IRRADIATED SPECIMENS ⁽²⁾						
Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA %	Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA % Fluence 10 ¹⁷ nvt > 1 mev
LN ₂	152602W	(206.8)	(206.8)	203.1	(1.8)	(9.3)	LN ₂	152601W	238.8	238.8	219.4	(4.7)	15.6 9.0
	152604W	(217.3)	(217.3)	200.1	(3.2)	(9.3)		152603W	246.1	246.1	219.4	12.3	21.8 9.0
	152614W	242.2	242.2	198.7	14.5	15.6		152605W	244.4	244.4	221.2	8.5	15.6 9.0
	152608W	243.8	243.8	203.1	14.9	12.5		152607W	(224.5)	(224.5)	(224.5)	(12.0)	(12.5) 9.0
	X	243.0	243.0	201.3	14.7	14.0		X	243.1	243.1	220.0	10.4	17.7
LN ₂ (5) ²	452702W	184.5					LN ₂ (5) ²	452701W	185.2				5.7
	452704W	212.5						452703W	184.6				5.7
	452706W	201.6						452705W	173.3				5.7
	452708W	172.0						452707W	180.0				5.7
	X	192.8						X	181.0				
LN ₂ (5) ²	253502W	274.9					LN ₂ (5) ²	253501W	(215.4)				9.0
	253504W	261.5						253503W	290.9				9.0
	253506W	243.0						253505W	277.6				9.0
	253508W	261.2						253507W	262.4				9.0
	X	260.2						X	272.0				

TABLE A-11 (cont.)

ALL WELD - STATIC TESTS													
CONTROL SPECIMENS ⁽²⁾							IRRADIATED SPECIMENS ⁽²⁾						
Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA %	Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA % Fluence 10 ¹⁷ nvt 1 mev
LN ₂	153414W	(216.5)	(216.5)	(194.5)	(6.8)	(9.7)		153401W	(238.2)	(238.2)	(216.7)	(6.6)	(15.6) 9.0
	153408W	(225.7)	(225.7)	(203.8)	(4.5)	(9.4)		153403W	245.5	245.5	222.3	8.3	9.4 9.0
	153406W	233.9	233.9	205.4	10.7	15.6	LN ₂	153405W	252.4	252.4	223.0	11.2	15.6 9.0
	153404W	245.9	245.9	205.0	10.1	(34.4)		153407W	(238.9)	(238.9)	(217.0)	(5.8)	(31.2) 9.0
	Y	239.9	239.9	205.2	10.4	15.6		X	249.0	249.0	222.6	9.8	12.5

COLD REDUCED ROD - STATIC TESTS													
CONTROL SPECIMENS ⁽³⁾							IRRADIATED SPECIMENS ⁽³⁾						
Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA %	Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA % Fluence 10 ¹⁷ nvt > 1 mev
LN ₂	-53902	288.0	263.9	277.8	12.4	34.5		-53901	293.8	265.4	288.6	10.0 ⁺	31.2 7.8
	-53904	289.2	264.3	277.7	13.3	35.6		-53903	300.0	276.9	289.7	9.8 ⁺	28.1 7.8
	-53906	291.8	265.0	277.0	11.7	37.5	LN ₂	-53905	298.4	269.7	290.2	9.2 ⁺	31.2 7.8
	-53908	286.7	261.4	277.3	11.6	35.6		-53907	293.4	265.6	289.0	8.7 ⁺	34.4 7.8
	X	288.9	263.6	277.0	12.2	35.8		X	296.4	269.4	289.4	9.4 ⁺	31.2

NOTES:

- (1) LN₂ and LH₂ irradiated specimen part numbers were 088776 and 1117845 respectively except specimen numbers 150716, 150719 and 150715 whose part number was 1117845.
- (2) Unnotched and notched specimen part numbers were 1117845 and 1116286 respectively.
- (3) Specimen part numbers was 1118388.
- (4) No data are available.
- (5) Notched specimens.
- + Derived value from chart data.
- () Indicates data were not used in computing means and standard deviation.

TABLE A-12
TEST RESULTS INDIVIDUAL SPECIMENS, H-MONEL

CAST PLATE - CTT TESTS															
CONTROL SPECIMENS ⁽¹⁾							IRRADIATED SPECIMENS ⁽¹⁾								
Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA %	Test Cond.	Specimen Number	TUS ksi	FTS ksi	TYS ksi	Elong. %	RA %	Fluence 10 ¹⁷ nvt 1 mev	
LH ₂	425	97.7	97.7	56.1	31.5	32.7		426	112.0	112.0	95.0	10.7	25.5	2.2	
	427	105.3	105.3	60.6	19.5	26.8		428	123.3	123.3	106.0	8.6	27.7	2.2	
	429	104.3	104.3	58.4	22.5	24.5	LH ₂	430	117.1	117.1	97.5	15.1	16.7	2.2	
	431	107.1	107.1	60.6	19.5	28.3		432	113.9	113.9	94.8	12.6	20.8	2.2	
	X	103.6	103.6	58.9	23.2	28.1		X	116.6	116.6	98.3	11.8	22.7		
	437	93.4						438	118.1					2.2	
	439	101.1						440	114.9					2.2	
	441	99.6					LH ₂	442	132.5					2.2	
(S) ⁽²⁾	443	109.2					(S) ⁽²⁾	444	124.3					2.2	
	X	100.8						X	122.4						

NOTES:

- (1) Unnotched and notched specimen numbers were 088776 and 088773 respectively.
- (2) Control data are from RNS 0128.
- (3) Notched specimens.

REVISIONS				
SYM	ZONE	DESCRIPTION	DATE	APPROVE

-
- IDENTIFICATION**
NT ENGINEER.
- R AGC-STD 30/10**
- CALLY INSPECT**
NCE PER AGC-46303A CL.I.
TO BE .125/ UNLESS
- R ASD 52/5 F.**
ENDS.
- STRAIGHT LINE**
OF THE
ND S.
- .260**
.250
- 45° x .078**
4 PLACES
- .120**
.130 e
4 PLACES
- .21 R**
2 PLACES
- .250**
.245 DIA
- .0902 DIA. THRU - 2 HOLES**
.0947
C'SINK 120° X .15 DIA
4-40 (112) NC-2B THD. THRU
- .562**
1.125 2 PLACES
- .469 2 PLACES**
- .380 2 PLACES**
.370
- 3.90**
2.400
.450
1.50
.750
- 90° BASIC**
- 16**
- A.002 / 8**
-B-
B.002
A.002 / 8
7
-A-
7

Figure A-1 - Specimen, Tensile Modified R-3

90

QTY REQD														SYM														CODE IDENT														PART OR IDENTIFYING NO.														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Figure A-2 - Specimen, Tensile, Notched $K_T = 6.3$

1. REMOVE ALL BURRS AND SHARP EDGES EQUIV TO .005/.015 R UNLESS OTHERWISE NOTED.
2. INTERPRET DRAWING PER STANDARDS PRESCRIBED IN MIL-D-70327.
3. SURFACE ROUGHNESS UNLESS OTHERWISE NOTED 125.

5. PENETRANT INSPECT PER AGC-STD-3010, METHOD B.

5. PENETRANT INSPECT PER AGC-STD-3010, METHOD B.
6. CAST MATERIAL - RADIOGRAPHICALLY INSPECT PER AGC-STD-1151. ACCEPTANCE PER AGC-46303 CLASS I.

$\triangle$ SAFE CENTERS REQUIRED, BOTH ENDS.

8. "AD" PER ASD 52 5 H WITH III7677&APPLICABLE DASH NO

DATA IS ESTABLISHED AS A STRAIGHT LINE
PASSING THRU THE CENTER OF THE SAFE CENTERS
ON BOTH ENDS.

- 10 CLEANLINESS, LEVEL 1 (VISUALLY CLEAN)
PER AGC-STD-9007.

DASH NO.	A DIM	B DIM BASIC
-1	8.895	6.125
-3	10.020	7.250
-5	11.145	8.375
-7	12.020	9.250
-9	12.895	10.125
-11	13.645	10.875
-13	13.770	11.000
-15	14.520	11.750
-17	14.520	11.750
-19	15.270	12.500
-21	15.395	12.625
-23	16.145	13.375
-25	16.870	14.100

REON		PART ACT CALC OM THRU IN WEIGHT EFFECTIVE SERIAL NO USAGE DATA		PART NEXT SERIAL DASH NO QTY ENG PM ASST		NEXT ASST DRAWING LEVEL		USED ON APPLICATION		PART DASH NO QTY ENG PM ASST		NEXT ASST DRAWING LEVEL		USED ON APPLICATION	
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CITY ENG ETR CODE IDENT PART OR IDENTIFYING NO		11THRU 25 NO INCLINATURE OR DESCRIPTION MATERIAL SPECIFICATION UNIT WT EONG ITS NO	
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LIST OF MATERIALS CONTRACT NO DRAWN BY DATE CHECKED BY DATE ISSUED BY DATE MATERIALS USED ENG NO PROJECT ASSURANCE TECH. ACTIVITY APP.		AEROJET-GENERAL CORPORATION SACRAMENTO CALIFORNIA ROCKET ENGINE OPERATIONS NUCLEAR TITLE SPECIMEN, UNSTITCHED TENSILE: FOR SHEET & PLATE DWG NO CODE IDENT NO DWG NO 05824 1117677 SCALE RELEASE DATE	
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Figure A-3 - Specimen, Unnotched Tensile - for Sheet and Plate

Figure A-4 - Tensile Specimen Modified, Notched $K_T = 17$

THIS DOCUMENT AND THE INFORMATION CONTAINED HEREIN IS NOT TO BE REPRODUCED, USED OR DISCLOSED TO ANYONE WITH OUT THE PERMISSION OF AERJET GENERAL CORPORATION EXCEPT THAT THE GOVERNMENT HAS THE RIGHT TO REPRODUCE USE AND DISCLOSE FOR GOVERNMENTAL PURPOSES INCLUDING THE RIGHT TO GIVE TO FOREIGN GOVERNMENTS FOR USE AS THE NATIONAL INTERESTS OF THE UNITED STATES MAY DEMAND ALL OR ANY PART OF THIS DOCUMENT AS TO WHICH AERJET GENERAL CORPORATION IS ENTITLED TO GRANT THIS RIGHT

NOTES:

1. REMOVE ALL BURRS AND SHARP EDGES EQUIV TO .005/.015 R UNLESS OTHERWISE NOTED.
2. INTERPRET DRAWING PER STANDARDS PRESCRIBED IN MIL-D-70327.
3. SURFACE ROUGHNESS UNLESS OTHERWISE NOTED 125/
4. MATERIAL TREATMENT, FINISH AND IDENTIFICATION TO BE DETERMINED BY COGNIZANT ENGINEER.
5. PENETRANT INSPECT PER AGC-STD-3010, METHOD B.
6. CAST MATERIAL - RADIOGRAPHICALLY INSPECT PER AGC-STD-1151. ACCEPTANCE PER AGC-46303, CL.1.
7. SAFE CENTERS PERMISSABLE, BOTH ENDS.
8. MARK PER ASD 5215 H WITH 1117845 AND APPLICABLE DASH NUMBER.
9. .197/.203 DIA SHALL BE SMALLER AT THE CENTER THAN AT THE ENDS. THE DIFFERENCE SHALL NOT EXCEED 1% OF NOMINAL DIA.
10. CLEANLINESS LEVEL 1 (VISUALLY CLEAN) PER AGC-STD-9007.

REVISIONS		DATE	APPROVED
ZONE	LTG		

QTY	RECD	STA	CODE	IDENT	PART OR IDENTIFYING NO	NOMINATURE OR DESCRIPTION	MATERIAL	SPECIFICATION	UNIT WT	ZONE	ITEM NO

LIST OF MATERIALS											
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES DECIMAL TOL .005 & UP FRACTIONAL TOL 1/16 & UP DO NOT SCALE DRAWING											
TREATMENT											
FINISH											
SIMILAR TO 116229											

REON		ACT		CALC		ON		THRU		PART		NEXT		FINAL		NEXT ASSY		USED ON	
PART NO	QTY	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO

CONTRACT NO		DRAWN		CHECKED		DESIGN		STRESS		MATERIAL PROCESS		PARTIALS ENDS		DESIGNER'S SIGNATURE		DESIGNER'S DATE	
AERJET-GENERAL CORPORATION		ROMANI		7-18-66		7-18-66		7-18-66		7-18-66		7-18-66		7-18-66		7-18-66	

TITLE		CODE IDENT NO		DWG NO	
SPECIMEN, TENSILE MODIFIED R-3-200		D 05824		1117845	

SCALE	RELEASE DATE	DATE
2		

Figure A-5 - Specimen, Tensile Modified R-3-200

Figure A-6 - Specimen, Tensile Modified R-3-250

DASH NO.	A DIM	B DIM
-1	8.75	5.990
-3	9.25	6.490
-5	9.75	6.990
-7	10.25	7.490
-9	10.75	7.990
-11	11.25	8.490
-13	11.75	8.990
-15	12.25	9.490
-17	12.75	9.990
-19	13.25	10.490
-21	13.75	10.990
-23	14.25	11.490
-25	14.75	11.990
-27	15.25	12.490
-29	15.75	12.990
-31	16.25	13.490

[illegible]

Figure A-8 - Notch Tensile Specimen for Sheet and Plate ($K_T = 6.3$)

- NOTES:
1. REMOVE ALL BURRS AND SHARP EDGES EQUIVALENT TO .005/.015 R UNLESS OTHERWISE NOTED.
 2. INTERPRET DRAWING PER STANDARDS PRESCRIBED IN MIL-D-70327.
 3. SURFACE ROUGHNESS 125 UNLESS OTHERWISE NOTED.
 4. 170/180 RADI TO BLEND WITH A DIA , NO UNDERCUT PERMISSIBLE.
 5. DIAMETER OF THE REDUCED SECTION SHALL BE TAPERED SMALLER TOWARD THE CENTER THAN AT THE ENDS. THE DIFFERENCE SHALL NOT EXCEED 1% OF NOMINAL DIAMETER AT CENTER
 6. PENETRANT INSPECT PER AGC-STD-3010, METHOD B, AFTER FINAL MACHINING.
 7. MATERIAL TO BE DETERMINED BY COGNIZANT ENGINEER.
 8. MARK PER ASD 5215 C WITH APPLICABLE SERIAL NO. PRIOR TO MACHINING.
 9. CLEAN PARTS WITH METHY. ETHYL KETONE OR EQUIVALENT PER AGC-10824 PRIOR TO MACHINING.
 10. PRESERVE AND PACKAGE PER AGC-46387, CLASS I.
 11. SAFE CENTERS PERMISSIBLE TO 4 ENDS.
 12. RADIOGRAPHICALLY INSPECT PER AGC-STD-1151.

DASH NO	A DIA
-1	252 ± .005
-2	.2007 ± .004

-3		A																																															
-1																																																	
QTY REQD	STR	CODE	DATE OF FABRICATION	NOMENCLATURE OR DESCRIPTION		MATERIAL		SPECIFICATION		UNIT WT	ZONE																																						
LIST OF WATER ALLS																																																	
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES DECIMAL FRACTIONS DIMENSIONS IN PARENTHESES ARE IN MILLIMETERS DO NOT SCALE DRAWING TREATMENT																																																	
<table border="1"> <tr> <td colspan="2">CONTRACT NO.</td> <td colspan="2">DRAWN BY</td> <td>DATE</td> <td colspan="2"> AEROJET GENERAL CORPORATION SACRAMENTO, CALIFORNIA ROCKET ENGINE DIVISION, NUCLEAR </td> </tr> <tr> <td colspan="2">CHECKED</td> <td colspan="2">DESIGN</td> <td></td> <td colspan="2">TITLE</td> </tr> <tr> <td colspan="2">STRESS</td> <td colspan="2">MATERIALS/PROCESS</td> <td></td> <td colspan="2">TECHNICAL SPECIFICATION</td> </tr> <tr> <td colspan="2">PHENOMENON</td> <td colspan="2">PROPOSED BY</td> <td></td> <td colspan="2">STANDARD ROUND</td> </tr> <tr> <td colspan="2">SIMILAR TO</td> <td colspan="2">APPROVED BY</td> <td></td> <td colspan="2"> DWG NO. CODE Dwg NO. 1118389 D 05824 SCALE 1/2" = 1'-0" RELEASED BY C-21-60 UNIT </td> </tr> </table>															CONTRACT NO.		DRAWN BY		DATE	AEROJET GENERAL CORPORATION SACRAMENTO, CALIFORNIA ROCKET ENGINE DIVISION, NUCLEAR		CHECKED		DESIGN			TITLE		STRESS		MATERIALS/PROCESS			TECHNICAL SPECIFICATION		PHENOMENON		PROPOSED BY			STANDARD ROUND		SIMILAR TO		APPROVED BY			DWG NO. CODE Dwg NO. 1118389 D 05824 SCALE 1/2" = 1'-0" RELEASED BY C-21-60 UNIT	
CONTRACT NO.		DRAWN BY		DATE	AEROJET GENERAL CORPORATION SACRAMENTO, CALIFORNIA ROCKET ENGINE DIVISION, NUCLEAR																																												
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STRESS		MATERIALS/PROCESS			TECHNICAL SPECIFICATION																																												
PHENOMENON		PROPOSED BY			STANDARD ROUND																																												
SIMILAR TO		APPROVED BY			DWG NO. CODE Dwg NO. 1118389 D 05824 SCALE 1/2" = 1'-0" RELEASED BY C-21-60 UNIT																																												

Figure A-9 - Tensile Specimen, Standard Round

1. REMOVE ALL BURRS AND SHARP EDGES EQUIV.
TO .005" C/SR UNLESS OTHERWISE NOTED.
2. INTERPRET DIMS PER STANDARDS PRESCRIBED
IN MIL-D-70327.
3. CLASSIFICATION OF CHARACTERISTICS PER
MIL-H-4411 DEMONSTRATED BY (C) CRITICAL, (U)
UNUSUAL, AND (S) SYMBOL UNUSUAL.
4. UNUSUAL S. REACTS TO BE 125 UNLESS
OTHERWISE NOTED.
5. SPACED-OUT DIMS INCLUDES CUTS OR ANY
OTHER FEA. ARE NOT PERMITTED ON ANY
SURFACE WITHIN THE S. AREA.
6. RADIOUS USE BLEND SMOOTHLY WITH NO
STEPS OR UNUSUALS PERMITTED.
7. A COMPLETE TEST SPECIFICATION CONSISTS
OF: (1) NAME OF THE PART WHICH HAS BEEN
DESIGNED TO THE F.P. CONFIGURATION
PRESCRIBED BY THE P. NUMBER. QUANTITY
OF ELEMENTS TO BE SPECIFIED. (2) PLANE
WALL ARE TO BE DETERMINED BY THE COM-
MUNAL ASS. ENGINEER.
8. DATUM IS DEFINED AS A PLANE PAS-
SING THROUGH THE CENTERS OF FEATURES
AND .
9. ANY MEASUREMENT MADE BETWEEN PLACES
AND MUST BE EQUAL TO OR GREATER
THAN THE ACTUAL MEASUREMENTS (THE WIDTH,
THE THICKNESS, THE DISTANCE BETWEEN PLACES
OR THE DISTANCE BETWEEN THE DIMENSIONS SPECIFIED).
10. DATUM IS DEFINED AS A PLANE PAS-
SING THROUGH THE EXACT CENTER OF THE SPECIMEN

PARTIAL SE		DIMENSION	
		A	B
111CP24-1		9.75	6.950
3		10.25	7.450
5		10.75	7.950
7		11.25	8.450
		11.75	8.950
-11		12.25	9.450
13		12.75	9.950
15		13.25	10.450
7		13.75	10.950
-9		14.25	11.450
1		14.75	11.950
3		15.25	12.450
5		15.75	12.950
-7		16.25	13.450
-9		16.75	13.950
1		17.25	14.450
-3		17.75	14.950
5		18.25	15.450
-37		18.75	15.950

[illegible]

Figure A-10 - Tensile Test Specimen - Unnotched

AEROJET-GENERAL CORPORATION