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FINAL REPORT

GTR-21

TEST 37R017

HIGH-TEMPERATURE RADIATION EFFECTS
ON RENE 41, WASPALOY, AND INCONEL 718

NERVA Program, Contract SNP-1

May 1970

MASTER

AEROJET NUCLEAR SYSTEMS COMPANY

A DIVISION OF AEROJET-GENERAL

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W. E. French

D. Brown

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I. INTRODUCTION

Most high temperature alloys are subject to severe embrittlement when irradiated at high temperatures or when tested at high temperatures subsequent to irradiation at lower temperatures. A survey of such tests is contained in Reference (1). Previous NERVA tests included three solution-hardening alloys (Hastelloy X, Inconel 625 and Stainless Steel AISI 347) to determine if they are suitable for nozzle and high-temperature propellant line applications. These results are described in Reference (2). The alloys were significantly damaged by thermal neutron fluences between 6×10^{17} and 1×10^{19} n/cm² and test temperatures as high as 2000°R, but in all cases ductility was adequate for the intended applications.

The objective of the current investigation (ANSC Test 37R017, GTR-21) was to determine the degree of radiation-induced ductility loss of three precipitation hardening alloys (Rene 41, Waspaloy and Inconel 718), which were being evaluated for 1560-1880°R NERVA turbine and propellant line applications.*

In addition to comparing the three alloys limited data was obtained that may enable correlation of boron content in Inconel 718 with damage, since other studies have provided similar correlations for austenitic steels (Reference (3)).

* The GTR-21 was conducted at the General Dynamics 10-megawatt Ground Test Reactor at Fort Worth, Texas. The test consisted of: (1) an evaluation of a polarographic hydrogen gas detector; (2) nuclear-radiation-induced conversions of parahydrogen to orthohydrogen; (3) thermal conductivity and electrical resistivity of selected NERVA materials; and (4) effect of radiation on structural materials tested at cryogenic and elevated temperatures. The experimental work was completed in June 1968.

Test procedures and data are described in reports from General Dynamics, Fort Worth Division (References 4, 5, 6, and 7).

High-temperature radiation embrittlement is also manifested by a reduction in stress-rupture life and stress-rupture elongation. Two of the alloys (Waspaloy and Inconel 718) were tested for stress-rupture properties at relatively high stresses at temperatures of 1660° and higher.

Most previous tests of these effects have been made for neutron fluences of 10^{20} n/cm² or higher. A limited number of tests have shown that the damage threshold may be as low as 10^{15} n/cm² < 0.48 eV* [Reference (8)].

Since the expected neutron fluence in some NERVA components is as low as 10^{15} n/cm², these tests included fluences between about 5×10^{15} and 5×10^{18} n/cm² in an attempt to establish damage thresholds.

II SUMMARY

In Rene 41, Waspaloy and Inconel 718 forgings, the tensile property most sensitive to radiation was elongation, which exhibited moderate to large decreases for nearly all test conditions a summary of elongation vs thermal neutron fluence for various test conditions for materials is shown in Table 1. The damage threshold for elongation decrease at 1660°R and above is below 10^{16} n/cm² < 0.48 eV for all materials. The 0.2% offset yield strengths did not show a significant change. Irradiation did not affect the stress-strain curves except to interrupt them at a lower strain due to fracturing, thus lowering the elongation. For those test conditions in which the work hardening was not complete, premature fracture reduced the ultimate strength.

Reduction of area and engineering fracture stress were usually changed due to premature fracture. Elongation damage appears to react its maximum at the higher fluences.

* Throughout this report the convention < 0.48 eV is employed to mean $E < 0.48$ eV.

1
TABLE 1

SUMMARY OF
ELONGATION VS THERMAL NEUTRON FLUENCE
FOR VARIOUS TEST CONDITIONS

<u>NEUTRON FLUENCE</u> <u>n/cm² <0.48eV</u>	<u>TEST</u> <u>TEMP</u> <u>°R</u>	<u>MEAN</u> <u>VALUE</u> <u>%</u>	<u>STANDARD</u> <u>DEVIATION</u>	<u>SAMPLE</u> <u>SIZE</u>
<u>Rene 41 Turbine Forging</u> Strain Rate 0.0013 in./in./min.				
None	1660	10.15	0.62	3
8.8 x 10 ¹⁵	1660	5.84	0.58	3
2.0 x 10 ¹⁷	1660	4.16	0.25	3
4.4 x 10 ¹⁸	1660	3.56	0.28	3
<u>Rene 41</u> Strain Rate 0.013 in./in./in./min.				
4.3 x 10 ¹⁸	1660	3.64	----	1
<u>Rene 41</u> Strain Rate 0.13 in./in./min.				
4.0 x 10 ¹⁸	1660	11.41	0.30	2
<u>Rene 41</u> Strain Rate 0.0013 in./in./min.				
None	1880	5.05	1.80	3
9.1 x 10 ¹⁵	1880	1.65	1.21	3
1.2 x 10 ¹⁷	1880	1.01	0.54	3
<u>Inconel 718 BAR (0.4ppmB)</u> Strain Rate 0.0013 in./in./min.				
None	1660	3.51	----	1
<u>Inconel 718 BAR (0.4ppmB)</u> Strain Rate 0.0020 in./in./min.				
None	1660	9.30	1.20	3
<u>Inconel 718 BAR (0.4ppmB)</u> Strain Rate 0.0013 in./in./min.				
1.9 x 10 ¹⁷	1660	2.58	0.55	3
3.7 x 10 ¹⁸	1660	0.32	0.22	3

TABLE 1 (Cont.)

<u>NEUTRON FLUENCE</u> <u>n/cm² <0.48eV</u>	<u>TEST</u> <u>TEMP</u> <u>°R</u>	<u>MEAN</u> <u>VALUE</u> <u>%</u>	<u>STANDARD</u> <u>DEVIATION</u>	<u>SAMPLE</u> <u>SIZE</u>
<u>Inconel 718 Rotor Turbine (37ppmB) Strain Rate 0.0013 in./in./min.</u>				
None	1360	16.89	1.55	2
None	1510	11.23	0.54	3
6.4 x 10 ¹⁵	1510	8.76	1.26	3
1.3 x 10 ¹⁷	1510	7.75	0.73	3
2.3 x 10 ¹⁸	1510	6.88	0.55	3
None	1585	6.09	1.31	2
1.5 x 10 ¹⁷	1585	4.18	0.58	3
None	1660	4.59	0.87	3
8.0 x 10 ¹⁵	1660	3.01	0.34	3
1.8 x 10 ¹⁷	1660	1.99	0.13	3
2.5 x 10 ¹⁸	1660	1.28	0.21	3
<u>Inconel 718 Rotor Turbine (37ppmB) Strain Rate 0.1300 in./in./min.</u>				
None	1660	12.56	0.76	3
2.2 x 10 ¹⁷	1660	8.19	0.26	3
<u>Inconel 718 Ring (46ppmB) Strain Rate 0.0020 in./in./min.</u>				
None	1660	9.00	1.40	2
<u>Inconel 718 Ring (46ppmB) Strain Rate 0.0013 in./in./min.</u>				
2.3 x 10 ¹⁷	1660	5.17	1.31	3
4.2 x 10 ¹⁸	1660	3.68	0.18	2
<u>Waspaloy Forging Strain Rate 0.0013 in./in./min.</u>				
None	1560	28.66	2.97	3
2.5 x 10 ¹⁷	1560	22.96	2.63	3

TABLE 1 (Cont.)

NEUTRON FLUENCE <u>n/cm² <0.48eV</u>	TEST TEMP <u>°R</u>	MEAN VALUE <u>%</u>	STANDARD DEVIATION	SAMPLE SIZE
<u>Waspaloy</u> Strain Rate 0.0013 in./in./min.				
None	1660	24.60	2.66	3
8.6 x 10 ¹⁵	1660	18.16	2.26	3
2.7 x 10 ¹⁷	1660	16.64	1.53	2
3.4 x 10 ¹⁸	1660	13.70	0.12	3
<u>Waspaloy</u> Strain Rate 0.1300 in./in./min.				
None	1660	21.79	0.34	3
3.7 x 10 ¹⁷	1660	19.24	5.38	3
<u>Waspaloy</u> Strain Rate 0.0013 in./in./min.				
None	1860	20.40	2.29	3
7.8 x 10 ¹⁵	1860	8.86	2.30	3
2.7 x 10 ¹⁷	1860	7.05	0.34	3
5.8 x 10 ¹⁸	1860	3.78	0.95	3

The two alloys tested in stress rupture showed significant reductions in time-to-failure, elongation and reduction of area. Inconel 718 showed severe notch sensitivity in stress rupture. At 1760°R all irradiated notched specimens failed in the notched area; mean time to failure after 1.59×10^{16} n/cm² < 0.48 eV exposure was 1.4 hours.

Detailed test data are presented in the Appendix, and tables from this part are referenced with the letter a preceding the number (A-1, A-2, etc.).

III. CONCLUSIONS AND RECOMMENDATIONS

These precipitation-hardening alloys are subject to severe high-temperature radiation embrittlement at and below fluences as low as 10^{16} n/cm² < 0.48 eV. Ductility losses are more severe at the higher temperatures (between 1600 and 1900°R). If these alloys are used in a high-temperature nuclear environment, design criteria and design allowables must be based on irradiated properties. Inconel 718 and Rene 41 should be classified as "brittle" at and above 1600°F. If these materials are used in this environment, design allowables should be based on postirradiation fracture properties. Waspaloy has adequate elongation at 1660°R to be classified as "ductile"; however, at fluences above 10^{16} and temperatures above 1660°R, it must be considered marginal.

The effect of boron content (0.4 and 47 ppm) on damage to Inconel 718 between was obscured by other variables, such as heat treatment or microstructure. Improvement of the radiation resistance of this alloy would require an extensive study of many variables in addition to boron content.

Limited studies of the strain rate dependence of radiation damage in these alloys indicate that properties would be better than shown here for applications involving loading rates of 0.1 in./in./min. or higher.

IV. TEST SPECIMENS AND PROCEDURES

Specimen pedigree data for Rene 41, Waspaloy, and Inconel 718 and the subsequent specimen processing are presented in Table 2. Chemical analyses of the materials are presented in Table 3. Twenty-four specimens of Rene 41 (6 control and 18 irradiated), fifty-four specimens of Waspaloy (17 control and 37 irradiated), and seventy specimens of Inconel 718 (21 control and 49 irradiated) were tested.

Tensile test specimens of Rene 41, Waspaloy, and Inconel 718 were round button-head unnotched configurations shown in Figure 1. Stress-rupture test specimens of Waspaloy and Inconel 718 were round unnotched configurations shown in Figure 1 and round combination notched configuration shown in Figure 2.

The specimens were mounted in a rack and irradiated while immersed in water (approximately 580⁰R), to three levels of neutron fluence. Total reactor operating time during the irradiation (13 October to 3 November 67) was 2310 MWh. Upon completion of the irradiation, the specimens were transferred to the Irradiated Materials Laboratory where tensile and stress-rupture tests were performed at several elevated temperatures.

The tensile testing was performed with two Instron test machines. One was a standard Model TT-C and the other was a Model TT-D split console type. A set of Rene 41 specimen strips and A-286 pull rods were employed during testing.

The stress-rupture specimens were tested on two Model CR-20 Riehle Creep Rupture Testing Machines having a capacity of 20,000 lb. Each machine is a dead-weight type with a single overhead lever having a 20:1 ratio. The specimen is placed under load by adding weights to the beam pan. Each

TABLE 2

SPECIMEN PEDIGREE OF RENE 41, WASPALOY, AND INCONEL 718

Forged or Rolled Stock as Received						Specimen Processing				
Code	Material	Vendor	Form and Dimensions	Heat Treat	Specification	Parent/Welded	Anneal	Age	Specification	Hardness
R	Rene 41	Viking Forge & Steel Co.	Pancake Forging 22" dia. x 2 1/2"	Annealed at 1975°F	AMS 5712	Parent	Stabilized at 1550°F	1400°F- 16 Hrs.	AMS- 5712	39 R _C
W	Waspaloy	Viking Forge & Steel Co.	Pancake Forging 22" dia. x 2 1/2"	Annealed at 1950°F Stabilized at 1550°F Aged at 1400°F	AGC 44006D	Parent	Original by Forger	Original by Forger	AGC- 44006	36 R _C
N	Inconel 718	Wyman-Gordon Co.	Rotor Turbine Forging	Annealed at 1800°F	AGC 44098 Am.#1	Parent	Original by Forger	1325°F/ 1150°F Total Time, 18 Hrs.	AGC- 46626	43 R _C
C		Reisner Metals Inc.	Ring Forging 23" O.D. x 21 1/2" I.D. x 4.7"	Annealed at 1950°F	AGC 44194 and 44098	Parent	Original by Forger	1350°F/ 1200°F Total Time, 20 Hrs.	AGC- 46604	42 R _C
L		ALLVAC Metals Co.	Bar Low Boron 3/4" x 3/4" x 72"	Annealed at 1800°F	AGC 46626 and 90093	Parent	Original by Forger	1325°F/ 1150°F Total Time, 18 Hrs.	AGC- 46626	43 R _C

TABLE 3

CHEMICAL ANALYSIS OF RENE 41, WASPALOY, AND INCONEL 718

Material		Element (% by weight)															
		Ni	Mo	Cr	Fe	C	Cb+Ta	Mn	Si	Al	Ti	Zr	Cu	Co	P	S	B
Inconel 718	Rotor Turbine Heat C-5722	54.3	2.83	18.7	Bal	0.050	5.19	0.04	0.077	0.59	0.98		0.02	0.05	0.005	0.004	0.0037
	Ring Heat 8289	53.3	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
	Bar Heat D-284	52.70	2.98	18.88	Bal	0.043	4.83	0.05	0.09	0.47	0.90		0.02	0.03	0.004	0.007	0.00004
Rene 41	Disc Forging Heat 6472	Bal	9.83	18.80	0.50	0.077		0.02	0.06	1.57	3.17			10.95		0.006	0.0050
Waspaloy	Disc Forging Heat 6462	Bal	4.27	18.82	0.78	0.048		0.02	0.06	1.31	3.04	0.063	0.02	13.6	0.008	0.006	0.0047

Figure 1 - Configuration of Round, Button-Head Tensile Specimens

NOTES:

1. SMOOTH TRANSITION IS REQUIRED BETWEEN ALL INTERSECTING RADII AND SURFACES TANGENT TO RADII.
2. THESE DIMENSIONS TO BE INSPECTED AND RECORDED. INSPECTION RECORDS SHALL BE MARKED WITH PART SERIALIZATION NO.
3. NO DIA IN THIS SECTION MAY BE LESS THAN THAT MEASURED AT THE CENTER OF DIMENSION 1.230.

Figure 2 - Configuration of High-Temperatures Stress-Rupture Combination-Notched Specimens

Riehle was equipped with creep measuring instrumentation which included an LVDT-type extensometer and a recording unit.

A 2000-watt Marshall furnace was employed for the elevated temperature tensile and stress-rupture testing. Calibration of the furnace was accomplished by using a dummy specimen with a chromel-alumel thermocouple resistance welded to the center of the gage-length and chromel-alumel thermocouples embedded in both the upper and lower specimen grips. During the actual tests, the temperature was maintained by monitoring the specimen grip thermocouples. An atmosphere of nitrogen was maintained in the furnace during all heating cycles.

To verify that the pull rods, the specimen grips, and the test specimens were all aligned to provide true axial loading of the test specimens, axiality checks were performed prior to and during the tensile and stress-rupture testing. These checks were made using a clip-on extensometer to measure the strain of a Rene-41 specimen as loads up to 3000 lb were applied. The maximum deviations at four locations (90° apart from the average strain at maximum load (3000 lb) was less than 3% for tensile tests and less than 5% for stress-rupture tests.

V. TEST RESULTS

A. PROPERTY VALUES

Results obtained for each group of specimens are summarized in Tables 4 through 8, each covering a material and test. Mean values and standard deviations are given for ultimate, yield and fracture strength, elongation, reduction of area, and time-to-failure.

Property values determined for individual specimens are given in the Appendix Tables A-1 through A-5. These tables are based on data provided in Reference 7.

TABLE 4

TENSILE PROPERTIES SUMMARY OF TEST RESULTS

RENE 41

ENVIRONMENT		STRAIN RATE	PROPERTY		SAMPLE
Neutron Fluence ⁽¹⁾ n/cm ² E < 0.48 eV	Test Temp ⁽²⁾ °R	In/In/Min	Mean Value	Std. ⁽³⁾ Dev.	SIZE
0.2% OFFSET YIELD STRESS, KSI					
None	1660	0.0013	114.26	2.49	3
8.8 x 10 ¹⁵	1660	0.0013	114.89	2.75	3
2.0 x 10 ¹⁷	1660	0.0013	115.24	2.50	3
4.4 x 10 ¹⁸	1660	0.0013	115.82	0.85	3
4.3 x 10 ¹⁸	1660	0.0130	119.24	---	1
4.0 x 10 ¹⁸	1660	0.1300	117.59	0.87	2
None	1860	0.0013	112.14	0.24	3
9.1 x 10 ¹⁵	1860	0.0013	116.10	2.06	3
1.7 x 10 ¹⁷	1860	0.0013	114.95	1.41	3
ULTIMATE STRENGTH, KSI					
None	1660	0.0013	160.81	3.59	3
8.8 x 10 ¹⁵	1660	0.0013	146.96	9.32	3
2.0 x 10 ¹⁷	1660	0.0013	142.08	4.92	3
4.4 x 10 ¹⁸	1660	0.0013	138.10	4.49	3
4.3 x 10 ¹⁸	1660	0.0130	146.54	---	1
4.0 x 10 ¹⁸	1660	0.1300	159.80	1.13	2
None	1860	0.0013	120.19	0.86	3
9.1 x 10 ¹⁵	1860	0.0013	119.44	3.57	3
1.7 x 10 ¹⁷	1860	0.0013	116.69	1.87	3
FRACTURE STRENGTH, KSI ⁽⁴⁾					
None	1660	0.0013	160.59	3.60	3
8.8 x 10 ¹⁵	1660	0.0013	146.96	9.32	3
2.0 x 10 ¹⁷	1660	0.0013	141.13	5.31	3

TABLE 4 (CONT'D)

TENSILE PROPERTIES SUMMARY OF TEST RESULTS

RENE 41

ENVIRONMENT		STRAIN RATE	PROPERTY		SAMPLE
Neutron Fluence ⁽¹⁾ n/cm ² E < 0.48 eV	Test Temp ⁽²⁾ °R	In/In/Min	Mean Value	Std. (3) Dev.	SIZE
FRACTURE STRENGTH, KSI ⁽⁴⁾ (cont.)					
4.4 x 10 ¹⁸	1660	0.0013	135.88	4.85	3
4.3 x 10 ¹⁸	1660	0.0130	146.39	---	1
4.0 x 10 ¹⁸	1660	0.1300	159.80	1.13	2
None	1860	0.0013	107.19	5.92	3
9.1 x 10 ¹⁵	1860	0.0013	112.44	9.34	3
1.7 x 10 ¹⁷	1860	0.0013	111.19	3.90	3
ELONGATION, % ⁽⁵⁾					
None	1660	0.0013	10.15	0.62	3
8.8 x 10 ¹⁵	1660	0.0013	5.84	0.58	3
2.0 x 10 ¹⁷	1660	0.0013	4.16	0.25	3
4.4 x 10 ¹⁸	1660	0.0013	3.59	0.28	3
4.3 x 10 ¹⁸	1660	0.0130	3.64	---	1
4.0 x 10 ¹⁸	1660	0.1300	11.41	0.30	2
None	1860	0.0013	5.05	1.80	3
9.1 x 10 ¹⁵	1860	0.0013	1.65	1.21	3
1.7 x 10 ¹⁷	1860	0.0013	1.01	0.54	3
REDUCTION IN AREA, %					
None	1660	0.0013	13.82	0.87	3
8.8 x 10 ¹⁵	1660	0.0013	14.62	2.13	3
2.0 x 10 ¹⁷	1660	0.0013	10.07	3.63	3
4.4 x 10 ¹⁸	1660	0.0013	9.82	2.74	3
4.3 x 10 ¹⁸	1660	0.0130	17.88	---	1
4.0 x 10 ¹⁸	1660	0.1300	16.89	1.97	2
None	1860	0.0013	9.51	1.29	3
9.1 x 10 ¹⁵	1860	0.0013	5.61	2.91	3
1.7 x 10 ¹⁷	1860	0.0013	6.41	2.73	3

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TABLE 4

TENSILE PROPERTIES SUMMARY OF TEST RESULTS

RENE 41

- (1) - Neutron fluences listed are nominal. Fluence for individual specimens varied as shown in table A-1
- (2) - Test temperatures are the temperatures of the specimens during tensile testing. The specimens were irradiated in water pool at approximately 580°R.
- (3) - Standard deviations may be influenced by the differences in fluence received by individual specimens.
- (4) - Fracture strength listed is the engineering stress at which the specimen fractured in tension.
- (5) - Elongation was computed from load deflection charts for 1.5 inch gage length.

TABLE 5

TENSILE PROPERTIES SUMMARY OF TEST RESULTS
WASPALLOY

ENVIRONMENT		STRAIN RATE	PROPERTY		SAMPLE
Neutron Fluence ⁽¹⁾ n/cm ² E > 0.48 eV	Test Temp ⁽²⁾ °R	In/In/Min	Mean Value	Std. (3) Dev.	SIZE
0.2 % OFFSET YIELD STRESS, KSI					
None	1560	0.0013	98.28	0.98	3
2.5 x 10 ¹⁷	1560	0.0013	98.52	2.84	3
None	1660	0.0013	98.97	0.68	3
8.6 x 10 ¹⁵	1660	0.0013	99.27	1.54	3
2.7 x 10 ¹⁷	1660	0.0013	98.85	1.59	2
3.4 x 10 ¹⁸	1660	0.0013	96.34	2.68	3
None	1660	0.1300	98.74	0.59	3
3.7 x 10 ¹⁷	1660	0.1300	90.25	9.45	3
None	1860	0.0013	82.65	2.42	3
7.8 x 10 ¹⁵	1860	0.0013	85.46	5.61	3
2.7 x 10 ¹⁷	1860	0.0013	83.96	2.05	3
5.8 x 10 ¹⁸	1860	0.0013	86.65	2.04	3
ULTIMATE STRENGTH, KSI					
None	1560	0.0013	160.92	2.93	3
2.5 x 10 ¹⁷	1560	0.0013	159.41	3.12	3
None	1660	0.0013	137.92	1.99	3
8.6 x 10 ¹⁵	1660	0.0013	139.27	1.23	3
2.7 x 10 ¹⁷	1660	0.0013	135.36	4.04	2
3.4 x 10 ¹⁸	1660	0.0013	136.98	0.09	3
None	1660	0.1300	163.49	1.85	3
3.7 x 10 ¹⁷	1660	0.1300	161.34	0.76	3
None	1860	0.0013	85.48	2.41	3
7.8 x 10 ¹⁵	1860	0.0013	87.22	3.53	3
2.7 x 10 ¹⁷	1860	0.0013	85.90	1.00	3
5.8 x 10 ¹⁸	1860	0.0013	86.82	1.86	3

TABLE 5 (CONT'D)

TENSILE PROPERTIES SUMMARY OF TEST RESULTS

WASPALLOY

ENVIRONMENT		STRAIN RATE	PROPERTY		SAMPLE
Neutron Fluence ⁽¹⁾ n/cm ² E < 0.48 eV	Test Temp ⁽²⁾ °R	In/In/Min	Mean Value	Std. ⁽³⁾ Dev.	SIZE
FRACTURE STRENGTH, KSI ⁽⁴⁾					
None	1560	0.0013	144.14	8.13	3
2.5 x 10 ¹⁷	1560	0.0013	151.92	8.24	3
None	1660	0.0013	114.56	8.20	3
8.6 x 10 ¹⁵	1660	0.0013	129.11	3.64	3
2.7 x 10 ¹⁷	1660	0.0013	126.90	2.86	2
3.4 x 10 ¹⁸	1660	0.0013	132.56	0.99	3
None	1660	0.1300	158.85	3.23	3
3.7 x 10 ¹⁷	1660	0.1300	158.41	3.44	3
None	1860	0.0013	52.16	5.08	3
7.8 x 10 ¹⁵	1860	0.0013	75.47	6.98	3
2.7 x 10 ¹⁷	1860	0.0013	76.07	2.93	3
5.8 x 10 ¹⁸	1860	0.0013	83.55	1.47	3
ELONGATION, % ⁽⁵⁾					
None	1560	0.0013	28.66	2.97	3
2.5 x 10 ¹⁷	1560	0.0013	22.96	2.63	3
None	1660	0.0013	24.60	2.66	3
8.6 x 10 ¹⁵	1660	0.0013	18.16	2.26	3
2.7 x 10 ¹⁷	1660	0.0013	16.64	1.53	2
3.4 x 10 ¹⁸	1660	0.0013	13.70	0.12	3
None	1660	0.1300	21.79	0.34	3
3.7 x 10 ¹⁷	1660	0.1300	19.24	5.38	3
None	1860	0.0013	20.40	2.29	3
7.8 x 10 ¹⁵	1860	0.0013	8.86	2.30	3
2.7 x 10 ¹⁷	1860	0.0013	7.05	0.34	3
5.8 x 10 ¹⁸	1860	0.0013	3.78	0.95	3

TABLE 5 (CONT'D)

TENSILE PROPERTIES SUMMARY OF TEST RESULTS

WASPALLOY

ENVIRONMENT		STRAIN RATE	PROPERTY		SAMPLE
Neutron Fluence ⁽¹⁾ n/cm ² E < 0.48 eV	Test Temp ⁽²⁾ °R	In/In/Min	Mean Value	Std. ⁽³⁾ Dev.	SIZE
REDUCTION IN AREA, %					
None	1560	0.0013	30.15	4.28	3
2.5 x 10 ¹⁷	1560	0.0013	23.79	2.20	3
None	1660	0.0013	33.02	4.45	3
8.6 x 10 ¹⁵	1660	0.0013	21.32	2.42	3
2.7 x 10 ¹⁷	1660	0.0013	20.24	1.41	2
3.4 x 10 ¹⁸	1660	0.0013	19.96	2.28	3
None	1660	0.1300	28.40	2.16	3
3.7 x 10 ¹⁷	1660	0.1300	27.78	1.82	3
None	1860	0.0013	23.10	3.05	3
7.8 x 10 ¹⁵	1860	0.0013	15.41	2.02	3
2.7 x 10 ¹⁷	1860	0.0013	12.10	1.57	3
5.8 x 10 ¹⁸	1860	0.0013	7.27	0.75	3

- (1) - Neutron fluences listed are nominal. Fluence for individual specimens varied as shown in table A-2
- (2) - Test Temperatures are the temperatures of the specimens during tensile testing. The specimens were irradiated in water pool at approximately 580°R.
- (3) - Standard deviations may be influenced by the differences in fluence received by individual specimens.
- (4) - Fracture strength listed is the engineering stress at which the specimen fractured in tension.
- (5) - Elongation was computed from load deflection charts for 1.5 inch gage length.

TABLE 6

TENSILE PROPERTIES SUMMARY OF TEST RESULTS

INCONEL 718

(0.4 ppmB)⁽⁶⁾ (37.0 ppmB)⁽⁷⁾ (46.0 ppmB)⁽⁸⁾

ENVIRONMENT		STRAIN RATE	PROPERTY		SAMPLE SIZE
Neutron Fluence ⁽¹⁾ n/cm ² E < 0.48 eV	Test Temp ⁽²⁾ °R	In/In/Min	Mean Value	Std. (3) Dev.	
0.2 % OFFSET YIELD STRESS, KSI					
None	1660	0.0013	142.41 ⁽⁶⁾	---	1
None	1660	0.0020	135.6 ⁽⁶⁾	5.8	3
1.9 x 10 ¹⁷	1660	0.0013	144.56 ⁽⁶⁾	3.01	3
3.7 x 10 ¹⁸	1660	0.0013	145.62 ⁽⁶⁾	4.74	3
None	1360	0.0013	147.69 ⁽⁷⁾	0.19	2
None	1510	0.0013	141.49 ⁽⁷⁾	3.50	3
6.4 x 10 ¹⁵	1510	0.0013	142.11 ⁽⁷⁾	5.30	3
1.3 x 10 ¹⁷	1510	0.0013	145.27 ⁽⁷⁾	4.10	3
2.3 x 10 ¹⁸	1510	0.0013	146.70 ⁽⁷⁾	2.96	3
None	1585	0.0013	141.36 ⁽⁷⁾	7.16	2
1.5 x 10 ¹⁷	1585	0.0013	139.30 ⁽⁷⁾	2.04	3
None	1660	0.0013	141.55 ⁽⁷⁾	3.50	3
8.0 x 10 ¹⁵	1660	0.0013	141.44 ⁽⁷⁾	2.42	3
1.8 x 10 ¹⁷	1660	0.0013	137.41 ⁽⁷⁾	0.27	3
2.5 x 10 ¹⁸	1660	0.0013	136.82 ⁽⁷⁾	0.46	3
None	1660	0.1300	136.89 ⁽⁷⁾	5.63	3
2.2 x 10 ¹⁷	1660	0.1300	141.70 ⁽⁷⁾	1.48	3
None	1660	0.0020	131.00 ⁽⁸⁾	2.83	2
2.3 x 10 ¹⁷	1660	0.0013	130.28 ⁽⁸⁾	0.43	3
4.2 x 10 ¹⁸	1660	0.0013	130.12 ⁽⁸⁾	0.18	2
ULTIMATE STRENGTH, KSI					
None	1660	0.0013	146.67 ⁽⁶⁾	---	1
None	1660	0.0020	150.3 ⁽⁶⁾	2.9	3
1.9 x 10 ¹⁷	1660	0.0013	151.33 ⁽⁶⁾	2.48	3
3.7 x 10 ¹⁸	1660	0.0013	145.94 ⁽⁶⁾	4.99	3
None	1360	0.0013	166.96 ⁽⁷⁾	1.12	2
None	1510	0.0013	161.01 ⁽⁷⁾	1.33	3

TABLE 6 (CONT'D)

TENSILE PROPERTIES SUMMARY OF TEST RESULTS

INCONEL 718

(0.4 ppmB)⁽⁶⁾ (37.0 ppmB)⁽⁷⁾ (46.0 ppmB)⁽⁸⁾

ENVIRONMENT		STRAIN RATE	PROPERTY		SAMPLE SIZE
Neutron Fluence ⁽¹⁾ n/cm ² E < 0.48 eV	Test Temp ⁽²⁾ °R	In/In/Min	Mean Value	Std. (3) Dev.	
ULTIMATE STRENGTH, KSI (Cont.)					
6.4 x 10 ¹⁵	1510	0.0013	162.08 ⁽⁷⁾	2.94	3
1.3 x 10 ¹⁷	1510	0.0013	164.31 ⁽⁷⁾	4.73	3
2.3 x 10 ¹⁸	1510	0.0013	165.35 ⁽⁷⁾	3.82	3
None	1585	0.0013	155.03 ⁽⁷⁾	5.83	2
1.5 x 10 ¹⁷	1585	0.0013	153.32 ⁽⁷⁾	0.45	3
None	1660	0.0013	149.16 ⁽⁷⁾	3.18	3
8.0 x 10 ¹⁵	1660	0.0013	148.34 ⁽⁷⁾	1.78	3
1.8 x 10 ¹⁷	1660	0.0013	143.91 ⁽⁷⁾	1.03	3
2.5 x 10 ¹⁸	1660	0.0013	143.93 ⁽⁷⁾	0.92	3
None	1660	0.1300	155.98 ⁽⁷⁾	5.65	3
2.2 x 10 ¹⁷	1660	0.1300	157.72 ⁽⁷⁾	1.88	3
None	1660	0.0020	145.00 ⁽⁸⁾	4.2	2
2.3 x 10 ¹⁷	1660	0.0013	140.10 ⁽⁸⁾	1.90	3
4.2 x 10 ¹⁸	1660	0.0013	136.78 ⁽⁸⁾	0.25	2
FRACTURE STRENGTH, KSI ⁽⁴⁾					
None	1660	0.0013	136.41 ⁽⁶⁾	---	1
1.9 x 10 ¹⁷	1660	0.0013	146.80 ⁽⁶⁾	0.25	3
3.7 x 10 ¹⁸	1660	0.0013	144.23 ⁽⁶⁾	2.11	3
None	1360	0.0013	148.95 ⁽⁷⁾	4.41	2
None	1510	0.0013	157.40 ⁽⁷⁾	2.50	3
6.4 x 10 ¹⁵	1510	0.0013	157.51 ⁽⁷⁾	1.85	3
1.3 x 10 ¹⁷	1510	0.0013	160.05 ⁽⁷⁾	7.10	3
2.3 x 10 ¹⁸	1510	0.0013	161.21 ⁽⁷⁾	6.11	3
None	1585	0.0013	152.96 ⁽⁷⁾	5.61	2
1.5 x 10 ¹⁷	1585	0.0013	151.51 ⁽⁷⁾	0.36	3
None	1660	0.0013	145.25 ⁽⁷⁾	2.30	3

TABLE 6 (CONT'D)

TENSILE PROPERTIES SUMMARY OF TEST RESULTS

INCONEL 718

(0.4 ppmB)⁽⁶⁾ (37.0 ppmB)⁽⁷⁾ (46.0 ppmB)⁽⁸⁾

ENVIRONMENT		STRAIN RATE	PROPERTY		SAMPLE SIZE
Neutron Fluence ⁽¹⁾ n/cm ² E ≤ 0.48 eV	Test Temp ⁽²⁾ °R	In/In/Min	Mean Value	Std. ⁽³⁾ Dev.	
FRACTURE STRENGTH, KSI ⁽⁴⁾ (cont.)					
8.0 x 10 ¹⁵	1660	0.0013	146.00 ⁽⁷⁾	1.51	3
1.8 x 10 ¹⁷	1660	0.0013	140.82 ⁽⁷⁾	1.77	3
2.5 x 10 ¹⁸	1660	0.0013	141.91 ⁽⁷⁾	1.42	3
None	1660	0.1300	146.86 ⁽⁷⁾	0.86	3
2.2 x 10 ¹⁷	1660	0.1300	153.58 ⁽⁷⁾	2.26	3
2.3 x 10 ¹⁷	1660	0.0013	113.1 ⁽⁸⁾	3.90	3
4.2 x 10 ¹⁸	1660	0.0013	101.23 ⁽⁸⁾	8.39	2
ELONGATION, % ⁽⁵⁾					
None	1660	0.0013	3.51 ⁽⁶⁾	---	1
None	1660	0.0020	9.3 ⁽⁶⁾⁽⁹⁾	1.2	3
1.9 x 10 ¹⁷	1660	0.0013	2.58 ⁽⁶⁾	0.55	3
3.7 x 10 ¹⁸	1660	0.0013	0.32 ⁽⁶⁾	0.22	3
None	1360	0.0013	16.89 ⁽⁷⁾	1.55	2
None	1510	0.0013	11.23 ⁽⁷⁾	0.54	3
6.4 x 10 ¹⁵	1510	0.0013	8.76 ⁽⁷⁾	1.26	3
1.3 x 10 ¹⁷	1510	0.0013	7.75 ⁽⁷⁾	0.73	3
2.3 x 10 ¹⁸	1510	0.0013	6.88 ⁽⁷⁾	0.55	3
None	1585	0.0013	6.09 ⁽⁷⁾	1.31	2
1.5 x 10 ¹⁷	1585	0.0013	4.18 ⁽⁷⁾	0.58	3
None	1660	0.0013	4.59 ⁽⁷⁾	0.87	3
8.0 x 10 ¹⁵	1660	0.0013	3.01 ⁽⁷⁾	0.34	3
1.8 x 10 ¹⁷	1660	0.0013	1.99 ⁽⁷⁾	0.13	3
2.5 x 10 ¹⁸	1660	0.0013	1.28 ⁽⁷⁾	0.21	3
None	1660	0.1300	12.56 ⁽⁷⁾	0.76	3
2.2 x 10 ¹⁷	1660	0.1300	8.19 ⁽⁷⁾	0.26	3
None	1660	0.0020	9.0 ⁽⁸⁾⁽⁹⁾	1.4	2
2.3 x 10 ¹⁷	1660	0.0013	5.17 ⁽⁸⁾	1.31	3
4.2 x 10 ¹⁸	1660	0.0013	3.68 ⁽⁸⁾	0.18	2

TABLE 6 (CONT'D)

TENSILE PROPERTIES SUMMARY OF TEST RESULTS

INCONEL 718

(0.4 ppmB)⁽⁶⁾ (37.0 ppmB)⁽⁷⁾ (46.0 ppmB)⁽⁸⁾

ENVIRONMENT		STRAIN RATE	PROPERTY		SAMPLE SIZE
Neutron Fluence ⁽¹⁾	Test Temp ⁽²⁾		Mean	Std. ⁽³⁾	
n/cm ² E<0.48 eV	°R	In/In/Min	Value	Dev.	
REDUCTION IN AREA, %					
None	1660	0.0013	6.35 ⁽⁶⁾	---	1
None	1660	0.0020	13.7 ⁽⁶⁾	0.6	3
1.9 x 10 ¹⁷	1660	0.0013	12.68 ⁽⁶⁾	2.56	3
3.7 x 10 ¹⁸	1660	0.0013	16.80 ⁽⁶⁾	1.63	3
None	1360	0.0013	42.55 ⁽⁷⁾	3.44	2
None	1510	0.0013	20.96 ⁽⁷⁾	0.81	3
6.4 x 10 ¹⁵	1510	0.0013	17.95 ⁽⁷⁾	2.61	3
1.3 x 10 ¹⁷	1510	0.0013	18.63 ⁽⁷⁾	1.50	3
2.3 x 10 ¹⁸	1510	0.0013	16.80 ⁽⁷⁾	3.08	3
None	1585	0.0013	15.67 ⁽⁷⁾	2.16	2
1.5 x 10 ¹⁷	1585	0.0013	12.98 ⁽⁷⁾	2.64	3
None	1660	0.0013	14.07 ⁽⁷⁾	1.74	3
8.0 x 10 ¹⁵	1660	0.0013	10.91 ⁽⁷⁾	2.91	3
1.8 x 10 ¹⁷	1660	0.0013	9.31 ⁽⁷⁾	3.01	3
2.5 x 10 ¹⁸	1660	0.0013	8.91 ⁽⁷⁾	3.45	3
None	1660	0.1300	27.37 ⁽⁷⁾	1.50	3
2.2 x 10 ¹⁷	1660	0.1300	23.09 ⁽⁷⁾	1.72	3
None	1660	0.0020	10.05 ⁽⁸⁾	2.4	2
2.3 x 10 ¹⁷	1660	0.0013	12.70 ⁽⁸⁾	2.30	3
4.2 x 10 ¹⁸	1660	0.0013	15.62 ⁽⁸⁾	1.82	2

- (1) - Neutron fluences listed are nominal. Fluence for individual specimens varied as shown in table A-3
- (2) - Test temperatures are the temperatures of the specimens during tensile testing. The specimens were irradiated in water pool at approximately 580°R.
- (3) - Standard deviations may be influenced by the differences in fluence received by individual specimens.
- (4) - Fracture strength listed is the engineering stress at which the specimen fractured in tension.

TABLE 6 (CONT'D)

TENSILE PROPERTIES SUMMARY OF TEST RESULTS

INCONEL 718

(0.4 ppmB)⁽⁶⁾ (37.0 ppmB)⁽⁷⁾ (46.0 ppmB)⁽⁸⁾

- (5) - Elongation was computed from load deflection charts for 1.5 inch gage length.
- (6) - 0.4 parts per million boron
- (7) - 37.0 parts per million boron
- (8) - 46.0 parts per million boron
- (9) - Elongation in four diameters

TABLE 7

STRESS-RUPTURE SUMMARY OF TEST RESULTS
WASPALLOY

ENVIRONMENT		PROPERTY						SAMPLE SIZE
Neutron Fluence ⁽¹⁾ n/cm ² E < 0.48 eV	Test Temp ⁽²⁾ °R	Time to Failure		Elongation, %		Reduction in Area, %		
		Mean Hour	Std. ⁽³⁾ Dev.	Mean Value	Std. ⁽³⁾ Dev.	Mean Value	Std. ⁽³⁾ Dev.	
None	1660	90.1 ⁽⁴⁾	25.2	14.8	1.8	21.5 ⁽⁶⁾	3.8	3
6.6 x 10 ¹⁵	1660	70.4 ⁽⁴⁾	6.6	7.2	0.2	12.6 ⁽⁶⁾	0.7	3
1.4 x 10 ¹⁷	1660	64.6 ⁽⁴⁾	13.8	8.0	0.6	13.4 ⁽⁶⁾	0.2	3
2.1 x 10 ¹⁸	1660	56.0 ⁽⁴⁾	13.0	5.7	1.0	11.9 ⁽⁶⁾	2.4	3
None	1860	24.7 ⁽⁵⁾	0.2	24.0	4.5	29.0 ⁽⁷⁾	3.4	2
6.3 x 10 ¹⁵	1860	14.3 ⁽⁵⁾	2.1	6.0	0.6	10.0 ⁽⁷⁾	0.6	2
1.5 x 10 ¹⁷	1860	13.1 ⁽⁵⁾	1.6	4.8	0.8	7.6 ⁽⁷⁾	2.5	2

(1) - Neutron fluences listed are nominal. Fluence for individual specimens varied as shown in table A-4

(2) - Test temperatures are the temperatures of the specimens during stress-rupture testing.

(3) - Standard deviations may be influenced by the differences in fluence received by individual specimens.

(4) - Specimens were round-unnotched button-head per AGC Drwg. 1134298.

(5) - Specimens were round-notched button-head per AGC Drwg. 1134453.

(6) - Elongation was computed from load deflection charts for 1.5 inch gage length.

(7) - Elongation was computed from load deflection charts for 0.978 inch gage length.

TABLE 8

STRESS-RUPTURE SUMMARY OF TEST RESULTS
 INCONEL 718
 (37.0 ppmB⁽⁸⁾ & 0.4 ppmB⁽⁹⁾)

ENVIRONMENT		PROPERTY						SAMPLE SIZE
Neutron Fluence ⁽¹⁾ n/cm ² E < 0.48 eV	Test Temp ⁽²⁾ °R	Time to Failure		Elongation, %		Reduction in Area, %		
		Mean Hour	Std. ⁽³⁾ Dev.	Mean Value	Std. ⁽³⁾ Dev.	Mean Value	Std. ⁽³⁾ Dev.	
None	1660	58.7 ⁽⁴⁾ (8)	9.4	5.3 ⁽⁶⁾	2.5	14.5	2.4	3
6.4 x 10 ¹⁵	1660	55.5 ⁽⁴⁾ (8)	9.5	4.0 ⁽⁶⁾	0.1	11.5	2.2	3
1.1 x 10 ¹⁷	1660	36.1 ⁽⁴⁾ (8)	6.4	1.3 ⁽⁶⁾	0.3	10.1	1.1	3
2.3 x 10 ¹⁸	1660	11.1 ⁽⁴⁾ (8)	2.6	0.3 ⁽⁶⁾	0.2	7.1	1.6	3
6.4 x 10 ¹⁵	1660	51.8 ⁽⁴⁾ (9)	---	3.3 ⁽⁶⁾	---	8.8	---	1
1.2 x 10 ¹⁷	1660	45.0 ⁽⁴⁾ (9)	9.6	1.9 ⁽⁶⁾	0.2	13.7	7.5	2
None	1760	29.8 ⁽⁵⁾ (8)	0.1	18.3 ⁽⁷⁾	10.5	20.2	8.4	2
6.4 x 10 ¹⁵	1760	23.9 ⁽⁵⁾ (8)	3.7	---	---	---	---	2
1.6 x 10 ¹⁷	1760	1.4 ⁽⁵⁾ (8)	0.8	0.1 ⁽⁷⁾	0.0	---	---	2

- (1) - Neutron fluences listed are nominal. Fluence for individual specimens varied as shown in table A-5
- (2) - Test temperatures are the temperatures of the specimens during stress-rupture testing.
- (3) - Standard deviations may be influenced by the difference in fluence received by individual specimens.
- (4) - Specimens were round-unnotched button-head per AGC Drwg. 1134298.
- (5) - Specimens were round-notched button-head per AGC Drwg. 1134453.
- (6) - Elongation was computed from load deflection charts for 1.5 inch gage length.
- (7) - Elongation was computed from load deflection charts for 0.978 inch gage length.
- (8) - 37.0 parts per million boron.
- (9) - 0.6 parts per million boron.

B. STRESS-STRAIN CURVES

Typical stress-strain curves for control and irradiated specimens of Rene 41, Waspaloy and Inconel 718 are shown in Figures 3, 4 and 5, respectively. Each curve was derived from a test chart of load vs cross-head travel. Values of Young's Moduli from Materials Properties Data Book, Report 2275, were used to construct the elastic portion of the curves. The moduli reported in the tables include test equipment strain; therefore these data are not suitable for use in stress-strain curves.

C. DOSIMETRY

The fluences reported for individual specimens in Table A-1 through A-5 are based on the mapping run and dosimetry obtained during irradiation of the specimens. Extrapolation and interpolation from dosimeter pocket locations resulted in the fluences reported.

D. NERVA APPLICATION

The results of this test will be used as a basis for material evaluation, prediction of material behavior, and planning of future tests. These data will be combined with data from other tests for further evaluation and incorporation into appropriate NERVA engineering documents. Typical applications would include the determination of whether ductile or brittle design criteria are required in the use of these materials and whether fracture-toughness test data will be necessary for proper design.

E. ANALYSIS

The analysis of the data generally followed a three-step process:

Figure 3 - Typical Stress-Strain Curves for Rene '41

Figure 4 - Typical Stress-Strain Curves for Waspaloy

Figure 5 - Typical Stress - Strain Curves for Inconel 718

1. Variance Check

The statistical methods are used with the assumptions that the observations are from normally distributed populations with equal variances. Variances of suspected groups were checked by comparing ratios of variances with the standard "F-test". None of the tests were found to contain groups with unequal variances for any property and material.

2. Significant Effects

The data from each test were arranged into balanced factorial matrixes for which data were available for several levels of each variable. Analyses of the factorial experiments by the method of Analysis of Variance were conducted. Thus, for each property of each material, the significant main effects and interactions were identified. Significance was determined by the F-test at the 95% confidence level. The mean values for each test condition are displayed graphically in Figures 6 through 12.

3. Contrasts

To define the magnitude of the main effects and interactions that were evaluated in Step 2, contrasts were made between the means of any groups which were of interest.

The statistical method for checking any or all contrasts in accomplished by use of the "q" statistic to provide limits for contrasts as follows:

$$\bar{X}_A - \bar{X}_B \pm q s_p / n$$

- A. TEST TEMP AND TEMP BY FLUENCE
INTERACTION SIGNIFICANT AT 95% CONFIDENCE
- B. NO SIGNIFICANT EFFECTS
- C. FLUENCE AND TEST TEMPERATURE SIGNIFICANT
AT 95% CONFIDENCE
- D. TEST TEMPERATURE SIGNIFICANT AT
95% CONFIDENCE

FLUENCE LEVELS:

CON = NO IRRADIATION

LOW = 9×10^{15} nvt ($E < 0.48$ ev)

MED = 2×10^{17} nvt ($E < 0.48$ ev)

Figure 6 - Effects of Radiation on Tensile Properties of Rene '41

Figure 7 - Effects of Radiation on Tensile Properties of Waspaloy (1560°R Tests Added)

A. STRAIN RATE SIGNIFICANT FACTOR AT 95% CONFIDENCE

B. NO SIGNIFICANT FACTORS

C. FLUENCE SIGNIFICANT 95% CONFIDENCE

D. FLUENCE AND THE INTERACTION
SIGNIFICANT AT 95% CONFIDENCE

FLUENCE LEVELS:

CON = NO IRRADIATION

IRR = 2.5×10^{17} nvt ($E < 0.48$ ev)

STRAIN RATES:

SR .0013 IN/IN/MIN

SR .13 IN/IN/MIN

TEST TEMPERATURE: 1660°R

Figure 8 - Effects of Fluence vs Strain Rate of Waspaloy

- A. TEST TEMPERATURE AND INTERACTION SIGNIFICANT AT 95% CONFIDENCE LEVEL
- B. SIGNIFICANT INTERACTION, WITH DIFFERENCES AT HIGH FLUENCE DUE TO TEST TEMPERATURE
- C. FLUENCE AND TEST TEMPERATURE SIGNIFICANT FACTORS
- D. TEST TEMPERATURE SIGNIFICANT FACTOR

FLUENCE LEVELS:

CON = NO IRRADIATION
 LOW = 7×10^{15} nvt ($E < 0.48$ ev)
 MED = 2×10^{17} nvt ($E < 0.48$ ev)
 HIGH = 3×10^{18} nvt ($E < 0.48$ ev)

Figure 9 - Effects of Radiation on Tensile Properties of Inconel 718

A. STRAIN RATE AND INTERACTION SIGNIFICANT
AT 95% CONFIDENCE LEVEL

B. NO SIGNIFICANT EFFECTS

C. STRAIN RATE AND FLUENCE SIGNIFICANT.
INTERACTION SIGNIFICANT

D. STRAIN RATE AND FLUENCE SIGNIFICANT FACTORS

FLUENCE LEVELS:

CON = NO IRRADIATION

IRR = 2×10^{17} nvt ($E < 0.48$ ev)

STRAIN RATES:

SR .0013 IN/IN/MIN

SR .13 IN/IN/MIN

TEST TEMPERATURE: 1660°R

Figure 10 - Effects of Fluence vs Strain Rate of Inconel 718

NOTE: FOR ALL PROPERTIES SHOWN, ANALYSIS OF VARIANCE INDICATES A SIGNIFICANT (99% CONFIDENCE) EFFECT DUE TO IRRADIATION, BUT NO EFFECT DUE TO AMOUNT OF RADIATION FROM "LOW" TO "HIGH" CAN BE DEMONSTRATED.

FLUENCE LEVELS:

CON = NO IRRADIATION
 LOW = 6.0×10^{15} nvt ($E < 0.48$ ev)
 MED = 1.4×10^{17} nvt
 HIGH = 2.1×10^{18} nvt

Figure 11 - Effects of Radiation on Stress-Rupture Properties of Waspaloy

NOTE: FOR ALL PROPERTIES SHOWN, ANALYSIS OF VARIANCE INDICATES A SIGNIFICANT (99% CONFIDENCE) EFFECT DUE TO IRRADIATION OVER THE RANGE OF "CONTROL" TO "HIGH" FLUENCE. "LOW" FLUENCE LEVEL APPEARS TO BE NEAR THE THRESHOLD - HIGHER FLUENCES INDICATE GREATER CHANGES IN PROPERTIES

FLUENCE LEVELS:

CON = NO IRRADIATION

LOW = 6.4×10^{15} nvt ($E < 0.48$ ev)

MED = 1.0×10^{17} nvt

HIGH = 2.3×10^{18} nvt

Figure 12 - Effects of Radiation on Stress-Rupture Properties of Inconel 718

where

$$\begin{aligned}\bar{X}_a &= \text{mean value of any set of data from } k \text{ tests} \\ &= \frac{\bar{X}_1 + \bar{X}_2 + \dots + \bar{X}_k}{k}\end{aligned}$$

$$\bar{X}_B = \text{mean value of any other set of data}$$

$$q = \text{table value (Table A-10, Natrella (Ref. 9), or A-18, Dixon \& Massey Ref. 10) for 95\% confidence.}$$

$$s_p = \text{Pooled standard deviation (from analysis of variance).}$$

$$n = \text{No. of replicates in each test.}$$

Contrasts for various effects of interest were calculated, tabulated (Appendix), and shown graphically (Tables 8, 9, 11, 12, 14, 15, 17, 19).

VI. EVALUATION OF RESULTS

A. RENE 41 TENSILE TESTS

1. Analysis

For each tensile property (ultimate strength, 0.2% offset yield strength, elongation and reduction of area), and analysis of variance was conducted on the 2 x 3 factorial effects of test temperature (three each) and fluence (control and two fluence levels). The experimental plan was unbalanced so that the effects of a third and higher fluence level

and changes in strain rate were not included in this analysis.

The analysis of variance identified the significant variables, and provided an estimate of standard deviation. The contrasts, are shown in Table A-6 "Contrast of Means (Differences and Percentages), Rene 41." These data are shown graphically in Table 9 as "differences", Table 10 as "percentages" and Figure 6. Table 11 is a summary of all effects indicating significant changes and direction of change.

A tabulation of the standard deviations of homogeneous groups of property data is shown in Table A-7. These values may be required in future analyses to provide an independent estimate of variance.

2. Irradiation and Test Temperature

The tensile test property most sensitive to radiation was elongation. Both irradiation and test temperature were significant ($\geq 95\%$ confidence) factors for elongation. Elongation decreased 3.9% when specimens were irradiated to $9 \times 10^{15} \text{ n/cm}^2 < 0.48\text{eV}$ at 1660°R , and 5.0% when irradiated to $2 \times 10^{17} \text{ n/cm}^2 > 0.48\text{eV}$ at 1660°R from a mean control value of 7.6% .

The elongation also decreased 4.1% with an increase in test temperature from 1660°R to 1860°R . Increasing fluence levels from 9×10^{15} to $2 \times 10^{17} \text{ n/cm}^2 < 0.48 \text{ eV}$ resulted in no effect on significant effect on elongation at 1660°R & 1860°R .

The effect of irradiation on ultimate strength depends on the test temperature. Ultimate strength decreased 31.2 ksi on the average with the increase in test temperature. Ultimate strength decreased due to irradiation when tested at 1660°R by 13.8 ksi at $9 \times 10^{15} \text{ n/cm}^2 < 0.48\text{eV}$ and by 18.7 ksi at $2 \times 10^{17} \text{ n/cm}^2$. No change was discernible when tested at 1860°R . The effect of irradiation fluence on ultimate strength was not significant.

TABLE 9
EFFECT OF TEST CONDITIONS ON PROPERTIES OF RENE' 41 CONTRASTS OF MEANS (DIFFERENCES)

(1) COMPARISONS ARE SECOND CONDITION COMPARED TO FIRST CONDITION

TABLE 10
EFFECT OF TEST CONDITIONS ON PROPERTIES OF RENE' 41 CONTRASTS OF MEANS (PERCENTAGES)

(1) COMPARISONS ARE SECOND CONDITION COMPARED TO FIRST CONDITION

TABLE 11

SUMMARY - EFFECT OF TEST CONDITIONS
ON PROPERTIES OF RENE 41⁽²⁾

Contrast ⁽¹⁾	Ultimate Stress	0.2% Offset Yield Stress	Elongation	Reduction of Area	Fracture Stress
Mean @ 1660°R vs Mean @ 1860°R	--	0	--	0	--
Control vs Med. Level Irrad. @ 1660°R	--	0	--	0	--
Control vs Low Level Irrad. @ 1660°R	--	0	--	0	0
Low vs Med. Level Irrad. @ 1660°R	0	0	0	0	0
Control vs Med. Level Irrad. @ 1860°R	0	0	--	0	0
Control vs Low Level Irrad. @ 1860°R	0	0	--	0	0
Low vs Med. Level Irrad. @ 1860°R	0	0	0	0	0
1660°R vs 1860°R (Control)	--	0	--	0	--
1660°R vs 1860°R (Low Level Irrad.)	--	0	--	--	--
1660°R vs 1860°R (Med. Level Irrad.)	--	0	--	0	--

(1) Comparisons are second condition compared to first condition.

(2) -- significant decrease at 95% confidence level.

0 no significant effect.

Fracture strength decreased 39.4 ksi on the average with an increase in test temperature. Irradiation of 2×10^{17} n/cm² <0.48eV at 1660°R reduced fracture strength by 19.4 ksi.

Fluence or test temperatures had no significant effects on the 0.2% offset yield strength and reduction of area.

The fluence levels for the above results were zero (control), 9×10^{15} n/cm², and 2×10^{17} n/cm² (<0.48eV). Additional tests at 4×10^{18} n/cm² thermal fluence (1660°R test temperature only) resulted in no change in tensile properties compared to the lower fluence levels.

B. WASPALOY TENSILE TESTS

1. Analysis

The test plan consisted of a matrix of test temperature-fluence combinations with three replications. The matrix was not filled, but two empty cells were left. In addition, two tests were repeated, using a high strain rate.

The plan was treated as a 2 x 4 factorial test. The two tests at 1560°R were ignored (rather than use missing data procedures) and the data were analyzed by Analysis of Variance.

The effect of strain rate was evaluated separately as a 2 x 2 factorial test (fluence and strain rate).

The contrasts are shown in Table A-8 Contrast of Means (Differences and Percentages), Waspaloy: These data are shown graphically

in Table 12 as "differences", Table 13 as "percentages" and Figures 7 and 8. Table 14 is a summary of all effects indicating significant changes and direction of change. A tabulation of the standard deviations of homogeneous groups of property data is shown in Table A-9.

2. Irradiation and Test Temperature

Elongation was the property most sensitive to irradiation. Irradiation and test temperature were both significant ($\geq 95\%$ confidence) factors. Irradiation decreased elongation (compare irradiated specimen values with unirradiated controls) but the different levels of fluence show no clearly defined effect. The analysis of variance indicated a significant interaction between temperature and irradiation. The mean elongation decreased 13.9% at 1860°R, and only 8.4% at 1660°R due to irradiation. Elongation decreased 7.5% due to increasing test temperature from 1560°R to 1660°R, and 8.3% from 1660°R to 1860°R.

Reduction of area was significantly affected by both test temperature and fluence. The reduction of area decreased 12.8% at 1660°R and 11% at 1860°R at $2.5 \times 10^{17} \text{ n/cm}^2 < 0.48\text{eV}$. There was no change at 1560°R. Reduction of area decreased 9.9% as test temperature was increased from 1660°R to 1860°R and appeared to be the same at 1560°R as at 1660°R. Although irradiation had a significant effect on reduction of area, the level of the fluence in the range tested was not important, over the test range.

Ultimate strength was significantly affected by test temperature, decreasing 52.4 ksi and 23.0 ksi with increasing temperature from 1660°R to 1860°R and 1560°R and 1660°R, respectively. Irradiation had no effect on ultimate strength.

The 0.2% offset yield strength was significantly affected by test temperature, decreasing 16.4 ksi as temperature increased from 1660°R to 1860°R. Values at 1560°R were the same as those at 1660°R. Irradiation

TABLE 12

EFFECT OF TEST CONDITIONS ON PROPERTIES OF WASPALOY CONTRASTS OF MEANS (DIFFERENCES)

(1) COMPARISONS ARE SECOND CONDITION COMPARED TO FIRST CONDITION

TABLE 12 (CONT'D)

EFFECT OF TEST CONDITIONS ON PROPERTIES OF WASPALOY CONTRASTS OF MEANS (DIFFERENCES)

(1) COMPARISONS ARE SECOND CONDITION COMPARED TO FIRST CONDITION

TABLE 13
EFFECT OF TEST CONDITIONS ON PROPERTIES OF WASPALOY CONTRASTS OF MEANS (PERCENTAGES)

(1) COMPARISONS ARE SECOND CONDITION COMPARED TO FIRST CONDITION

TABLE 13 (contd)

CONTRAST (1)	REDUCTION OF AREA, %							FRACTURE STRESS, KSI									
	-							+									
	75	50	25	0	25	50	75	100	75	50	25	0	25	50	75	100	
CONTROL VS MED FLUENCE (1560°R)																	
CONTROL VS LOW FLUENCE (1660°R)																	
CONTROL VS MED FLUENCE (1660°R)																	
LOW VS HIGH FLUENCE (1660°R)																	
CONTROL VS LOW FLUENCE (1860°R)																	
CONTROL VS MED FLUENCE (1860°R)																	
LOW VS HIGH FLUENCE (1860°R)																	
MEAN IRRAD (1660°R) VS MEAN IRRAD (1860°R)																	
CONTROL VS MEAN IRRAD (1660°R)																	
CONTROL VS MEAN IRRAD (1860°R)																	
1560°R VS 1660°R (CONTROL)																	
1660°R VS 1860°R (CONTROL)																	
MEAN (1560°R) VS MEAN (1660°R)																	
MEAN (1660°R) VS MEAN (1860°R)																	
1560°R VS 1660°R (MED FLUENCES)																	
1660°R VS 1860°R (MED FLUENCES)																	
MEANS, 0.0013 VS 0.1300 IN/IN/MIN																	
MEANS, CONTROL VS IRRAD (2.5×10^{17})																	
CONTROL VS IRRAD AT 0.0013 IN/IN/MIN																	
CONTROL VS IRRAD AT 0.1300 IN/IN/MIN																	

(1) COMPARISONS ARE SECOND CONDITION COMPARED TO FIRST CONDITION

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TABLE 14

SUMMARY - EFFECT OF TEST CONDITIONS
ON PROPERTIES OF WASPALOY, FLUENCE/TEST TEMPERATURE
EXPERIMENT⁽²⁾

Contrast ⁽¹⁾	Ultimate Stress	0.2% Offset Yield Stress	Elongation	Reduction of Area	Fracture Stress
Control vs Med. Fluence (1560°R)	0	0	0	0	0
Control vs Low Fluence (1660°R)	0	0	--	--	0
Control vs Med. Fluence (1660°R)	0	0	--	--	0
Low vs High Fluence (1660°R)	0	0	0	0	0
Control vs Low Fluence (1860°R)	0	0	--	0	+
Control vs Med. Fluence (1860°R)	0	0	--	--	+
Low vs High Fluence (1860°R)	0	0	0	--	0
Mean Irrad (1660°R) vs Mean Irrad (1860°R)	--	--	--	--	--
Control vs Mean Irrad (1660°R)	0	0	--	--	0
Control vs Mean Irrad (1860°R)	0	0	--	--	+
1560°R vs 1660°R (Control)	--	0	0	0	--
1660°R vs 1860°R (Control)	--	--	0	--	--
Mean 1560°R vs Mean 1660°R	--	0	--	0	--
Mean 1660°R vs Mean 1860°R	--	--	--	--	--
1560°R vs 1660°R (Med Fluence)	--	0	--	0	--
1660°R vs 1860°R (Med Fluence)	--	--	--	--	--
Mean 0.0013 vs 0.13 in/in/min	+	0	0	0	+
Mean Control vs Irradiated	0	0	0	--	0
Control vs Irrad (0.0013 in/in/min)	0	0	0	0	0
Control vs Irrad (0.1300 in/in/min)	0	0	0	0	0

(1) Comparisons are second condition compared to first condition.

(2) + significant increase at 95% confidence level.

- significant decrease at 95% confidence level.

0 no significant effect.

had no significant effect on yield strength.

Fracture strength significantly decreased with increasing temperatures and increased with irradiation.

3. Irradiation and Strain Rate

Strain rate was a significant ($\geq 95\%$ confidence) factor affecting ultimate strength. Strength averaged 25.8 ksi higher for 0.1300 in/in/min than for 0.0013 in/in/min. No effect due to irradiation was noted.

Elongation was decreased 8.0% by irradiation when tested at 0.0013 in/in/min. The higher strain rate of 0.1300 in/in/min did not significantly effect elongation.

Reduction of area was decreased 12.8% by irradiation when tested at 0.0013 in/in/min. A strain rate of 0.1300 in/in/min did not significantly effect reduction in area.

Strain rate was a significant factor affecting fracture strength. Strength averaged 37.9 ksi higher for 0.1300 in/in/min than 0.0013 in/in/min. No effect due to irradiation was noted.

The 0.2% offset yield strength was not affected by either irradiation or strain rate.

C. INCONEL 718 TENSILE TESTS

1. Analysis

The test plan consisted of tensile tests at various test temperatures, with specimens exposed to several levels of radiation and

control specimens (unexposed). In addition several specimens (irradiated and controls) were tested at a high strain rate. These specimens were machined from a rotor forging, and contained 37 parts per million (ppm) boron. A few specimens were tested that were machined from a ring forging (46 ppm boron) and from a low-boron (0.4 ppm) bar. The low-boron bar specimens failed out of the gage section and provided no useful data. Therefore, data used in the analysis are from the rotor forging only.

The experiments were analyzed as factorials by calculating the analysis of variance to identify significant main effects and interactions. The contrasts are shown in Table A-10 "Contrast of Means (Differences and Percentages), Inconel 718. These data are shown graphically in Table 15 as "differences", Table 16 as "percentages" and Figures 9 and 10. Table 17 is a summary of all effects indicating significant changes and direction of change. A tabulation of the standard deviations of homogeneous groups of property data is shown in Table A-11.

2. Irradiation and Test Temperature

Elongation was significantly ($\geq 95\%$ confidence) affected by both test temperature and fluence. Increasing test temperature from 1510°R to 1660°R resulted in a decrease of 6% elongation. The irradiated specimens indicated a mean decrease of 3.4% elongation at 1510°R and 2.5% at 1660°R from control values.

Reduction of area decreased significantly due to the increase in test temperature from 1510°R to 1660°R . The mean decrease in area reduction was 7.8%. The effect of fluence on reduction of area indicated marginal significance; the tests indicated no definite conclusions.

Ultimate strength was significantly affected by test temperature and its interaction with fluence. The ultimate strength

TABLE 15

EFFECT OF TEST CONDITIONS ON PROPERTIES OF INCONEL 718 CONTRAST OF MEANS (DIFFERENCES)

(1) COMPARISONS ARE SECOND CONDITION COMPARED TO FIRST CONDITION

TABLE 15 (contd)

	REDUCTION OF AREA, %										FRACTURE, STRESS, KSI									
	-					+					-					+				
	20	15	10	5	0	5	10	15	20		30	20	10	0	10	20	30			
MEAN AT 1510°R VS MEAN AT 1660°R																				
CONTROLS, 1510°R VS 1660°R																				
MEAN IRRAD, 1510°R VS 1660°R																				
1510°R, CONTROL VS MEAN IRRAD																				
1660°R, CONTROL VS MEAN IRRAD																				
1510°R, LOW IRRAD VS HIGH IRRAD																				
1660°R, LOW IRRAD VS HIGH IRRAD																				
LOW IRRAD, 1510°R VS 1660°R																				
MED IRRAD, 1510°R VS 1660°R																				
HIGH IRRAD, 1510°R VS 1660°R																				
MEANS, 0.0013 VS 0.1300 IN/IN/MIN																				
MEANS, CONTROL VS IRRADIATED																				
CONTROL VS IRRAD AT 0.0013 IN/IN/MIN																				
CONTROL VS IRRAD AT 0.13 IN/IN/MIN																				

(1) COMPARISONS ARE SECOND CONDITION COMPARED TO FIRST CONDITION

TABLE 16

EFFECT OF TEST CONDITIONS ON PROPERTIES OF INCONEL 718 CONTRAST OF MEANS (PERCENTAGES)

(1) COMPARISONS ARE SECOND CONDITION COMPARED TO FIRST CONDITION

TABLE 16 (contd)

CONTRAST ⁽¹⁾	REDUCTION OF AREA, %								FRACTURE STRESS, KSI							
	-				+				-				+			
	75	50	25	0	25	50	75		20	15	10	5	0	5	10	15
MEAN AT 1510°R VS MEAN AT 1660°R																
CONTROLS, 1510°R VS 1660°R																
MEAN IRRAD, 1510°R VS 1660°R																
1510°R, CONTROL VS MEAN IRRAD																
1660°R, CONTROL VS MEAN IRRAD																
1510°R, LOW IRRAD VS HIGH IRRAD																
1660°R, LOW IRRAD VS HIGH IRRAD																
LOW IRRAD, 1510°R VS 1660°R																
MED IRRAD, 1510°R VS 1660°R																
HIGH IRRAD, 1510°R VS 1660°R																
MEANS, 0.0013 VS 0.1300 IN/IN/MIN																
MEANS, CONTROL VS IRRAD (2 x 10 ¹⁷)																
CONTROL VS IRRAD AT 0.0013 IN/IN/MIN																
CONTROL VS IRRAD AT 0.13 VS IN/IN/MIN																

(1) COMPARISONS ARE SECOND CONDITION COMPARED TO FIRST CONDITION

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TABLE 17

SUMMARY - EFFECT OF TEST CONDITIONS
ON PROPERTIES OF INCONEL 718, FLUENCE/TEST
TEMPERATURE EXPERIMENT⁽²⁾

Contrast (1)	Ultimate Stress	0.2% Offset Yield Stress	Elongation	Reduction of Area	Fracture Stress
Mean at 1510°R vs Mean at 1660°R	--	0	--	--	--
Controls, 1510°R vs 1660°R	--	0	--	--	--
Mean Irrad, 1510°R vs 1660°R	--	0	--	--	--
1510°R, Control vs Mean Irrad.	0	0	--	0	0
1660°R, Control vs Mean Irrad.	0	0	--	0	0
1510°R, Low Irrad. vs High Irrad.	0	0	--	0	0
1660°R, Low Irrad. vs High Irrad.	0	0	0	0	0
Low Irrad, 1510°R vs 1660°R	--	0	--	--	--
Med Irrad, 1510°R vs 1660°R	--	0	--	--	--
High Irrad, 1510°R vs 1660°R	--	--	--	--	--
Mean, 0.0013 vs 0.1300 in/in/min	+	0	+	+	+
Mean, Control vs Irrad (2×10^{17})	0	0	--	0	0
Control vs Irrad at 0.0013 in/in/min.	--	0	--	0	0
Control vs Irrad at 0.1300 in/in/min.	0	0	--	0	+

(1) Comparisons are second condition compared to first condition.

(2) + significant increase at 95% confidence level

- significant decrease at 95% confidence level

0 no significant effect

decreased with increasing test temperature. The amount of strength decrease was dependent on the fluence level. At the low irradiation level 13.7 ksi was lost; 20.4 ksi at medium irradiation; and 21.4 ksi at high irradiation, due to the temperature increase.

Fracture strength was also affected by test temperature, but the interaction with irradiation was not significant. Increasing the test temperature from 1510°R to 1660°R resulted in a loss of 15.5 ksi fracture strength.

The yield strength at 0.2% offset indicated little effect due to test temperature or irradiation considered separately, but a significant interaction was detected. The yield strengths are equal at 1510°R and 1660°R for unirradiated controls, with a 7% loss at 3×10^{18} n/cm² < 0.48eV, due to increased test temperature appearing at the higher levels of irradiation.

3. Irradiation and Strain Rate

Elongation was significantly ($\geq 95\%$ confidence) affected by both strain rate and fluence. Elongation averaged 7.2% higher for 0.1300 in/in/min than for 0.0013 in/in/min. Elongation decreased by an average of 3.5% when irradiation was 2×10^{17} n/cm² < 0.48eV.

Reduction of area was also significantly affected by the strain rate with an increase of 13.6% at 0.1300 in/in/min over the mean value at 0.0013 in/in/min.

The ultimate strength was affected by strain rate and its interaction with fluence. The ultimate strength averaged 10.3 ksi higher at 0.1300 in/in/min over the mean value at 0.0013 in/in/min. No effect on ultimate strength was detected at the higher strain rate, while a loss of

5.3 ksi was found due to irradiation.

Fracture strength was affected by strain rate and interacted with fluence. The mean fracture strength was 7.2 ksi higher at the 0.1300 in/in/min strain rate. The fracture strength increased 6.7 ksi due to irradiation at 0.1300 in/in/min, while no change due to fluence was noted at 0.0013 in/in/min.

No effect on yield strength was detected over the range of strain rate and fluence.

D. WASPALOY STRESS-RUPTURE TESTS

1. Analysis

The data were analyzed by analysis of variance to determine whether any of the parameters, (time to failure, elongation, and reduction of area) were significantly affected by the irradiation environment. The nature of any significant effect was determined from the study of contrasts. The minimum creep rate was found to be constant at all fluence levels and 3-sigma limits were calculated.

The contrasts are shown in Table A-12, Contrasts of Means (Differences and Percentages), Stress-Rupture Waspaloy. These data are shown graphically in Table 18 Waspaloy, and Figure 11-Waspaloy Table 19 Waspaloy is a summary of alleffects indicating significant changes and direction of change.

A tabulation of the standard deviations of homogeneous groups of property data is shown in Table A-14.

TABLE 18
EFFECT OF TEST CONDITIONS ON STRESS-RUPTURE PROPERTIES ⁽²⁾ OF WASPALOY CONTRAST OF MEANS (DIFFERENCES & PERCENTAGES)

	MEAN DIFFERENCES & 95% CONFIDENCE LIMITS																	
	TIME TO FAILURE, HR						ELONGATION, %						REDUCTION OF AREA, %					
	-																	

(1) COMPARISONS ARE SECOND CONDITION COMPARED TO FIRST CONDITION

(2) STRESS: 105 KSI

TEMPERATURE: 1660°R

FLUENCE LEVELS: CONTROL = NO IRRADIATION
 LOW 6.0×10^{15} n/cm² (E 0.48 ev)
 MEDIUM = 1.4×10^{17} n/cm²
 HIGH = 2.1×10^{18} n/cm²

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TABLE 19SUMMARY - EFFECTS OF TEST CONDITIONS
ON STRESS-RUPTURE PROPERTIES OF WASPALOY⁽²⁾

Contrast (1)	Time to Failure	Elongation	Reduction of Area
Control vs Mean of Irradiated	--	--	--
Control vs Low Fluence Level	--	--	--
Control vs Medium Fluence Level	--	--	--
Control vs High Fluence Level	--	--	--
Low vs Medium Fluence Level	0	0	0
Low vs High Fluence Level	0	0	0
Medium vs High Fluence Level	0	0	0

(1) Comparisons are second condition compared to first conditions

(2) + significant increase at 95% confidence level

-- significant decrease at 95% confidence level

0 no significant effect

2. Irradiation

The time to failure, elongation, and reduction of area were significantly ($\geq 95\%$ confidence) decreased by irradiation. Although the irradiated specimens were significantly different from the control specimens for the above properties, no difference due to range of fluence from 6×10^{15} to 10^{18} n/cm² $>0.48\text{eV}$ was discernible. The irradiated specimens failed 41 hours sooner than the controls, which failed at 105 hours, on the average. The mean elongation dropped from 13.9% to 7.0% upon irradiation. The reduction of area decreased from 19.4% for controls to a mean value of 12.7% for irradiated specimens.

E. INCONEL 718 STRESS-RUPTURE TESTS

1. Analysis

The data were analyzed by analysis of variance to determine if any of the parameters, (time to failure, elongation, and reduction of area) were significantly affected by the irradiation environment. The nature of any significant effect was determined from the study of contrasts. The minimum creep rate was found to be constant at all fluence levels and 3-sigma limits were calculated.

The contrasts are shown in Table A-13, Contrast of Means (Differences and Percentages), Stress-Rupture Inconel 718. These data are shown graphically Table 20-Inconel 718, and Figure 12 Inconel 718. Table 21-Inconel 718 is a summary of all effects indicating significant changes and direction of change.

A tabulation of the standard deviations of homogeneous groups of property data is shown in Table A-14.

TABLE 20
EFFECT OF TEST CONDITIONS ON STRESS-RUPTURE PROPERTIES ⁽²⁾ OF INCONEL 718
CONTRAST OF MEANS (DIFFERENCES & PERCENTAGES)

CONTRAST ⁽¹⁾	MEAN DIFFERENCES & 95% CONFIDENCE LIMITS																																									
	TIME TO FAILURE, HR												ELONGATION, %												REDUCTION OF AREA, %																	
	-						+						-						+						-						+											
	60	40	20	0	20	40	60	6	4	2	0	2	4	6	9	6	3	0	3	6	9																					
CONTROL VS MEAN OF IRRADIATED																																										
CONTROL VS LOW FLUENCE LEVEL																																										
CONTROL VS MEDIUM FLUENCE LEVEL																																										
CONTROL VS HIGH FLUENCE LEVEL																																										
LOW VS MEDIUM FLUENCE LEVEL																																										
LOW VS HIGH FLUENCE LEVEL																																										
MEDIUM VS HIGH FLUENCE LEVEL																																										
	PERCENT DIFFERENCE & 95% CONFIDENCE LIMITS																																									
	TIME TO FAILURE, HR												ELONGATION, %												REDUCTION OF AREA, %																	
	120						80						40						0						40						80						120					
	120	80	40	0	40	80	120	120	80	40	0	40	80	120	60	40	20	0	20	40	60																					
CONTROL VS MEAN OF IRRADIATED																																										
CONTROL VS LOW FLUENCE LEVEL																																										
CONTROL VS MEDIUM FLUENCE LEVEL																																										
CONTROL VS HIGH FLUENCE LEVEL																																										
LOW VS MEDIUM FLUENCE LEVEL																																										
LOW VS HIGH FLUENCE LEVEL																																										
MEDIUM VS HIGH FLUENCE LEVEL																																										

(1) COMPARISONS ARE SECOND CONDITION COMPARED TO FIRST CONDITION

(2) STRESS: 110 KSI

TEMPERATURE: 1660°R

FLUENCE LEVELS: CONTROL = NO IRRADIATION
 LOW = 6.4×10^{15} n/cm² (E 0.48 ev)
 MEDIUM = 1.0×10^{17} n/cm²
 HIGH = 2.3×10^{18} n/cm²

TABLE 21

SUMMARY EFFECTS OF TEST CONDITIONS
ON STRESS-RUPTURE PROPERTIES OF INCONEL 718⁽²⁾

Contrast ⁽¹⁾	Time to Failure	Elongation	Reduction of Area
Control vs Mean of Irradiated	0	--	--
Control vs Low Fluence Level	0	0	0
Control vs Medium Fluence Level	0	--	0
Control vs High Fluence Level	--	--	--
Low vs Medium Fluence Level	0	0	0
Low vs High Fluence Level	--	--	0
Medium vs High Fluence Level	0	0	0

(1) Comparisons are second condition compared to first condition

(2) + significant increase at 95% confidence Level

-- significant decrease at 95% confidence level

0 no significant effect

2. Irradiation

The time to failure, elongation, and reduction of area were significantly ($\geq$ 95% confidence) affected by irradiation. The average time to failure for control specimens was 59 hours. The failure time was decreased by 48 hours at the high fluence level. The control specimens exhibited 5.8% elongation on the average and dropped to 0.3% at the high fluence level. Reduction of area decreased from 14.5% for controls to 7.1% at the high fluence level.

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APPENDIX

This Appendix presents detailed test data for the high-temperature alloys Rene 41, Waspaloy, and Inconel 718.

TABLES

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TABLE A-1

TENSILE RESULTS INDIVIDUAL SPECIMENS

RENE 41

CONTROL SPECIMEN								IRRADIATED SPECIMEN								
Specimen Number	Strain Rate (in./in./min)	Test Temp (°R)	TYS (ksi)	TUS (ksi)	FTS (ksi)	Elong. (%)	RA (%)	Specimen Number	Strain Rate (in./in./min)	Test Temp (°R)	TYS (ksi)	TUS (ksi)	FTS (ksi)	Elong. (%)	RA (%)	Neutron Fluence n/cm ² E < 0.48eV
R1 01	0.0013	1660	112.88	157.09	156.77	9.44	13.13	R1 04	0.0013	1660	112.14	140.08	140.08	5.58	14.62	8.60(15)
R1 02			Broke on Loading					R1 05			117.63	157.57	157.57	6.50	12.49	8.80(15)
R1 03			112.76	161.08	161.08	10.48	14.80	R1 06			114.91	143.24	143.24	5.43	16.75	9.00(15)
R2 07			117.14	164.25	163.93	10.53	13.53									
$\bar{X}$			114.26	160.81	160.59	10.15	13.82	$\bar{X}$			114.89	146.96	146.96	5.84	14.62	
								R1 13	0.0013	1660	117.86	144.55	142.96	4.29	6.57	2.10(17)
								R1 14			114.98	145.28	145.28	4.32	13.81	2.00(17)
								R1 15			112.89	136.42	135.15	3.87	9.83	1.89(17)
								$\bar{X}$			115.24	142.08	141.13	4.16	10.07	
								R1 16	0.0013	1660	115.49	134.48	130.68	3.46	11.70	4.41(18)
								R1 17			116.79	143.13	140.27	3.91	6.68	4.51(18)
								R1 18			115.19	136.7	136.7	3.40	11.08	4.40(18)
								$\bar{X}$			115.82	138.10	135.88	3.59	9.82	
								R2 22	0.013	1660	119.24	146.54	146.39	3.64	17.88	4.29(18)
								R2 23	0.13		116.97	159.00	159.00	11.62	15.50	4.10(18)
								R2 24	0.13		118.20	160.60	160.60	11.20	18.28	3.90(18)
								$\bar{X}$			117.59	159.80	159.80	11.41	16.89	
R2 08	0.0013	1860	112.40	120.73	114.00	3.01	9.19	R2 10	0.0013	1860	117.49	121.32	118.13	0.80	3.70	9.20(15)
R2 09			112.10	120.63	104.21	6.39	10.93	R2 11			113.73	115.32	101.66	3.03	4.16	9.20(15)
R2 26			111.93	119.2	103.35	5.76	8.41	R2 12			117.07	121.67	117.54	1.12	8.96	9.00(15)
$\bar{X}$			112.14	120.19	107.19	5.05	9.51	$\bar{X}$			116.10	119.44	112.44	1.65	5.61	
								R2 19	0.0013	1860	114.23	114.54	107.06	1.63	4.84	1.78(17)
								R2 20			114.05	117.99	111.68	0.700	4.83	1.66(17)
								R2 21			116.58	117.53	114.82	0.687	9.57	1.51(17)
								$\bar{X}$			114.95	116.69	111.19	1.01	6.41	

TABLE A-2
TENSILE RESULTS INDIVIDUAL SPECIMENS
WASPALOY

CONTROL SPECIMEN								IRRADIATED SPECIMENS								
Specimen Number	Strain Rate (in./in./min)	Test Temp (°R)	TYS (ksi)	TUS (ksi)	FTS (ksi)	Elong. (%)	RA (%)	Specimen Number	Strain Rate (in./in./min)	Test Temp (°R)	TYS (ksi)	TUS (ksi)	FTS (ksi)	Elong. (%)	RA (%)	Neutron Fluence n/cm ² E < 0.48eV
W 01	0.0013	1560	99.39	162.39	148.24	26.16	27.99	W 04	0.0013	1560	97.51	157.75	146.43	24.54	26.23	2.27(17)
W 02			97.90	162.83	149.40	27.87	27.39	W 07			101.72	163.01	161.40	19.92	21.95	2.51(17)
W 03			97.55	157.55	134.77	31.94	35.08	W 10			96.32	157.47	147.93	24.41	23.18	2.73(17)
$\bar{X}$			98.28	160.92	144.14	28.66	30.15	$\bar{X}$			98.52	159.41	151.92	22.96	23.79	
W 12	0.0013	1660	98.21	135.65	105.09	27.67	38.08	W 17	0.0013	1660	100.56	137.99	126.44	17.52	22.17	8.8(15)
W 13			99.51	138.74	119.13	23.19	29.72	W 18			99.67	139.38	127.64	20.67	23.19	8.6(15)
W 16			99.18	139.38	119.45	22.95	31.25	W 19			97.57	140.44	133.25	16.28	18.59	8.3(15)
$\bar{X}$			98.97	137.92	114.56	24.60	33.02	$\bar{X}$			99.27	139.27	129.11	18.16	21.32	
								W 20	0.0013	1660	Bent on Loading					
								W 21			99.97	132.50	124.88	15.55	19.24	2.80(17)
								W 22			97.72	138.22	128.92	17.72	21.23	2.61(17)
								$\bar{X}$			98.85	135.36	126.90	16.64	20.24	
								W 23	0.0013	1660	98.68	137.03	133.69	13.61	22.57	3.65(18)
								W 24			96.93	136.88	131.88	13.83	18.31	3.40(18)
								W 26			93.42	137.02	132.10	13.65	19.01	3.14(18)
								$\bar{X}$			96.34	136.98	132.56	13.70	19.96	
W 67	0.13	1660	98.62	165.61	162.55	21.54	30.77	W 44	0.13	1660	95.88	160.75	157.56	22.03	29.59	3.80(17)
W 68			98.22	162.20	157.40	22.17	26.53	W 45			95.52	161.07	155.47	22.65	25.95	3.79(17)
W 70			99.39	162.67	156.60	21.65	27.89	W 46			79.34	162.20	162.20	13.04	27.81	3.46(17)
$\bar{X}$			98.74	163.49	158.85	21.79	28.40	$\bar{X}$			90.25	161.34	158.41	19.24	27.78	
W 27	0.0013	1860	85.33	88.21	57.53	21.15	19.62	W 30	0.0013	1860	79.34	83.50	67.50	11.50	16.32	8.10(15)
W 28			81.99	84.56	47.43	22.22	25.31	W 31			86.70	87.66	80.46	7.33	13.09	7.80(15)
W 29			80.62	83.66	51.51	17.82	24.36	W 32			90.35	90.51	78.45	7.74	16.82	7.60(15)
$\bar{X}$			83.65	85.48	52.16	20.40	23.10	$\bar{X}$			85.46	87.22	75.47	8.86	15.41	

TABLE A-2 (CONT'D)
TENSILE RESULTS INDIVIDUAL SPECIMENS
WASPALLOY

CONTROL SPECIMEN								IRRADIATED SPECIMENS								
Specimen Number	Strain Rate (in./in./ min)	Test Temp (°R)	TYS (ksi)	TUS (ksi)	FTS (ksi)	Elong. (%)	RA (%)	Specimen Number	Strain Rate (in./in./ min)	Test Temp (°R)	TYS (ksi)	TUS (ksi)	FTS (ksi)	Elong. (%)	RA (%)	Neutron Fluence n/cm ² E < 0.48 eV
								W 34	0.0013	1860	83.35	85.33	74.76	6.93	13.67	2.40(17)
								W 36			82.29	85.32	79.42	7.44	10.53	2.20(17)
								W 37			86.25	87.06	74.02	6.79	12.10	3.50(17)
								$\bar{X}$			83.96	85.90	76.07	7.05	12.10	
								W 39	0.0013	1860	88.58	88.74	84.72	4.65	7.88	5.60(18)
								W 40			84.51	85.02	84.02	3.91	7.49	6.21(18)
								W 43			86.87	86.71	81.90	2.77	6.43	5.65(18)
								$\bar{X}$			86.65	86.82	83.55	3.78	7.27	

TABLE A-3
TENSILE RESULTS INDIVIDUAL SPECIMENS
INCONEL 718 (L-0.4 ppmB; N-37 ppmB; C-46 ppmB)

CONTROL SPECIMEN								IRRADIATED SPECIMEN								
Specimen Number	Strain Rate (in./in./min)	Test Temp (°R)	TYS (ksi)	TUS (ksi)	FTS (ksi)	Elong. (%)	RA (%)	Specimen Number	Strain Rate (in./in./min)	Test Temp (°R)	TYS (ksi)	TUS (ksi)	FTS (ksi)	Elong. (%)	RA (%)	Neutron Fluence n/cm ² E < 0.48eV
L 05	0.0013	1660	142.41	146.47	136.41	3.51	6.35	L 01	0.0013	1660	141.12	148.46	146.87	1.95	15.58	2.30(17)
L Series	0.002	1660	136	152		10	13	L 02			145.88	152.76	146.52	2.84	10.72	2.36(17)
			135	152		10	14	L 12			146.69	152.76	147.01	2.94	11.74	1.00(17)
			136	147		8	13.7									
$\bar{X}$			135.6	150.3		9.3	13.7	$\bar{X}$			144.56	151.33	146.90	2.58	12.68	
								L 04	0.0013	1660	142.04	142.36	142.36	0.17	15.39	3.40(18)
								L 06			151.00	151.64	146.52	0.57	18.59	3.69(18)
								L 07			143.82	143.82	143.82	0.22	16.43	3.90(18)
								$\bar{X}$			145.62	145.94	144.23	0.32	16.80	
N 02	0.0013	1360	147.87	167.58	153.59	16.36	41.15	N 12	0.0013	1510	147.16	165.40	159.64	9.81	20.39	6.00(15)
N 03			147.50	166.34	144.31	17.43	43.96	N 13			142.57	159.79	156.28	7.36	15.19	5.80(15)
N 08	0.0013	1510	139.02	161.71	156.28	11.84	20.03	N 14			136.60	161.06	156.62	9.11	18.26	7.40(15)
N 10			145.50	159.48	155.66	10.82	21.39	$\bar{X}$			142.11	162.08	157.51	8.76	17.95	
N 11			139.96	161.85	160.27	11.02	21.47	N 15	0.0013	1510	141.08	159.00	151.96	7.19	17.60	1.37(17)
$\bar{X}$			141.49	161.01	157.40	11.23	20.96	N 17			145.47	165.84	162.97	8.58	20.35	1.29(17)
								N 19			149.27	168.08	165.22	7.48	17.93	1.42(17)
								$\bar{X}$			145.27	164.31	160.05	7.75	18.63	
								N 20	0.0013	1510	145.98	165.03	159.31	6.90	13.31	2.44(18)
								N 21			144.16	161.71	156.28	6.33	17.9	2.30(18)
								N 23			149.95	169.32	168.05	7.42	19.16	2.24(18)
								$\bar{X}$			146.70	165.35	161.21	6.88	16.80	
N 04	0.0013	1585	146.42	159.15	156.93	7.01	17.19	N 05	0.0013	1585	140.26	153.71	151.15	4.82	15.31	1.53(17)
N 58			136.29	150.90	148.99	5.16	14.14	N 06			140.69	153.42	151.51	3.70	13.51	1.50(17)
								N 07			136.96	152.82	151.86	4.02	10.11	1.41(17)
$\bar{X}$			141.36	155.03	152.96	6.09	15.67	$\bar{X}$			139.30	153.32	151.51	4.18	12.98	

TABLE A-3 (CONT'D)
TENSILE RESULTS INDIVIDUAL SPECIMENS
INCONEL 718 (L-0.4 ppmB; N-37 ppmB; C-46 ppmB)

CONTROL SPECIMEN								IRRADIATED SPECIMEN								
Specimen Number	Strain Rate (in./in./min)	Test Temp (°R)	TYS (ksi)	TUS (ksi)	FTS (ksi)	Elong. (%)	RA (%)	Specimen Number	Strain Rate (in./in./min)	Test Temp (°R)	TYS (ksi)	TUS (ksi)	FTS (ksi)	Elong. (%)	RA (%)	Neutron Fluence n/cm ² E < 0.48eV
N 24	0.0013	1660	142.78	149.46	145.96	5.41	15.91	N 27	0.0013	1660	142.78	149.46	146.28	3.36	9.36	7.70(15)
N 25			137.60	145.84	142.67	3.67	13.85	N 28			142.89	149.27	147.35	2.68	14.27	8.00(15)
N 26			144.26	152.18	147.11	4.68	12.46	N 29			138.65	146.28	144.37	3.00	9.10	8.30(15)
$\bar{X}$			141.55	149.16	145.25	4.59	14.07	$\bar{X}$			141.44	148.34	146.00	3.01	10.91	
								N 30	0.0013	1666	137.10	142.86	140.62	1.85	10.34	1.69(17)
								N 31			137.56	144.92	142.68	2.11	11.67	1.82(17)
								N 32			137.56	143.96	139.16	2.02	5.92	1.94(17)
								$\bar{X}$			137.41	143.91	140.82	1.99	9.31	
								N 33	0.0013	1660	137.01	144.02	140.84	1.52	7.27	2.19(18)
								N 34			137.15	144.80	143.53	1.20	12.87	2.05(18)
								N 35			136.29	142.96	141.37	1.12	6.58	3.18(18)
								$\bar{X}$			136.82	143.93	141.91	1.28	8.91	
N 36	0.13	1660	133.24	152.96	146.28	13.00	25.68	N 41	0.13	1660	143.39	159.32	156.13	8.21	21.16	2.06(17)
N 37			134.06	152.49	146.45	11.69	27.89	N 42			141.01	158.20	152.79	8.43	24.48	2.18(17)
N 39			143.38	162.50	147.85	13.00	28.53	N 43			140.69	155.65	151.83	7.92	23.62	2.25(17)
$\bar{X}$			136.89	155.98	146.86	12.56	27.37	$\bar{X}$			141.70	157.72	153.58	8.19	23.09	
C Series AGC data	0.002	1660	133.0	148.0		10.0	12.2	C 01	0.0013	1660	130.55	142.25	109.06	6.68	15.05	2.36(17)
			129.0	142.0		8.0	8.8	C 02			129.79	138.63	113.68	4.47	10.45	2.30(17)
								C 04			130.51	139.42	116.82	4.35	12.61	2.20(17)
$\bar{X}$			131.00	145.0		9.0	10.5	$\bar{X}$			130.28	140.10	113.1	5.17	12.70	
								C 05	0.0013	1660	130.25	136.60	95.30	3.81	16.90	4.10(18)
								C 08			129.99	136.96	107.16	3.55	14.33	4.30(18)
								$\bar{X}$			130.12	136.78	101.23	3.68	15.62	

TABLE A-4

STRESS-RUPTURE INDIVIDUAL SPECIMENS
WASPALLOY

CONTROL SPECIMENS						IRRADIATED SPECIMENS						
Specimen Number	Test Temp (°R)	Stress (ksi)	Time to Failure (h)	Elong. (%)	RA (%)	Specimen Number	Test Temp (°R)	Stress (ksi)	Time to Failure (h)	Elong. (%)	RA (%)	Neutron Fluence n/cm ² E < 0.48eV
W 47	1660	115	14.5	---	31.0	W 53	1660	105	69.4	7.2	12.7	5.80(15)
W 48		105	61.1	16.8	25.7	W 54		105	64.4	7.4	11.9	6.00(15)
W 50		105-135	105.6	13.4	18.2	W 56		105	77.4	7.0	13.3	6.10(15)
W 72		105-125	103.7	14.3	20.6							
$\bar{X}$			90.1	14.8	21.5	$\bar{X}$			70.4	7.2	12.6	
						W 57	1660	105	73.8	7.3	13.5	1.38(17)
						W 58		105	71.3	8.2	13.3	1.42(17)
						W 60		105	48.7	8.4	13.6	1.50(17)
						$\bar{X}$			64.6	8.0	13.4	
						W 61	1660	105	60.7	5.4	13.5	2.05(18)
						W 62		105	41.4	6.9	13.1	2.12(18)
						W 63		105	66.1	4.9	9.2	2.23(18)
						$\bar{X}$			56.0	5.7	11.9	
WS 01	1860	70-80	24.8	20.8	26.6	WS 03	1860	70	15.7	5.6	9.6	6.20(15)
WS 02		70-80	24.5	27.2	31.4	WS 04		70	12.8	6.4	10.4	6.36(15)
$\bar{X}$			24.7	24.0	29.0	$\bar{X}$			14.3	6.0	10.0	
						WS 05	1860	70	14.2	5.3	9.3	1.53(17)
						WS 06		70	11.9	4.2	5.8	1.58(17)
						$\bar{X}$			13.1	4.8	7.6	

TABLE A-5

STRESS-RUPTURE INDIVIDUAL SPECIMENS
INCONEL 718 (N-37 ppmB; L-0.4 ppmB)

CONTROL SPECIMENS						IRRADIATED SPECIMENS						
Specimen Number	Test Temp (°R)	Stress (ksi)	Time to Failure (h)	Elong. (%)	RA (%)	Specimen Number	Test Temp (°R)	Stress (ksi)	Time to Failure (h)	Elong. (%)	RA (%)	Neutron Fluence n/cm ² E < 0.48eV
N 44	1660	115	29.1	3.0	9.6	N 47	1660	110	49.9	4.1	13.9	6.39(15)
N 45		110	69.4	6.9	15.1	N 48		110	66.5	3.9	9.6	6.40(15)
N 46		110	54.7	7.2	16.5	N 49		110	50.1	--	10.9	6.40(15)
N 57		110	51.9	3.3	11.9							
$\bar{X}$			58.7	5.3	14.5	$\bar{X}$			55.5	4.0	11.5	
						N 50	1660	110	41.2	1.1	9.5	1.02(17)
						N 51		110	38.3	1.7	9.5	1.03(17)
						N 52		110	28.9	1.1	11.4	1.06(17)
						$\bar{X}$			36.1	1.3	10.1	
						N 53	1660	110	11.8	0.3	7.0	2.29(18)
						N 55		110	8.2	0.5	5.6	2.32(18)
						N 56		110	13.2	0.2	8.7	2.37(18)
						$\bar{X}$			11.1	0.3	7.1	
						L 08	1660	110	51.8	3.3	8.8	6.37(15)
						L 03	1660	110	5.0	0.3	6.9	2.40(17)
						L 11		110	38.2	1.7	19.0	1.03(17)
						L 13		110	51.7	2.0	8.4	1.28(17)
						$\bar{X}$			45.0	1.9	13.7	
NS 01	1760	75	0.2	0.0	--	NS 03	1760	75	21.3	0.4	---	6.40(15)
NS 02		75-110	29.8	10.9	14.2	NS 04		75-95	26.5	---	---	6.39(15)
NS 07		75-110	29.7	25.7	26.1							
$\bar{X}$			29.8	18.3	20.2	$\bar{X}$			23.9	---	---	
						NS 05	1760	75	1.9	0.1	---	1.60(17)
						NS 06		75	0.8	0.1	---	1.58(17)
						$\bar{X}$			1.4	0.1	---	

TABLE A-6
CONTRACT OF MEANS, RENE 41
FLUENCE/TEST TEMPERATURE EXPERIMENT
(Differences & Percentages)

Contrast (1)	MEAN DIFFERENCE AND 95% CONFIDENCE LIMITS ⁽²⁾				
	Ultimate Stress, ksi ± 13.2	Yield Stress, ksi ± 5.6	Elongation, % ± 2.7	Reduction of Area, % ± 7.1	Fracture Stress, ksi ± 18.9
Mean 1660°R Test vs Mean 1860°R Test	-31.2*	-0.4	-4.1*	-5.6	-39.4*
Control vs Medium Level Irrad. (1660°R)	-18.7*	+1.0	-5.9*	-3.7	-19.4*
Control vs Low Level Irrad. (1660°R)	-13.8*	+0.6	-4.3*	+0.8	-13.6
Low vs Medium Level Irrad. (1660°R)	-4.9	+0.4	-1.6	-4.5	-5.8
Control vs Medium Level Irrad. (1860°R)	-3.5	+2.8	-4.1*	-3.1	+4.1
Control vs Low Level Irrad. (1860°R)	-0.8	+4.0	-3.5*	-3.9	+5.3
Low vs Medium Level Irrad. (1860°R)	-2.7	-1.2	-0.6	+0.8	-1.2
1660°R vs 1860°R (Control)	-40.6*	-2.1	-5.0*	-4.3	-53.5*
1660°R vs 1860°R (Low Level Irrad.)	-27.6*	+1.2	-4.2*	-9.0*	-34.6*
1660°R vs 1860°R (Medium Level Irrad.)	-25.4*	-0.3	-3.2*	-3.7	-30.0*
	PERCENT DIFFERENCE AND 95% CONFIDENCE LIMITS ⁽²⁾				
Mean 1660°R Test vs Mean 1860°R Test	-20.8±8.8*	-0.3±4.9	-61.2±40.0*	-43.8±55.5	-26.3±12.6*
Control vs Medium Level Irrad. (1660°R)	-11.6±8.2*	+0.9±4.9	-58.4±26.7*	-26.8±51.4	-12.1±11.8*
Control vs Low Level Irrad. (1660°R)	-8.5±8.2*	+0.6±4.9	-42.6±26.7*	-5.8±51.4	-8.5±11.8
Low vs Medium Level Irrad. (1660°R)	-3.3±9.0	+0.3±4.9	-27.6±46.6	-30.8±48.6	-3.9±12.9
Control vs Medium Level Irrad. (1860°R)	-2.9±11.0	+2.5±5.0	-80.4±52.9*	-32.6±74.7	+3.8±17.6
Control vs Low Level Irrad. (1860°R)	-0.7±11.0	+3.6±5.0	-68.6±52.9*	-41.1±74.7	+4.9±17.6
Low vs Medium Level Irrad. (1860°R)	-2.3±11.1	-1.0±4.8	-37.5±168.8	+14.3±126.8	-1.1±16.8
1660°R vs 1860°R (Control)	-25.2±8.2*	-1.9±4.9	-49.5±26.7*	-31.1±51.4	-33.3±11.8*
1660°R vs 1860°R (Low Level Irrad.)	-18.8±9.0*	+1.1±4.9	-72.4±46.6*	-61.6±48.6*	-23.5±12.9*
1660°R vs 1860°R (Medium Level Irrad.)	-17.9±9.3*	-0.3±4.9	-76.2±64.3*	-36.6±70.3	-21.2±13.4*

(1) Comparisons are second condition compared to first condition.

(2) Significant contrasts at the 95% confidence level indicated by asterisk.

TABLE A-7

POOLED STANDARD DEVIATIONS FOR VARIOUS TENSILE PROPERTIES
OF RENE 41

PROPERTY	STANDARD DEVIATION	DEGREES OF FREEDOM
Ultimate Stress	4.82 ksi	12
0.2% Offset Yield Stress	2.08 ksi	14
Elongation	1.01 %	14
Reduction of Area	2.65 %	14
Fracture Stress	6.90 ksi	12

TABLE A-8
CONTRAST OF MEANS, WASPALOY
FLUENCE TEST TEMPERATURE EXPERIMENT

Contrast ⁽¹⁾	MEAN DIFFERENCE AND 95% CONFIDENCE LIMITS ⁽²⁾				
	Ultimate Stress, ksi ± 6.9	Yield Stress, ksi ± 7.7	Elongation % ± 6.0	Reduction of Area % ± 8.0	Fracture Stress, ksi ± 15.3
Control vs Medium Fluence (1560°R)	-1.5	+0.2	-5.8	-6.1	+7.8
Control vs Low Fluence (1660°R)	+1.4	+0.3	-6.4*	-11.7*	+14.5
Control vs Med Fluence (1660°R)	-2.5	+0.1	-8.0*	-12.8*	+12.3
Low vs High Fluence (1660°R)	-2.3	-3.0	-4.5	-1.3	+3.5
Control vs Low Fluence (1860°R)	+1.7	+2.9	-11.6*	-7.7	+23.5*
Control vs Med. Fluence (1860°R)	+0.4	+1.4	-13.4*	-11.0*	+24.1*
Low vs High Fluence (1860°R)	-0.4	+1.2	-5.0	-8.1*	+8.0
Mean Irrad. (1660°R) vs Mean Irrad. (1860°R)	-56.6*	-12.8*	-9.6*	-8.4*	-51.2*
Control vs Mean Irrad. (1660°R)	-0.7	-0.8	-8.4*	-12.5*	+14.9
Control vs Mean Irrad. (1860°R)	+1.1	+2.8	-13.9*	-11.5*	+26.4*
1560°R vs 1660°R (Control)	-23.0*	+0.7	-4.1	+2.8	-29.5*
1660°R vs 1860°R (Control)	-52.4*	-16.4*	-4.2	-9.9*	-62.6*
Mean (1560°R) vs Mean (1660°R)	-22.8*	0.0	-7.5*	-3.4	-22.2*
Mean (1660°R) vs Mean (1860°R)	-51.1*	-13.7*	-8.3*	-9.2*	-54.2*
1560°R vs 1660°R (Med. Fluence)	-24.0*	+0.4	-6.3*	-3.6	-25.0*
1660°R vs 1860°R (Med. Fluence)	-49.5*	-14.9*	-9.6*	-8.1*	-50.8*
	PERCENT DIFFERENCE AND 95% CONFIDENCE LIMITS ⁽²⁾				
Control vs Medium Fluence (1560°R)	-0.9+4.3	+0.2+7.8	-20.2+20.9	-21.2+26.5	+5.4+10.6
Control vs Low Fluence (1660°R)	+1.0+5.0	+0.3+7.8	-29.9+28.0*	-35.5+24.2*	+10.0+13.4
Control vs Med. Fluence (1660°R)	-1.8+5.0	-0.1+7.8	-38.8+29.1*	-38.8+29.1*	+8.5+13.4
Low vs High Fluence (1660°R)	-1.7+5.0	-3.0+7.8	-24.7+33.0	-6.1+37.6	+2.7+11.9
Control vs Low Fluence (1860°R)	+2.0+8.1	+3.5+9.3	-56.9+29.4*	-33.3+34.6	+45.2+29.4*
Control vs Med. Fluence (1660°R)	+0.5+8.1	+1.7+9.3	-65.7+29.4*	-47.6+34.6*	+46.3+29.4*
Low vs High Fluence (1860°R)	-0.5+7.9	+1.4+9.0	-56.8+68.2	-52.6+51.9*	+10.6+20.3
Mean Irrad. (1660°R) vs Mean Irrad. (1860°R)	-41.2+5.0*	-13.0+7.8*	-59.4+37.1*	-43.4+39.0*	-39.5+11.8*

(1) Comparisons are second condition compared to first condition.

(2) Significant contrasts at the 95% confidence level indicated by asterisk.

Fluence Levels: Control = no irradiation
Low = 8.5×10^{15} nvt (E 0.48eV)
Medium = 2.5×10^{17} nvt
High = 3.5×10^{18} nvt

TABLE A-8 (cont'd)
 CONTRAST OF MEANS, WASPALOY
 FLUENCE TEST TEMPERATURE EXPERIMENT

Contrast (1)	PERCENT DIFFERENCE AND 95% CONFIDENCE LIMITS (2)				
	Ultimate Stress, ksi ± 6.9	Yield Stress, ksi ± 7.7	Elongation % ± 6.0	Reduction of Area % ± 8.0	Fracture Stress, ksi ± 15.3
Control vs Mean Irrad. (1660°R)	-0.5±5.0	-0.8±7.8	-34.1±24.4*	-36.4±24.2*	+13.0±13.4
Control vs Mean Irrad. (1860°R)	+1.3±8.1	+3.4±9.3	-68.1±29.4*	-49.8±34.6*	+50.8±29.4*
1560°R vs 1660°R (Control)	-14.3±4.3*	+0.7±7.8	-14.3±20.9	+9.3±26.5	-20.5±10.6*
1660°R vs 1860°R (Control)	-38.0±5.0*	-16.6±7.8*	-17.1± 4.4	-30.0±24.2*	-54.6±13.4*
Mean (1560°R) vs Mean (1660°R)	-14.2±4.3*	0.0±7.8	-29.1±23.3*	-12.5±29.6	+16.7±11.5*
Mean (1660°R) vs Mean (1860°R)	-37.2±5.0*	-13.9±7.8*	-45.4±32.4*	-38.9±33.9*	-43.1±12.2*
1560°R vs 1660°R (Med. Fluence)	-15.1±4.3*	+0.4±7.8	-27.5±26.2*	-15.1±33.6	-16.5±10.1*
1660°R vs 1860°R (Med. Fluence)	-36.6±5.1*	-15.1±7.8*	-57.8±36.1*	-48.8±48.2*	-40.0±12.1*

(1) Comparisons are second condition compared to first condition.

(2) Significant contrasts at the 95% confidence level indicated by asterisk.

Fluence Levels: Control = no irradiation

Low = 8.5×10^{15} nvt (E 0.48eV)

Medium = 2.5×10^{17} nvt

High = 3.5×10^{18} nvt

TABLE A-8 (cont'd)
 CONTRAST OF MEANS, WASPALOY
 STRAIN RATE/FLUENCE EXPERIMENT,
 TESTED AT 1660°R

Contrast (1)	MEAN DIFFERENCE AND 95% CONFIDENCE LIMITS ⁽²⁾				
	Ultimate Stress, ksi ± 5.8	Yield Stress, ksi ± 13.8	Elongation % ± 8.8	Reduction of Area % ± 7.8	Fracture Stress, ksi ± 16.2
1. Means, 0.0013 vs 0.13 in/in/min	+25.8*	-4.5	-0.1	+1.5	+37.9*
2. Means, Control vs Irradiated	- 2.3	-4.3	-5.3	-6.7	+5.9
3. Control vs Irrad. @ 0.0013 in/in/min	- 2.5	-0.1	-8.0	-12.8*	+12.3
4. Control vs Irrad. @ 0.13 in/in/min	- 2.1	-8.5	-2.6	-0.6	-0.5
	PERCENT DIFFERENCE AND 95% CONFIDENCE LIMITS ⁽²⁾				
	Ultimate Stress	Yield Stress	Elongation	Reduction of Area	Fracture Stress
1. Means, 0.0013 vs 0.13 in/in/min	+18.9±4.2*	-4.5±13.9	-0.5±42.7	+5.6±29.3	+31.4±13.4*
2. Means, Control vs Irradiated	-1.5±3.8	-4.3 ±14.0	-22.8±37.9	-21.8±25.4	+4.3±11.8
3. Control vs Irrad. @ 0.0013 in/in/min	-1.8±4.2	-0.1±13.9	-32.5±35.8	-38.8±23.6*	+10.7±14.1
4. Control vs Irrad. @ 0.13 in/in/min	-1.3±3.5	-8.6±14.0	-11.9±40.4	-2.1±27.5	-0.3±10.2

(1) Comparisons are second condition compared to first condition.

(2) Significant contrasts at the 95% confidence level indicated by asterisk.

Irradiation Level, 2.5×10^{17} nvt (e 0.48eV)

TABLE A-9
 POOLED STANDARD DEVIATIONS FOR VARIOUS TENSILE PROPERTIES
 OF WASPALOY

PROPERTY	STANDARD DEVIATION	DEGREES OF FREEDOM
Ultimate Stress	2.38 ksi	19
0.2% Offset Yield Stress	2.65 ksi	19
Elongation	2.07 %	19
Reduction of Area	2.75 %	19
Fracture Stress	5.30 ksi	19

TABLE A-10

CONTRAST OF MEANS, INCONEL 718
FLUENCE/TEST TEMPERATURE EXPERIMENT

Contrast (1)	MEAN DIFFERENCE AND 95% CONFIDENCE LIMITS ⁽²⁾				
	Ultimate Stress, ksi ± 7.9	Yield Stress, ksi ± 9.2	Elongation, % ± 1.8	Reduction of Area, % ± 6.6	Fracture Stress, ksi ± 11.1
Mean at 1510°R vs Mean at 1660°R	-16.8*	-4.6	-6.0*	-7.8*	-15.5*
Controls, 1510°R vs 1660°R	-11.8*	+0.1	-6.6*	-6.9*	-12.1*
Mean irradiated, 1510°R vs 1660°R	-18.5*	-6.1	-5.7*	-8.1*	-16.7*
1510°R, Control vs Mean Irradiated	+2.9	+3.2	-3.4*	-3.2	+2.2
1660°R, Control vs Mean irradiated	-3.8	-3.0	-2.5*	-4.4	-2.4
1510°R, Low Irradiated, vs High Irradiated	+3.2	+4.6	-1.9*	-1.2	+3.8
1660°R, Low irradiated, vs High Irradiated	-4.5	-4.7	-1.7	-1.9	-4.1
Low Irradiated, 1510°R vs 1660°R	-13.7*	-0.6	-5.8*	-7.1	-11.4*
Medium Irradiated, 1510°R vs 1660°R	-20.4*	-7.9	-5.8*	-9.3*	-19.3*
High Irradiated, 1510°R vs 1660°R	-21.4*	-9.9*	-5.6*	-7.8*	-19.3*
	PERCENT DIFFERENCE AND 95% CONFIDENCE LIMITS ⁽²⁾				
Mean at 1510°R vs Mean at 1660°R	-10.3+4.8*	-3.2 ±6.4	-69.0+20.7*	-41.9+35.5*	-9.7+7.0*
Controls, 1510°R vs 1660°R	-7.3+4.9*	+0.1±6.5	-58.9+16.1*	-32.9+31.4*	-7.7+7.1*
Mean irradiated, 1510°R vs 1660°R	-11.3+4.8*	-4.2±6.4	-73.2+23.0*	-45.3+37.1*	-10.5+7.0*
1510°R, Control vs Mean Irradiated	+1.8+4.9	+2.3±6.5	-30.1+16.1*	-15.2+31.4	+1.4+7.1
1660°R, Control vs Mean Irradiated	-2.5+5.3	-2.1±6.5	-54.3+39.1*	-31.0+46.8	-1.7+7.6
1510°R, Low Irradiated, vs High Irradiated	+2.0+4.9	+3.2±6.5	-21.6+20.5*	-6.7+36.7	+2.4+7.1
1660°R, Low Irradiated, vs High Irradiated	-3.0+5.3	-3.3±6.5	-56.7+60.0	-17.4+60.6	-2.8+7.6
Low Irradiated, 1510°R vs 1660°R	-8.5+4.9*	-0.4±6.5	-65.9+20.5*	-39.4+36.7*	-7.2+7.1*
Medium Irradiated, 1510°R vs 1660°R	-12.4+4.8*	-5.4±6.3	-74.4+23.1*	-50.0+35.5*	-12.1+69*
High Irradiated, 1510°R vs 1660°R	-12.9+4.8*	-6.7±6.3*	-81.1+26.1*	-46.4+39.3*	-12.0+6.9*

(1) Comparisons are second condition compared to first condition.

(2) Significant contrasts at the 95% confidence level indicated by asterisk.

Fluence Levels: Control = no irradiation

Low = 7×10^{15} nvt (E 0.48eV)

Medium = 2×10^{17} nvt

High = 3×10^{18} nvt

TABLE A-10 (cont'd)

CONTRAST OF MEANS, INCONEL 718
STRAIN RATE/FLUENCE EXPERIMENT,
TESTED AT 1660°R

Contrast (1)	MEAN DIFFERENCE AND 95% CONFIDENCE LIMITS ⁽²⁾				
	Ultimate Stress, ksi ± 5.2	Yield Stress, ksi ± 9.2	Elongation % ± 1.5	Reduction of Area, % ± 5.0	Fracture Stress, ksi ± 4.9
1. Means, 0.0013 vs 0.13 in/in/min	+10.3*	-0.3	+7.1*	+13.6*	+7.2*
2. Means, Control vs Irradiated	-1.8	+0.3	-3.5*	-4.6	+1.1
3. Control vs Irradiated @ 0.0013 in/in/min	-5.3*	-4.2	-2.6*	-4.8	-4.5
4. Control vs Irradiated @ 0.13 in/in/min	+1.7	+4.8	-4.4*	-4.3	+6.7*
	PERCENT DIFFERENCE AND 95% CONFIDENCE LIMITS ⁽²⁾				
	Ultimate Stress	Yield Stress	Elongation	Reduction of Area	Fracture Stress
1. Means, 0.0013 vs 0.13 in/in/min	+7.0±3.5*	-0.1±6/6	+215.2±45.5*	+115.8±42.7*	+5.0±3.4*
2. Means, Control vs Irradiated	-1.2±3.4	+0.2±6.6	-40.7±17.4*	-21.9±24.1	+0.8±3.4
3. Control vs Irradiated @ 0.0013 in/in/min	-3.6±3.5*	-3.0±6.5	-56.5±32.6*	-34.0±35.5	-3.1±3.4
4. Control vs Irradiated @ 0.13 in/in/min	+1.1±3.3	+3.5±6.7	-34.9±11.9*	-15.7±18.2	+4.6±3.3*

(1) Comparisons are second condition compared to first condition

(2) Significant contrasts at the 95% confidence level indicated by asterisk.

Irradiation Level: 2×10^{17} nvt ($E < 0.48\text{eV}$)

TABLE A-11

POOLED STANDARD DEVIATIONS FOR VARIOUS TENSILE PROPERTIES
OF INCONEL 718

PROPERTY	STANDARD DEVIATION	DEGREES OF FREEDOM
Ultimate Stress	2.80 ksi	16
0.2% Offset Yield Stress	3.25 ksi	16
Elongation	0.65 %	19
Reduction of Area	2.40 %	19
Fracture Stress	4.00 ksi	19

TABLE A-12
CONTRAST OF MEANS, WASPALOY
STRESS-RUPTURE EXPERIMENT

	MEAN DIFFERENCE AND 95% CONFIDENCE LIMITS ⁽²⁾		
	Time to Failure, Hr. ± 26.2	Elongation, % ± 2.7	Reduction of Area % ± 4.8
Control vs Mean of Irradiated	-41.0*	-6.9*	-6.7*
Control vs Low Fluence Level	-34.3*	-6.7*	-6.8*
Control vs Medium Fluence Level	-40.1*	-5.9*	-5.9*
Control vs High Fluence Level	-48.6*	-8.2*	-7.5*
Low vs Medium Fluence Level	- 5.8	+0.8	+0.9
Low vs High Fluence Level	-14.3	-1.5	-0.7
Medium vs High Fluence Level	- 8.5	-2.3	-1.6

	PERCENT DIFFERENCE AND 95% CONFIDENCE LIMITS ⁽²⁾		
Control vs Mean of Irradiated	-39.0±25.0*	-49.9±19.4*	-34.7±24.7*
Control vs Low Fluence Level	-32.8±25.0*	-48.2±19.4*	-35.1±24.7*
Control vs Medium Fluence Level	-38.2±25.0*	-42.4±19.4*	-30.4±24.7*
Control vs High Fluence Level	-46.4±25.0*	-59.0±19.4*	-38.7±24.7*
Low vs Medium Fluence Level	-8.2±37.2	+11.1±37.5	+7.1±38.1
Low vs High Fluence Level	-20.3±37.2	-20.8±37.5	-5.6±38.1
Medium vs High Fluence Level	-13.2±40.6	-28.8±33.8	-11.9±25.6

(1) Comparisons are second condition compared to first condition.

(2) Significant contrasts at the 95% confidence level indicated by asterisk.

Fluence Levels: Control = no irradiation

Low = 6.0×10^{15} nvt (E 0.48eV)

Medium = 1.4×10^{17} nvt

High = 2.1×10^{18} nvt

TABLE A-13

CONTRAST OF MEANS, INCONEL 718
STRESS-RUPTURE EXPERIMENT

Contrast ⁽¹⁾	MEAN DIFFERENCE AND 95% CONFIDENCE LIMITS ⁽²⁾		
	Time to Failure, Hr. ± 26.2	Elongation, % ± 2.7	Reduction of Area % ± 4.8
Control vs Mean of Irradiated	-24.5	-3.9*	-4.9*
Control vs Low Fluence Level	-3.2	-1.8	-3.0
Control vs Medium Fluence Level	-22.6	-4.5*	-4.4
Control vs High Fluence Level	-47.6*	-5.5*	-7.4*
Low vs Medium Fluence Level	-19.4	-2.7	-1.4
Low vs High Fluence Level	-44.4*	-3.7*	-4.4
Medium vs High Fluence Level	-25.9	-1.0	-2.9
	PERCENT DIFFERENCE AND 95% CONFIDENCE LIMITS ⁽²⁾		
Control vs Mean of Irradiated	-41.7±44.6	-67.8±46.6*	-34.0±33.1*
Control vs Low Fluence Level	-5.5±44.6	-31.0±46.6	-20.7±33.1
Control vs High Fluence Level	-38.5±44.6	-77.6±46.6*	-30.3±33.1
Control vs High Fluence Level	-81.1±44.6*	-94.8±46.6*	-51.0±33.1*
Low vs Medium Fluence Level	-35.0±47.2	-67.5±67.5	-12.2±41.7
Low vs High Fluence Level	-80.0±47.2*	-92.5±67.5*	-38.3±41.7
Medium vs High Fluence Level	-69.3±72.6	-76.9±207.7	-29.0±48.0

(1) Comparisons are second condition compared to first condition.

(2) Significant contrasts at the 95% confidence level indicated by asterisk.

Temperature: 1660°R

Stress: 110 ksi

Fluence Levels: Control = no irradiation

Low = 6.4×10^{15} nvt (E 0.48eV)

Medium = 1.0×10^{17} nvt

High = 2.3×10^{18} nvt

TABLE A-14

STANDARD DEVIATIONS FOR VARIOUS STRESS-RUPTURE
PROPERTIES OF WASPALOY AND INCONEL 718

PROPERTY	STANDARD DEVIATION	DEGREES OF FREEDOM
Time to Failure	9.17 Hr	15
Elongation	0.93 %	15
Reduction of Area	1.70 %	15

Pooled values for Waspaloy and Inconel 718 are shown.

Test Temperature: 1660°R

Fluence Range: Control thru 10^{18} nvt (E 0.48 eV)

Stress: 105 ksi (Waspaloy)
110 ksi (Inconel 718)