**Westinghouse
Astronuclear
Laboratory**

Carrington

WANL-TME-2791
June, 1971

**NEUTRON IRRADIATION EFFECTS
ON THE TENSILE PROPERTIES OF
INCONEL 718, WASPALOY
AND A-286**

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Subcontract NP-1
CODE IDENT NO. 14683

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INFORMATION CATEGORY

UNCLASSIFIED

R. A. Jones 6-29-71
AUTHORIZED CLASSIFIER DATE

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ABSTRACT

Sheet tensile specimens of three NERVA candidate structural alloys were irradiated at 585°R in the Plum Brook Reactor and subsequently tested at temperatures from 540°R to 1940°R. Thermal and fast neutron fluences as high as 1.5×10^{20} n/cm² and 2×10^{19} n/cm² respectively were obtained. A-286 and Waspaloy exhibited yield strength increases and ultimate strength and elongation decreases at temperatures below 1140°R and severe elongation decreases above 1340°R. The total elongation decreases were much more significant than those of the uniform elongation. Inconel 718 exhibited similar effects except for a slight unexplained decrease in yield strength at all temperatures after irradiation.

None of the alloys appeared to be superior in resistance to high temperature irradiation embrittlement.

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TABLE OF CONTENTS

<u>Section</u>		<u>Page</u>
1.0	TEST PROCEDURE	1
	1.1 Material	1
	1.2 Specimens	1
	1.3 Test Plans	1
	1.4 Irradiation	3
	1.5 Testing	3
2.0	TEST RESULTS	5
3.0	CONCLUSIONS FROM THE STATISTICAL ANALYSIS	7
4.0	DISCUSSION	13
5.0	SUMMARY	21
Appendix A	INCONEL 718 TUBULAR SPECIMEN IRRADIATION	23
	BIBLIOGRAPHY	27

LIST OF ILLUSTRATIONS

<u>Figure</u>		<u>Page</u>
1	Sheet Tensile Specimens	2
2	Change in Yield Strength vs. Fluence at 540°R	8
3	Tensile Properties of Irradiated A-286	9
4	Tensile Properties of Irradiated Inconel 718	10
5	Effect of Thermal Fluence on Total Elongation at 1740°R	11
6	Uniform Elongation vs. Test Temperature Prior to Irradiation	17
7	Uniform Elongation vs. Test Temperature After Irradiation	18
8	Total Elongation Above 1140°R Prior to Irradiation	19
9	Total Elongation Above 1140°R After Irradiation	20
10	Inconel-718 Tubular Specimens	24
11	Inconel-718 Tubular Specimen Elongation Values	25

LIST OF TABLES

<u>Table</u>		<u>Page</u>
1	Material Characterization Data	29
2	Chemical Composition, w/o	30
3	Material Heat Treatment	31
4	Irradiation Conditions	31
5	Inconel 718 Sheet Tensile Data	32
6	Waspaloy Sheet Tensile Data	33
7	A-286 Sheet Tensile Data	34
8	A-286 Sheet 0.2% Offset Yield Strength Average Values (KSI)	35
9	A-286 Sheet Ultimate Strength Average Values	35
10	A-286 Sheet Uniform Elongation Average Values	36
11	A-286 Sheet Total Elongation Average Values	36
12	Inconel 718 Sheet 0.2% Offset Yield Strength Average Values	37
13	Inconel 718 Sheet Ultimate Strength Average Values	38
14	Inconel 718 Sheet Uniform Elongation Average Values	39
15	Inconel 718 Sheet Total Elongation Average Values	40
16	Waspaloy Sheet 0.2% Offset Yield Strength Average Values	41
17	Waspaloy Sheet Ultimate Strength Average Values	41
18	Waspaloy Sheet Uniform Elongation Average Values	42
19	Waspaloy Sheet Total Elongation Average Values	42
20	A-286 Sheet 0.2% Offset Yield Strength 95/99 Limits	43
21	A-286 Sheet Ultimate Strength 95/99 Limits	43
22	A-286 Sheet Uniform Elongation 95/99 Limits	44
23	A-286 Sheet Total Elongation 95/99 Limits	44
24	Inconel 718 Sheet 0.2% Offset Yield Strength 95/99 Limits	45
25	Inconel 718 Sheet Ultimate Strength 95/99 Limits	46

LIST OF TABLES (CONTINUED)

<u>Table</u>		<u>Page</u>
26	Inconel 718 Sheet Uniform Elongation 95/99 Limits	47
27	Irradiated Inconel 718 Sheet Total Elongation 95/99 Limits	48
28	Waspaloy Sheet 0.2% Offset Yield Strength 95/99 Limits	49
29	Waspaloy Sheet Ultimate Strength 95/99 Limits	49
30	Waspaloy Sheet Uniform Elongation 95/99 Limits	50
31	Waspaloy Sheet Total Elongation 95/99 Limits	50
32	Inconel 718 Tube Test Results	51
33	Temperature Conversion Chart	52

INTRODUCTION

The purpose of the experiment was to obtain statistical data for design use and comparative radiation effects information for three NERVA reactor structural material candidates: Inconel 718, Waspaloy and A-286. A statistically designed test plan was used to obtain data over a wide temperature and neutron fluence range with a minimum number of test specimens. In addition, the response of two heat treatments of Inconel 718 and lot-to-lot variation in A-286 to the test conditions were measured.

Inconel 718 and Waspaloy are basically nickel-20% chromium alloys with the first containing 17% iron and the second 14% cobalt. A-286 is iron based, containing 25% nickel and 15% chromium. All three alloys are precipitation hardenable. A comparison of their general metallurgy and application to the NERVA reactors can be found in WANL-TME-1995⁽¹⁾.

Earlier NERVA irradiation tests^(2,3) indicated little room-temperature effects in Inconel 718 although at liquid nitrogen temperatures strength increases and ductility reductions were noted for A-286 and other materials, particularly aluminum and titanium alloys. However, the fluences attained were less than 10^{18} n/cm² ($E > 1$ MeV). Investigations⁽⁴⁾ by others of Type 304 stainless steel showed that tensile property changes could become quite significant at higher fluences. Of particular interest were large reductions in tensile elongations.

At higher test temperatures, above 1500°R*, iron and nickel-based alloys have been found to be embrittled by irradiation^(6,7). NERVA studies⁽⁸⁾ have shown that the embrittlement in Inconel 718 is severe, with elongations less than 1% found at 1750°R.

The test plans used in these experiments were designed primarily to study the high temperature embrittlement phenomena. Thermal fluences ($E < 0.48$ eV) were selected since they have been found to most directly affect this embrittlement. These data will define the upper operating temperature limits of the components due to the embrittlement phenomena

* A temperature conversion chart is shown in Table 33.

and supply useful information for analyzing accidental temperature overshoot conditions. At the same time, the simultaneous fast neutron fluence ($E > 1$ MeV) attained at the highest level is sufficient to give pertinent information at the lower temperatures. These lower temperature (below 1500°R) data are useful since they cover the range in which actual reactor operation will occur. Cryogenic irradiations with subsequent testing at temperatures up to 1000°R and fast fluences of 10^{20} n/cm² are being conducted to better characterize the lower temperature range.

1.0 TEST PROCEDURE

1.1 MATERIAL

All three materials were tested in sheet form. Pertinent identification data and chemistry are given in Tables 1 and 2. Table 3 shows the heat treatment given each type of specimen.

A few tubular specimens of Inconel 718 were included in the irradiation since this is the configuration to be used in the primary axial support system of the NERVA reactor. Details and results of this test are reported separately in Appendix A.

1.2 SPECIMENS

Specimen configuration is shown in Figure 1. A pin loaded design was selected because of ease of remote loading and security of assembly and alignment. Doublers were welded to the specimen heads for support. Specimen thickness was that of the as-received sheet.

Since test machine crosshead movement is used to determine specimen deflection, the entire one-inch reduced section is considered as the gage length. Gage marks or extensometers are generally impractical for this type of testing because of the high temperatures and remote handling. Test machine load-time charts (at constant crosshead speed) are sufficiently accurate for the required data.

1.3 TEST PLANS

Because of the wide range of the test variables of interest, a factorial experimental test plan was designed for each material which considered all combinations of the variable levels. The variables considered for each material test plan were:

- Inconel 718 - (1) heat treatment
- (2) thermal fluence - 0, 10^{18} , 10^{19} and 10^{20} n/cm² ($E < 0.48$ eV)
- (3) test temperature - 540, 740, 940, 1140, 1340, 1540, 1740
and 1940°R

Figure 1. Sheet Tensile Specimen

- Waspaloy - (1) thermal fluence - $0, 10^{18}, 10^{19}$ and 10^{20} n/cm² ($E < 0.48$ eV)
 (2) test temperature - 1140, 1340, 1540 and 1740°R
- A-286 - (1) lot-to-lot variation
 (2) thermal fluence - $0, 10^{18}, 10^{19}$ and 10^{20} n/cm² ($E < 0.48$ eV)
 (3) test temperature - 540, 740, 940, 1140, 1340, 1540, 1740 and 1940°R

In addition, specimens of Waspaloy were tested at 540°R for comparison. Duplications of tests were used for the Waspaloy plan (32 specimens) but only one specimen per condition was used for the other two test plans (64 specimens each). In addition, several spare specimens were included for retesting questionable values or damaged specimens. Specimens of each material were tested separately but a random test order was used within each test plan. Fast fluence levels corresponding to each thermal fluence level were used in interpreting the radiation effects but were not specified in the irradiation plan.

Properties determined were 0.2% offset yield strength, ultimate tensile strength, uniform elongation (plastic deformation at maximum load) and total elongation.

1.4 IRRADIATION

Fluence levels were attained in the LA-1 (highest fluence) and RD-2 (lower fluences) test holes of the 60 MW Plum Brook Reactor (PBR). Pertinent irradiation conditions are shown in Table 4. Actual fluence levels for each specimen are shown in the individual specimen data tables. Cobalt (37.2 barns), nickel (0.40 barns), iron (0.59 barns) and titanium (0.24 barns) flux wires which were irradiated in the horizontal plane of and parallel to the specimen gage lengths were used for flux determination. The estimated uncertainty at the 95% confidence level for the fluence values is $\pm 20\%$. Irradiation conditions were determined and reported by PBR personnel⁽⁹⁾.

Specimens were immersed in the 585°R reactor coolant water during irradiation.

1.5 TESTING

Irradiated specimens were shipped to the Nuclear Aerospace Research Facility (NARF) of the Fort Worth, Texas division of General Dynamics for testing. A 20,000 pound Instron Model TT-D split console tensile testing machine located in the NARF Irradiation

Materials Laboratory (IML) hot cell was used. Temperatures were obtained with a 2000-watt Marshall tube furnace with a dry nitrogen atmosphere. A temperature calibration between the specimen grip assembly and a dummy thermocoupled specimen was made prior to testing at each temperature. The grip temperature was then used to control the furnace temperature during testing. Temperature ramps ranged from 15 minutes at 740°R to 90 minutes at 1940°R with a hold time at temperature of 10 minutes. Crosshead speed during testing was 0.002 inch per minute. Spare specimens in the test plan were tested at conditions for which the preliminary data looked questionable or to extend the original test plan scope. For example, room temperature (540°R) Waspaloy data was not originally planned.

All data shown in this report were obtained from the Instron load-deflection charts. The uniform elongations obtained are chart plastic deflections to maximum load.

Data reduction was by General Dynamics. The raw test data and details of the testing procedures are reported in the literature⁽¹⁰⁾.

2.0 TEST RESULTS

Results are shown in Tables 5, 6 and 7. Each data set was analyzed separately by the WANL Reliability Department to determine the response of the data to the test variables. Details of the analysis can be found elsewhere^(11, 12, 13). Generally, the analysis of variance method was used with responses compared at the 0.05 significance level. Thermal fluence levels were used in the analysis.

Because of the scatter in the fluence values obtained for the A-286 specimens, an analysis of covariance technique and a regression analyses were applied to the test results. However, the most consistent results were obtained from using the analysis of variance method and this is the method used in analyzing all of the data. The resultant adjusted A-286 data are shown in Tables 8 through 11. All analyzed data tables show sample size, "pooled" sample standard deviation and degrees of freedom used.

The analyzed Inconel 718 data are shown in Tables 12 through 15. In this test, the variability in the fluence levels, although very high, did not affect the analyzed data variability. However, the measured responses at the 1740°R and 1940°R temperature levels were less consistent than at the other temperatures and were not included in the analysis of variance results. Average measured values are shown for these conditions. The Waspaloy analyses results are shown in Tables 16 through 19. Again, the fluence variations were not found to be excessive.

The magnitude of the variability in the elongation values appeared to be a function of the nominal value. That is, the variability increases as the magnitude of the elongation increases. These values were, therefore, transformed using a logarithmic transformation wherein the analysis of variance was performed on the values of the logarithm, of the % elongation plus 1. This allows for the fact that elongation average values near zero cannot have large absolute variations. The data reported have been reconverted to percentage values although the standard deviations have not been. The standard deviation thus will be constant when plotted on a logarithmic scale.

NERVA program requirements for the application of materials properties data require the use of a .95/.99 tolerance limit. This requires a confidence of 95% that at least 99% of the distribution would be greater than the limit. These values have been calculated and are given in Tables 20 through 31.

3.0 CONCLUSION FROM THE STATISTICAL ANALYSIS

The following conclusions were drawn from the statistical analysis of the data.

1) Strength values for the two randomly selected lots of A-286 were not significantly different. However, the elongation values were significantly different at the higher test temperatures.

2) For Inconel 718, the 1750°F solution treatment and associated age resulted in higher ultimate strength up to 1740°R and higher total elongation than the 1950°F heat treatment. The yield strength and uniform elongation were not affected by the heat treatment.

3) The yield strength of A-286 and Waspaloy increased significantly after irradiation at test temperature below 1140°R (Figures 2, 3 and 4). Inconel 718 yield strength values decreased slightly with irradiation at all temperatures.

4) All three alloys exhibited significant reductions in ultimate tensile strength with fluence at temperatures up to 1140°F (Figures 3 and 4). Above 1740°F Inconel 718 and Waspaloy again showed a decrease.

5) Waspaloy specimens generally failed without necking (at maximum load) at temperatures below 1540°R and at all temperatures after irradiation to 10^{20} n/cm² ($E < 0.48$ eV). However, no interaction was found between test temperature and fluence for the uniform elongation while the interaction was significant for the total elongation. The uniform elongation was reduced approximately 35% at the highest fluence values at 1140°R and above. Above 1340°R the unirradiated and irradiated values both decreased rapidly. Neither the test temperature nor fluence showed any effect on the total elongation below 1540°R. However, the values decreased rapidly with both fluence and temperature at the higher temperatures with fluence having the more significant effect (Figure 5).

6) For Inconel 718, the uniform elongation decreases slightly as a function of fluence over the entire test temperature range. A similar decrease is found in the total elongation values except that the effect is more pronounced at temperatures above 1540°R (Figures 4 and 5). A minimum in the elongation is found at approximately the 1740°R test temperature.

* ΔP = CHANGE IN PROPERTY
 P_0 = UNIRRADIATED VALUE

Figure 2. Change in Yield Strength vs. Fluence at 540°R

* ΔP = CHANGE IN PROPERTY WITH IRRADIATION
 P_o = UNIRRADIATED VALUE

Figure 3. Tensile Properties of Irradiated A-286

Figure 4. Tensile Properties of Irradiated Inconel 718

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Figure 5. Effect of Thermal Fluence on Total Elongation at 1740°R

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7) The uniform elongation of A-286 is fairly constant up to 1340°R above which it drops rapidly. After irradiation a slight embrittlement is found at all test temperatures but particularly at 740°R and 940°R and above 1340°R. The decrease is approximately 50% at 1540°R and the highest fluence. At the higher test temperature the effect is more variable with indications of an increase at the 10^{18} n/cm² level but decreases at higher fluences.

Unlike the other two alloys A-286 does not show a serious total elongation decrease at the higher temperatures before irradiation. Little effect of fluence is noted up to 1340°R. However, at higher temperatures the values decrease rapidly with fluence with the maximum embrittlement found at 1740°R.

4.0 DISCUSSION

The property changes due to irradiation at the lower test temperatures are primarily the result of lattice displacement damage caused by the bombarding high energy (fast) neutrons displacing atoms from their normal lattice positions. The resultant random concentration of vacancies and interstitials is thermodynamically unstable and will "anneal out" with thermal activation. With increasing temperature the annealing will go through various stages such as recombination of close pairs, accumulation of both types of defects into increasingly larger clusters and, annihilation at sinks such as grain boundaries and inclusions. Billington and Crawford⁽¹⁴⁾ have reviewed the annealing stages in copper and Kelly⁽¹⁵⁾ has reviewed the proposed mathematical models for annealing.

Prior to annealing, the radiation induced defects are effective in impeding dislocation motion and thus raise the yield strength. Kelly⁽¹⁵⁾ has recently reviewed the various proposed mechanisms for this effect.

Figure 3 shows the fractional changes in properties for A-286 at temperatures between 540°R and 1340°R at the highest fluence value. The yield strength is found to increase significantly with increasing temperature up to about 940°R. In the next 200°R range the property almost completely recovers. The increase is tentatively credited to redistribution of the defect size spectrum. That is, as the defects coalesce and grow they are more effective in impeding dislocation movement. Above 940°R several mechanisms are suggested for the rapid recovery: (1) the number of defects decreases very rapidly because of coalescence, (2) activation energy is available for defect annealing at sinks and (3) activation energy is available for dislocations to break away from the defects. Further low temperature irradiations including annealing studies which are now underway may provide additional information on these effects.

The uniform elongation changes nearly identically to the yield strength except that the property decreases with irradiation rather than increases. One possible explanation is that in the hardened matrix, deformation is inhomogeneous on a microscale. That is, as the stress increases, plastic deformation eventually occurs but is excluded from regions where the dislocation density is very high due to the irradiation. This shows up as a lower gross uniform elongation.

The elongation which occurs during necking, as approximated by the total elongation minus the uniform elongation, is not significantly affected by irradiation at the lower test temperature.

Figure 3 shows that the ultimate tensile strength decreases with irradiation but, unlike that for the elongation and yield strength, the effect is greatest at the lowest test temperature (540°R). The property recovers with increasing temperature and is the same as the unirradiated at 1340°R. The decrease in ultimate tensile strength is not well understood and, in fact, many materials show significant increases at low temperatures^(16, 17).

The lower temperature irradiation effects in Waspaloy are not as well defined since no specimens were tested between 540°R and 1140°R. At 540°R the effects are similar to those in A-286 except that the elongation showed almost no change with irradiation. At 1140°R there were no strength changes but the irradiation had reduced the uniform elongation by 20% at 10^{19} n/cm², ($E > 1$ MeV).

The fractional property changes in Inconel 718 shown in Figure 4 are radically different than those found for the other two alloys. The yield strength decreases with fluence to about 95% of its original value at 6.8×10^{18} n/cm², $E > 1$ MeV, for all test temperatures (Figure 2). This anomaly is as yet unexplained. Levine⁽⁸⁾ reported a slight increase (~5%) in yield strength at room temperature for Inconel 718 bar material irradiated to 4×10^{18} n/cm² ($E > 1$ MeV) in the same PBR environment. This effect is much smaller than that found for the other alloys in this test.

As expected, the uniform elongation of Inconel 718 decreased with fluence at room temperature. However, the effect did not increase with temperature as did the A-286 nor anneal out above 940°R. The elongation effect is presumably related to the yield strength decrease and is similarly unexplained.

Except for the decrease in yield strength for Inconel 718 (which is very small) none of the irradiation effects noted for the three alloys at the fluence levels tested and at temperatures up to 1340°R will be detrimental to their application in NERVA. Strength increases are favorable, and the elongation, though degraded, is still sufficient.

The low temperature radiation effects discussed above are caused by lattice disruption due to fast neutron bombardment. The property changes resulting from this disruption will recover at sufficiently high temperatures. At 1340°R and above, the data indicate that all three alloys are much more seriously embrittled by neutron irradiation than at the lower temperatures. Actually, previous extensive studies^(3, 8, 19, 20) by many laboratories have shown that both nickel and iron-base alloys are subject to irradiation embrittlement at these temperatures. The primary purpose of the present studies was to characterize this effect in the three NERVA alloys. Particularly, the degree of embrittlement and the temperature at which it may become serious are of interest since these will set the upper operating temperature limit for the materials.

Claudson⁽¹⁸⁾ has demonstrated that for Inconel 718 and presumably other alloys which are metallurgically stable at the irradiation temperature, lower irradiation temperatures result in a conservative estimate of the degree of embrittlement found in the high temperature tests. Since the NERVA exposure times and temperatures are limited to these conditions, the more practical PBR coolant water conditions were used in the irradiation. This also allowed the lower temperature tests to be included in the same irradiation plan.

The high temperature embrittlement has been found to be associated with intergranular failure. This is the normal failure mode for all three of the alloys tested above 1340°R. A slow tensile strain rate was selected since this also promotes intergranular failure.

At higher test temperatures, grain boundaries weaken relative to the grain matrix to the point that with applied stress they tend to slide over one another in an attempt to rearrange and thus relieve the stress. Cracks are then nucleated at boundary intersection points and at protrusions on the boundary surfaces. These eventually link up and lead to failure. Measured elongation is low because the stresses needed for grain boundary sliding are less than those for matrix deformation so that very little gross deformation occurs.

Most investigators have attributed the radiation promotion of grain boundary failure, and thus further embrittlement to the formation of helium bubbles on the grain boundaries. The helium is a transmutation product of boron when bombarded with a thermal neutron ($B^{10}(n, \alpha) Li^7$). Boron has a very high thermal neutron capture cross section and is segregated

at the grain boundaries. Various mechanisms for the boron effect have been reviewed by Studt, Dixon and Baciarelli⁽²¹⁾. At the fluence levels attained in this test, helium promotion of grain boundary crack growth is the most likely mechanism of irradiation enhanced embrittlement. However, at higher fast fluences, transmutation of the other constituents elements to form helium⁽²²⁾ or dislocation loops and voids⁽²³⁾, all of which will limit ductility by hardening the matrix, may cause embrittlement.

In the present tests there was no appreciable decrease in yield strength or ultimate tensile strength after irradiation and testing at high temperature for A-286 and Waspaloy. However, for Inconel 718 both heat treatments exhibited the yield strength decrease noted for the low temperature tests. The ultimate tensile strength also decreases slightly at 1940°R for the 1750°F solution treated material and seriously at 1740°R (10%) and 1940°R (31%) for the 1950°F heat treated material.

The uniform elongation of all three materials both unirradiated (Figure 6) and irradiated (Figure 7) showed extensive embrittlement. Irradiation decreased the property only slightly except at 1540°R. However, the total elongations are reduced to a much greater extent. Prior to irradiation (Figure 8) A-286 showed high ductility and only a minor embrittlement between 1540°R and 1740°R. The embrittlement of Waspaloy was initiated at a much higher temperature than Inconel 718 and to a much greater extent than A-286. Inconel 718 was severely embrittled even without irradiation. The minimum ductility was less than 3% for the 1950°F solution treated material at about 1740°R.

Rather unexpectedly after irradiation to $1.4 \times 10^{20} \text{ n/cm}^2$ ($E < 0.48 \text{ eV}$) the total elongation (Figure 9) were all very similar. The embrittlement begins between 1140°R and 1340°R and reaches the 2% elongation level at $1640^\circ\text{R} \pm 10^\circ\text{R}$ for all three alloys. The primary effect of fluence was to eliminate any necking strain; thus the irradiated uniform and total elongation curves are very similar, particularly at the highest temperatures. At this level of irradiation none of the materials appears to be superior except that Inconel 718 elongation reached zero while the other materials retained a slight ability to plastically deform.

Figure 6. Uniform Elongation vs. Test Temperature Prior to Irradiation

Figure 7. Uniform Elongation vs. Test Temperature After Irradiation

Figure 8. Total Elongation Above 1140°R Prior to Irradiation

Figure 9. Total Elongation Above 1140°R After Irradiation

5.0 SUMMARY

Tensile specimens of sheet A-286, Waspaloy and Inconel 718 were irradiated to fluence levels of 10^{19} n/cm², $E > 1$ MeV and 10^{20} n/cm², $E < 0.48$ eV and then tested over the temperature range 540°R to 1940°R. At the lower test temperatures, yield strengths increased and ultimate strengths and elongations decreased. The exception was Inconel 718 which exhibited a yield strength decrease over the entire test temperature range. All of these effects are relatively minor and would not affect NERVA operation to the fluences obtained. The property changes found are credited to lattice displacement damage and appear to recover between 1140°R and 1340°R.

Above 1340°R a serious reduction in tensile elongation is found. Elongation values approach zero for all three materials at 1740°R. While uniform elongation values are reduced only slightly, almost no necking elongation occurs. Although the unirradiated total elongations at the higher temperatures are very different between the three alloys, after irradiation they are very similar, with none offering any particular advantage.

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APPENDIX A

INCONEL 718 TUBULAR SPECIMEN IRRADIATION

Seven thin-walled tubular specimens of Inconel 718 were irradiated in the PBR and tested with four control specimens at temperatures between 1140°R and 1740°R to determine if application geometry might affect the characteristics of the expected high temperature embrittlement in this alloy. The specimen design is shown in Figure 10. Irradiation and testing procedures were identical to those for the Inconel 718 sheet specimens reported earlier. Heat treatment consisted of a 1750°F solution treatment and the associated age as shown in Table 3. Although the target fluence for all irradiated specimens was 1×10^{19} n/cm² ($E < 0.48$ eV), the actual measured fluences varied by over an order of magnitude.

Tensile results are shown in Table 32, and the total elongation plotted versus temperature in Figure 11. The differences between the tubular and sheet data are that the tube elongations are much lower initially at the lower test temperatures, and the irradiated specimen tested at 1740°R retained fairly high ductility. The tubular specimen had 6.1% uniform elongation while the sheet data at a similar fluence level indicate about a 3% value. The 1640°R irradiated elongation value is relatively high, but the fluence it received was also very low.

Because of the scarcity of data and the large variability, no definite conclusions as to specimen configuration effects can be made. However, the data do show that the thin wall application design should not promote a more severe embrittlement nor lower the embrittlement temperature.

Figure 10. Inconel-718 Tubular Specimens

Figure 11. Inconel 718 Tubular Specimen Elongation Values

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TABLE 1

MATERIAL CHARACTERIZATION DATA

<u>Material</u>	<u>Specification</u>	<u>Supplier</u>	<u>Heat Number</u>	<u>Grain** Size</u>	<u>Sheet Thickness - in.</u>
Waspaloy	----	Hamilton Precision Metals	VD115		0.010
Inconel 718*	WANL PDS 30030-1 Rev. A	Latrobe Steel Company	C50026	#8	0.022
A-286	AMS 5525-C	Allegheny Ludlum Steel Corp.	90456	#6	0.032
A-286	AMS 5525-C	Allegheny Ludlum Steel Corp.	82312	#7	0.034

* Lescalloy 718 Vac Arc, Registered Trademark of the Latrobe Steel Co.

** ASTM No.

TABLE 2
CHEMICAL COMPOSITION, w/o

	<u>Waspaloy</u>	<u>Inconel 718</u>	<u>A-286 (90456)</u>	<u>A-286 (82312)</u>
Al	1.51	0.47	0.16	0.16
Cr	20.35	18.61	15.1	15.2
C	0.06	0.03	0.04	0.05
Cu	< 0.05	0.02		
Fe	< 0.05	Bal.	Bal.	Bal.
Mn	< 0.10	0.07	1.49	1.50
Ni	Bal.	52.28	25.4	25.7
Si	< 0.20	0.09	0.40	0.53
S	0.01	0.008	0.003	0.003
Ti	2.95	0.97	2.12	2.05
Mo	4.00	2.89	1.25	1.38
B	0.003	0.004	0.006	0.006
Zr	0.05			
P		0.004	< 0.01	< 0.01
Ta		0.07		
Cb		5.00		
V			0.30	0.31
Co	14.00	0.07		

TABLE 3
MATERIAL HEAT TREATMENT

<u>Material</u>	<u>Solution Heat Treatment</u>		<u>Age</u>	
	<u>Temperature</u>	<u>Time</u>	<u>Temperature</u>	<u>Time</u>
Waspaloy	1950°F	30 min. AC*	1550°F	4 hrs. AC
			1400°F	16 hrs. AC
Inconel 718	1750°F	1 hr. AC	1325°F	8 hrs. FC**
			1150°F	8 hrs. AC
Inconel 718	1950°F	1 hr. AC	1400°F	10 hrs. FC
			1200°F	8 hrs. AC
A-286	1800°F	30 min. AC	1325°F	16 hrs. AC

* Air Cool

** Furnace cool at rate of 100°F/hr to next aging temperature.

TABLE 4
IRRADIATION CONDITIONS

<u>Material</u>	<u>PBR Power Cycle</u>	<u>Irradiation Time</u>	<u>Total MW Hours</u>
Inconel 718	103	417 hrs.	844
Waspaloy	100	506 hrs.	989
A-286	105	355 hrs.	838
	106	357 hrs.	891

TABLE 5

INCONEL 718 SHEET TENSILE DATA

Specimen No.	Heat Treatment T	Thermal Fluence (E < 0.49 eV) n/cm	Fast Fluence (E > 1 MeV) n/cm	Test Temperature R	Yield Strength KSI	Ultimate Strength KSI	Uniform Elongation %	Total Elongation %
716	1730	0	0	540	167.8	205.2	20.1	24.3
934	1930	0	0	540	169.9	197.9	18.0	18.8
702	1730	0	0	740	166.2	198.6	17.3	19.4
924	1930	0	0	740	157.2	188.3	14.5	14.8
707	1730	0	0	940	157.3	193.6	14.1	18.7
913	1930	0	0	940	157.2	186.1	15.7	17.0
713	1730	0	0	1140	155.4	187.6	14.9	17.4
909	1930	0	0	1140	147.8	177.3	17.0	19.1
736	1730	0	0	1340	154.0	182.3	15.5	18.1
915	1930	0	0	1340	146.9	170.6	13.8	14.6
733	1730	0	0	1540	152.3	166.7	6.9	9.2
935	1930	0	0	1540	139.0	162.7	7.2	7.2
711	1730	0	0	1740	117.5	120.0	0.7	15.1
705	1730	0	0	1740	119.9	122.5	0.7	6.8
917	1930	0	0	1740	125.3	128.0	0.6	2.8
722	1730	0	0	1940	54.5	57.1	0.8	25.5
918	1930	0	0	1940	55.5	63.9	2.4	9.0
916**	1930	0	0	1940	61.7	71.6	3.8	3.8
714	1730	3.1 (18)*	3.2 (16)	540	164.8	200.2	17.4	17.4
932	1930	10.1 (18)	6.1 (16)	540	163.9	194.3	13.3	13.3
719	1730	2.6 (18)	2.9 (16)	740	164.0	197.0	16.2	18.9
906	1930	7.7 (18)	5.4 (16)	740	152.0	187.5	13.6	13.6
706	1730	2.4 (18)	2.7 (16)	940	156.5	190.3	16.9	19.3
922	1930	7.1 (18)	5.0 (16)	940	149.2	178.9	16.4	17.6
727	1730	1.8 (18)	2.3 (16)	1140	153.6	183.3	17.0	20.8
929	1930	5.3 (18)	4.3 (16)	1140	148.2	172.5	17.5	17.5
721	1730	1.7 (18)	2.6 (16)	1340	150.9	184.0	16.6	19.4
903	1930	4.7 (18)	4.1 (16)	1340	145.3	172.3	11.6	12.8
715	1730	1.4 (18)	1.8 (16)	1540	142.8	162.9	3.7	7.6
928	1930	3.7 (18)	3.4 (16)	1540	136.5	157.5	4.9	4.9
738	1730	2.3 (18)	2.7 (16)	1740	112.4	115.2	0.6	3.4
902	1930	7.0 (18)	5.0 (16)	1740	116.6	116.6	0.0	0.0
936**	1930	7.0 (18)	5.0 (16)	1740	121.6	121.6	0.0	0.0
734	1730	2.3 (18)	2.7 (16)	1940	57.0	58.7	0.8	1.4
709**	1730	2.3 (18)	2.7 (16)	1940	55.4	59.2	0.9	0.9
912	1930	7.0 (18)	5.0 (16)	1940	53.4	53.4	0.0	0.0
731	1730	1.54 (19)	7.3 (16)	540	166.1	201.6	17.2	17.2
701**	1730	1.08 (19)	5.9 (16)	540	169.6	201.3	19.4	21.7
920	1930	1.96 (19)	12.0 (16)	540	160.1	189.9	13.6	13.6
927**	1930	1.34 (19)	9.2 (16)	540	161.9	194.1	17.0	17.0
710	1730	1.2 (19)	6.1 (16)	740	160.3	192.6	16.4	18.4
905	1930	1.49 (19)	10.0 (16)	740	162.9	185.4	11.6	11.6
735	1730	1.08 (19)	5.9 (16)	940	161.8	193.5	19.4	22.5
933	1930	1.35 (19)	9.3 (16)	940	150.0	180.5	15.5	16.6
725	1730	0.83 (19)	4.7 (16)	1140	149.5	187.3	16.7	21.3
908	1930	1.01 (19)	7.9 (16)	1140	144.8	174.7	15.0	18.4
708	1730	0.75 (19)	4.5 (16)	1340	146.6	178.5	15.7	19.9
910	1930	0.92 (19)	7.7 (16)	1340	145.6	170.9	12.2	13.4
730	1730	0.58 (19)	4.1 (16)	1540	144.0	164.5	3.7	8.0
901	1930	0.71 (19)	6.6 (16)	1540	144.4	162.1	3.5	4.2
723	1730	1.08 (19)	5.9 (16)	1740	110.9	116.0	2.0	2.0
926	1930	1.34 (19)	9.3 (16)	1740	121.4	123.6	0.6	0.6
720	1730	1.08 (19)	5.9 (16)	1940	51.2	54.0	0.7	1.2
930	1930	1.34 (19)	9.3 (16)	1940	48.2	48.2	0.0	0.0
728	1730	3.0 (20)	10.0 (18)	540	161.3	183.9	11.9	15.0
911	1930	1.4 (20)	6.8 (18)	540	160.2	179.6	11.3	12.8
729	1730	3.0 (20)	10.0 (18)	740	157.0	178.2	13.9	17.2
921	1930	1.4 (20)	6.8 (18)	740	151.4	169.1	12.1	14.3
724	1730	3.0 (20)	10.0 (18)	940	149.9	170.9	14.0	18.2
923	1930	1.4 (20)	6.6 (18)	940	148.3	167.6	14.7	17.2
717	1730	3.0 (20)	10.0 (18)	1140	139.8	172.1	15.5	20.1
925	1930	1.4 (20)	6.8 (18)	1140	138.8	166.3	17.3	19.6
712	1730	3.0 (20)	10.0 (18)	1340	137.6	180.8	17.0	22.1
914	1930	1.4 (20)	6.8 (18)	1340	141.5	170.9	15.7	19.3
732	1730	3.5 (20)	13.0 (18)	1540	137.5	163.3	3.4	3.4
704**	1730	0.61 (20)	2.8 (18)	1540	145.5	171.2	4.9	4.9
907	1930	1.6 (20)	8.0 (18)	1540	137.4	157.5	3.4	3.4
726	1730	0.61 (20)	2.8 (18)	1740	116.9	119.3	0.5	1.0
904	1930	0.61 (20)	2.8 (18)	1740	115.0	115.0	0.0	0.0
919**	1930	0.71 (20)	3.4 (18)	1740	93.8	93.8	0.0	0.0
703	1730	0.61 (20)	2.8 (18)	1940	49.7	49.7	0.0	0.0
931	1930	0.61 (20)	2.8 (18)	1940	34.2	34.2	0.0	0.0

* 3.1 (18) = 3.1×10^{18}

** Not used in statistical analysis

TABLE 6
WASPALOY SHEET TENSILE DATA

Specimen No.	Thermal Fluence ($E < 0.48$ eV) (n/cm ²)	Fast Fluence ($E > 1$ MeV) (n/cm ²)	Test Temperature (°R)	0.2% Offset Yield Strength (KSI)	Ultimate Strength (KSI)	Uniform Elongation (KSI)	Total Elongation (%)
779	0	0	540	112.7	185.7	22.7	22.7
770*	0	0	1140	135.7	173.0	17.7	17.7
763	0	0	1140	109.1	177.8	24.0	24.0
762	0	0	1140	99.1	172.6	22.3	22.3
776	0	0	1340	109.5	170.6	21.7	21.7
741	0	0	1340	107.0	174.6	21.6	21.6
767	0	0	1540	101.2	163.1	15.6	23.4
750	0	0	1540	121.8	166.7	12.5	19.7
765	0	0	1740	97.2	106.3	1.2	11.0
761	0	0	1740	99.2	109.5	2.9	11.9
752	1.3 (18)	1.9 (16)	540	119.0	182.5	18.3	18.3
747	1.3 (18)	1.9 (16)	1140	107.5	177.0	22.8	22.8
778	1.3 (18)	1.9 (16)	1140	106.0	175.0	22.5	22.5
759	1.3 (18)	1.9 (16)	1340	99.2	168.3	18.8	18.8
746	1.3 (18)	1.9 (16)	1340	102.0	169.4	22.9	23.4
777*	1.7 (18)	2.5 (16)	1540	103.2	134.9	3.8	4.2
773	1.8 (18)	2.7 (16)	1540	102.4	169.8	18.7	18.7
748	1.4 (18)	1.9 (16)	1540	101.2	159.5	13.5	20.2
742	7.9 (17)	1.4 (16)	1740	100.8	108.7	3.3	5.3
775	8.7 (17)	1.5 (16)	1740	101.2	109.1	1.1	5.3
754	1.0 (19)	4.7 (16)	540	120.6	178.6	17.0	17.0
774	0.8 (19)	4.3 (16)	540	119.0	178.6	18.7	18.7
753	0.5 (19)	3.6 (16)	1140	107.5	172.6	22.4	22.4
740	0.5 (19)	3.6 (16)	1140	107.2	172.7	24.5	25.2
743	0.9 (19)	4.5 (16)	1340	105.6	172.6	23.5	23.5
771	0.9 (19)	4.5 (16)	1340	110.3	172.6	20.3	20.3
772	0.8 (19)	4.5 (16)	1540	106.7	165.5	16.8	18.3
760	0.8 (19)	4.5 (16)	1540	104.4	168.6	8.6	8.6
756	1.2 (19)	5.9 (16)	1740	100.4	107.5	1.6	3.4
766	1.1 (19)	5.2 (16)	1740	100.4	111.9	2.1	2.1
749	1.1 (20)	1.1 (19)	540	136.9	167.4	22.1	22.1
758	1.8 (20)	1.1 (19)	1140	96.4	171.8	22.7	23.7
745	1.8 (20)	1.1 (19)	1140	96.4	171.4	19.8	19.8
755	1.8 (20)	1.1 (19)	1340	110.3	171.9	22.8	22.8
744	1.8 (20)	1.1 (19)	1340	103.2	159.9	15.9	15.9
769	1.0 (20)	0.9 (19)	1540	109.9	159.1	8.6	8.6
751*	1.0 (20)	0.9 (19)	1540	129.8	158.7	5.8	5.8
768	0.8 (20)	0.8 (19)	1540	104.0	146.0	6.3	6.3
764	1.0 (20)	0.9 (19)	1740	100.0	100.0	0.2	0.2
757	1.0 (20)	0.9 (19)	1740	103.2	110.7	1.0	1.0

* Not used in statistical analysis.

TABLE 7
A-286 SHEET TENSILE DATA

Specimen No.	Lot	Thermal Fluence (E < 0.48 eV) (n/cm ²)	Fast Fluence (E > 1 MeV) (n/cm ²)	Test Temperature °R	0.2% Offset Yield Strength KSI	Ultimate Strength KSI	Uniform Elongation %	Total Elongation %
16	A*	0	0	540	99.4	155.8	23.3	27.1
84	B**	0	0	540	100.6	151.5	22.5	26.3
2	A	0	0	740	99.3	139.5	19.4	21.2
74	B	0	0	740	91.1	141.5	19.9	21.9
7	A	0	0	940	91.4	139.5	23.0	24.4
43	B	0	0	940	91.7	141.5	20.1	22.2
13	A	0	0	1140	94.5	139.3	24.2	25.9
87	B	0	0	1140	94.3	139.0	18.5	22.6
5	A	0	0	1340	86.6	132.3	24.1	25.6
65	B	0	0	1340	102.8	135.4	18.8	20.7
33***	A	0	0	1540	65.2	119.6	14.1	18.3
36	A	0	0	1540	87.2	115.7	19.7	22.4
85	B	0	0	1540	87.5	112.8	14.4	40.0
11	A	0	0	1740	83.4	85.5	0.6	21.3
67	B	0	0	1740	74.1	74.7	0.5	33.0
22	A	0	0	1940	30.3	30.3	0.3	34.9
68	B	0	0	1940	31.4	31.6	0.3	34.4
14	A	1.04 (18)	1.8 (16)	540	96.6	151.0	23.7	27.2
88	B	1.02 (18)	1.6 (16)	540	99.8	152.4	22.7	27.3
19	A	1.33 (18)	2.0 (16)	740	92.3	142.3	20.7	23.0
56	B	1.25 (18)	2.1 (16)	740	94.6	142.6	20.3	22.6
6	A	2.03 (18)	2.5 (16)	940	91.8	139.2	23.7	25.3
72	B	1.34 (18)	2.1 (16)	940	89.9	139.0	20.8	22.0
27	A	1.44 (18)	2.0 (16)	1140	91.4	137.4	21.4	24.1
79	B	1.66 (18)	2.3 (16)	1140	89.6	138.6	19.9	23.6
21***	A	2.51 (18)	0	1340	100.4	133.9	9.9	12.2
29	A	1.84 (18)	2.5 (16)	1340	87.0	128.4	22.2	24.9
53	B	1.79 (18)	2.5 (16)	1340	86.1	132.0	18.5	20.3
15	A	1.47 (18)	2.2 (16)	1540	90.9	114.2	12.4	16.9
78	B	2.2 (18)	3.0 (16)	1540	85.0	115.7	8.8	8.8
18	A	1.47 (18)	2.2 (16)	1740	63.0	77.5	2.1	5.0
52	B	1.4 (18)	2.1 (16)	1740	73.5	75.2	0.5	1.6
34	A	1.47 (18)	2.2 (16)	1940	27.6	29.4	5.4	24.7
62	B	1.4 (18)	2.1 (16)	1940	32.4	35.1	1.2	6.1
31***	A	0.65 (19)	6.4 (16)	540	89.8	148.8	25.5	28.4
1	A	0.96 (16)	8.0 (16)	540	105.3	151.5	16.7	20.1
70***	B	0.68 (19)	7.1 (16)	540	122.5	148.2	19.2	22.5
83	B	1.01 (19)	9.0 (16)	540	103.4	147.0	22.9	25.9
10	A	1.23 (19)	9.2 (16)	740	101.8	142.3	22.3	24.3
55	B	0.9 (19)	8.3 (16)	740	95.5	140.9	20.0	25.4
35	A	0.85 (19)	7.6 (16)	940	90.0	139.2	26.4	27.8
90	B	0.97 (19)	8.7 (16)	940	89.6	141.0	20.2	23.3
25	A	1.35 (19)	1.0 (17)	1140	92.4	136.2	22.7	24.9
58	B	1.27 (19)	1.1 (17)	1140	87.8	135.6	19.7	22.1
8	A	0.96 (19)	8.0 (16)	1340	92.7	130.5	23.7	25.1
60	B	1.38 (19)	1.1 (17)	1340	86.6	133.6	17.7	21.6
38	A	1.74 (19)	1.1 (17)	1540	88.7	111.3	8.6	12.1
89	B	1.77 (19)	1.2 (17)	1540	84.5	110.7	7.3	8.4
23	A	0.92 (19)	8.0 (16)	1740	79.7	80.9	0.6	5.4
76	B	1.01 (19)	9.0 (16)	1740	74.1	74.1	0.0	0.0
39	A	0.96 (19)	8.0 (16)	1940	35.2	35.4	0.4	6.7
80	B	1.01 (19)	9.0 (16)	1940	31.2	33.0	0.7	2.0
28	A	1.2 (20)	1.0 (19)	540	122.9	139.3	21.8	25.8
61	B	2.8 (20)	2.0 (19)	540	108.2	129.8	19.8	24.1
37	A	1.7 (20)	1.6 (19)	740	114.6	132.0	15.7	18.0
69	B	2.7 (20)	2.0 (19)	740	114.2	132.1	16.9	20.1
24	A	3.0 (20)	2.5 (19)	940	111.6	132.0	19.7	24.2
13	B	2.6 (20)	2.0 (19)	940	112.5	135.7	13.8	16.8
4	A	1.5 (20)	1.4 (19)	1140	100.6	137.0	22.0	23.1
75	B	2.5 (20)	2.0 (19)	1140	91.7	136.1	20.2	22.0
12	A	2.4 (20)	1.7 (19)	1340	88.8	129.0	22.6	25.2
64	B	0.61 (20)	6.2 (19)	1340	100.6	135.4	16.0	17.5
32	A	2.7 (20)	1.9 (19)	1540	84.6	111.5	9.2	10.5
57	B	0.62 (20)	1.9 (19)	1540	83.9	110.5	5.6	5.6
26	A	2.5 (20)	1.5 (19)	1740	80.0	81.3	0.6	0.9
54	B	0.62 (20)	6.2 (18)	1740	75.1	75.1	0.0	0.0
17	A	1.4 (20)	1.2 (19)	1940	31.4	32.5	1.9	2.5
66	B	0.63 (20)	6.2 (19)	1940	25.7	25.7	0.2	1.5

* Allegheny Ludlum Heat No. 90456

** Allegheny Ludlum Heat No. 82312

*** Not used in statistical analysis

TABLE 8
A-286 SHEET 0.2% OFFSET YIELD STRENGTH AVERAGE VALUES (KSI)

Test Temperature °R	Fluence (n/cm ²)				E > 1 MeV E < 0.48 eV
	0	2.2×10^{16} 1.5×10^{18}	0.9×10^{17} 1.1×10^{19}	1.5×10^{19} 1.6×10^{20}	
540	100.0	98.20	104.35	115.55	
740	95.20	93.45	98.65	114.40	
940	91.55	90.85	89.80	112.05	
1140	94.40	90.50	90.10	96.15	
1340	94.70	86.55	89.65	94.70	
1540	87.35	87.95	86.60	84.25	
1740	78.75	68.25	76.90	77.55	
1940	30.85	30.00	33.20	28.55	

 $\bar{X}$ has sample size of n = 2

s = 4.42 KSI with degrees of freedom f = 31

TABLE 9
A-286 SHEET ULTIMATE STRENGTH AVERAGE VALUES (KSI)

Test Temperature °R	Fluence (n/cm ²)				E > 1 MeV E < 0.48 eV
	0	2.2×10^{16} 1.5×10^{18}	0.9×10^{17} 1.1×10^{19}	1.5×10^{19} 1.6×10^{20}	
540	153.65	151.70	149.25	134.55	
740	140.50	142.75	141.60	132.05	
940	140.50	139.10	140.10	133.85	
1140	139.15	138.00	135.90	136.55	
1340	133.85	130.20	132.05	132.20	
1540	114.25	114.95	111.00	111.00	
1740	80.10	76.35	77.50	78.20	
1940	30.95	32.25	34.20	29.10	

 $\bar{X}$ has sample size of n = 2

s = 2.90 KSI with degrees of freedom f = 31

TABLE 10

A-286 SHEET UNIFORM ELONGATION AVERAGE VALUES

(Values were Obtained Using $\log_{10} (\% + 1.0)$, then Converted to %)

Test Temperature °R	Fluence (n/cm^2)				E > 1 MeV E < 0.48 eV
	0	2.2×10^{16} 1.5×10^{18}	0.9×10^{17} 1.0×10^{19}	1.5×10^{19} 1.6×10^{20}	
540	22.9	23.2	19.6	20.8	
740	19.7	20.5	21.1	16.3	
940	21.5	22.2	23.1	16.5	
1140	21.2	20.6	21.1	21.1	
1340	21.3	20.3	20.5	19.0	
1540	16.8	10.5	7.93	7.20	
1740	0.55	1.16	0.26	0.26	
1940	0.30	2.75	0.54	0.87	

 $\bar{X}$ has sample size of $n = 2$ s (on log scale) = 0.087 with degrees of freedom
 $f = 31$

TABLE 11

A-286 SHEET TOTAL ELONGATION AVERAGE VALUES

(Values were Obtained Using $\log_{10} (\% + 1.0)$, then Converted to %)

Test Temperature °R	Fluence (n/cm^2)				E > 1 MeV E < 0.48 eV
	0	2.2×10^{16} 1.5×10^{18}	0.9×10^{17} 1.0×10^{19}	1.5×10^{19} 1.6×10^{20}	
540	26.7	27.3	22.8	24.9	
740	21.5	22.8	24.8	19.0	
940	23.3	23.6	25.4	20.2	
1140	24.2	23.8	23.4	22.6	
1340	23.0	22.5	23.3	21.0	
1540	29.9	12.3	10.1	7.71	
1740	26.5	2.95	1.53	0.38	
1940	35.6	12.5	3.81	1.96	

 $\bar{X}$ has sample size of $n = 2$ s (on log scale) = 0.145 with degrees of freedom
 $f = 31$ s' (on log scale and including between lot differences) = 0.163 with effective degrees of freedom $f' = 13$

TABLE 12
INCONEL 718 SHEET 0.2% OFFSET YIELD STRENGTH AVERAGE VALUES (KSI)

Test Temperature °R	1750°F Heat Treatment				
	Fluence (n/cm ²)				
	0	3.7×10^{16}	7.3×10^{16}	6.8×10^{18}	E > 1 MeV
	0	3.7×10^{18}	1.1×10^{19}	1.5×10^{20}	E < 0.48 eV
540	170.24	166.63	167.33	161.05	
740	164.85	161.25	161.95	155.66	
940	159.75	156.15	156.85	150.56	
1140	153.22	149.61	150.31	144.02	
1340	152.03	148.42	149.12	142.84	
1540	147.72	144.11	144.81	138.52	
1740	119.90*	112.40*	110.90*	116.90*	
1940	54.50*	57.00*	51.20*	49.70*	

Test Temperature °R	1950°F Heat Treatment				
	Fluence (n/cm ²)				
	0	3.7×10^{16}	7.3×10^{16}	6.8×10^{18}	E > 1 MeV
	0	3.7×10^{18}	1.1×10^{19}	1.5×10^{20}	E < 0.48 eV
540	166.14	162.53	163.23	156.95	
740	160.75	157.14	157.84	151.56	
940	155.65	152.04	152.74	146.46	
1140	149.11	145.50	146.20	139.92	
1340	147.92	144.32	145.02	138.73	
1540	143.61	140.00	140.70	134.42	
1740	125.30*	116.60*	121.40*	115.00*	
1940	55.50*	53.40*	48.20*	34.20*	

$\bar{X}$ has sample size of n = 8

s = 3.10 KSI with degrees of freedom f = 38

* Individual test values (not averages).

TABLE 13

INCONEL 718 SHEET ULTIMATE STRENGTH AVERAGE VALUES (KSI)

Test Temperature °R	1750°F Heat Treatment				
	Fluence (n/cm ²)				E > 1 MeV E < 0.48 eV
	0	3.7×10^{16}	7.3×10^{16}	6.8×10^{18}	
	0	3.7×10^{18}	1.1×10^{19}	1.5×10^{20}	
540	205.68	201.38	199.88	185.88	
740	197.58	196.38	193.13	177.78	
940	193.98	188.73	191.13	173.38	
1140	186.58	182.03	185.13	173.33	
1340	180.58	182.28	178.83	179.98	
1540	168.83	164.33	167.43	164.63	
1740	122.50*	115.20*	116.00*	119.30*	
1940	57.10*	58.70*	54.00*	49.70*	

Test Temperature °R	1950°F Heat Treatment				
	Fluence (n/cm ²)				E > 1 MeV E < 0.48 eV
	0	3.7×10^{16}	7.3×10^{16}	6.8×10^{18}	
	0	3.7×10^{18}	1.1×10^{19}	1.5×10^{20}	
540	197.42	193.12	191.62	177.62	
740	189.32	188.12	184.87	169.52	
940	185.72	180.47	182.87	165.12	
1140	178.32	173.77	176.87	165.07	
1340	172.32	174.02	170.57	171.72	
1540	160.57	156.07	159.17	156.37	
1740	128.00*	116.60*	123.60*	115.00*	
1940	63.90*	53.40*	48.20*	34.20*	

 $\bar{X}$ has sample size of n = 2

s = 2.23 KSI with degrees of freedom f = 23

* Individual test values (not averages)

TABLE 14
INCONEL 718 SHEET UNIFORM ELONGATION AVERAGE VALUES

 (Values were Obtained Using $\log_{10} (\%+1.0)$, then Converted to %)

1750°F Heat Treatment					
Test Temperature °R	Fluence (n/cm^2)				E > 1 MeV E < 0.48 eV
	0	3.7×10^{16}	7.3×10^{16}	6.8×10^{18}	
	0	3.7×10^{18}	1.1×10^{19}	1.5×10^{20}	
540	17.8	15.9	15.2	14.3	
740	16.9	15.1	14.5	13.6	
940	18.9	16.9	16.2	15.2	
1140	19.2	17.2	16.5	15.5	
1340	17.3	15.5	14.8	13.9	
1540	5.32	4.69	4.47	4.16	
1740	0.70*	0.60*	2.00*	0.50*	
1940	0.80*	0.80*	0.70*	0.00*	

1950°F Heat Treatment					
Test Temperature °R	Fluence (n/cm^2)				E > 1 MeV E < 0.48 eV
	0	3.7×10^{16}	7.3×10^{16}	6.8×10^{18}	
	0	3.7×10^{18}	1.1×10^{19}	1.5×10^{20}	
540	16.3	14.6	13.9	13.1	
740	15.5	13.8	13.2	12.4	
940	17.3	15.5	14.8	13.9	
1140	17.6	15.8	15.1	14.2	
1340	15.8	14.1	13.5	12.7	
1540	4.81	4.24	4.03	3.74	
1740	0.60*	0.00*	0.60*	0.00*	
1940	2.40*	0.00*	0.00*	0.00*	

 $\bar{X}$ has sample size of $n = 8$
 s (on log scale) = 0.061 with degrees of freedom $f = 38$

* Individual test values (not averages).

TABLE 15

INCONEL 718 SHEET TOTAL ELONGATION AVERAGE VALUES

(Values were Obtained Using $\log_{10} (\%+1.0)$, then Converted to %)

1750°F Heat Treatment					
Test Temperature °R	Fluence (n/cm^2)				E > 1 MeV E < 0.48 eV
	0	3.7×10^{16} 3.7×10^{18}	7.3×10^{16} 1.1×10^{19}	6.8×10^{18} 1.5×10^{20}	
540	19.9	17.9	17.9	16.9	
740	19.4	17.5	17.5	16.5	
940	22.4	20.2	20.2	19.1	
1140	23.5	21.3	21.2	20.0	
1340	21.0	19.0	18.9	17.9	
1540	7.06	6.32	6.31	5.92	
1740	6.80*	3.40*	2.00*	1.00*	
1940	25.5*	0.00*	1.20*	0.00*	
1950°F Heat Treatment					
Test Temperature °R	Fluence (n/cm^2)				E > 1 MeV E < 0.48 eV
	0	3.7×10^{16} 3.7×10^{18}	7.3×10^{16} 1.1×10^{19}	6.8×10^{18} 1.5×10^{20}	
540	15.9	14.4	14.3	13.5	
740	15.5	14.0	14.0	13.2	
940	18.0	16.2	16.2	15.3	
1140	18.9	17.0	17.0	16.1	
1340	16.8	15.2	15.2	14.3	
1540	5.53	4.93	4.92	4.61	
1740	2.80*	0.00*	0.60*	0.00*	
1940	9.0*	0.00*	0.00*	0.00*	

 $\bar{X}$ has sample size of $n = 8$ s (on log scale) = 0.070 with degrees of freedom $f = 38$

* Individual test values (not averages)

TABLE 16

WASPALLOY SHEET 0.2% OFFSET YIELD STRENGTH AVERAGE VALUES (KSI)

Test Temperature $\bar{O}_R$	Yield* Strength KSI
1140	103.65
1340	105.89
1540	106.45
1740	100.30

$\bar{X}$ has sample size of $n = 8$

$s = 4.96$ KSI with degrees of freedom $f = 25$

* Test results were not affected by fluence

TABLE 17

WASPALLOY SHEET ULTIMATE STRENGTH AVERAGE VALUES (KSI)

Test Temperature $\bar{O}_R$	Fluence (n/cm^2)				
	0	1.9×10^{16}	4.5×10^{16}	1.0×10^{19}	
	0	1.2×10^{18}	0.8×10^{19}	1.3×10^{20}	$E > 1 \text{ MeV}$ $E < 0.48 \text{ eV}$
1140	175.49	174.94	175.84	169.19	
1340	171.61	171.06	171.96	165.31	
1540	163.91	163.36	164.26	157.61	
1740	109.59	109.04	109.64	103.29	

$\bar{X}$ has sample size of $n = 8$

$s = 4.25$ KSI with degrees of freedom $f = 25$

TABLE 18

WASPALLOY SHEET UNIFORM ELONGATION AVERAGE VALUES

(Values were Obtained Using $\log_{10} (\% + 1.0)$, then Converted to %)

Test Temperature °R	Fluence (n/cm^2)				E > 1 MeV E < 0.48 eV
	0	1.9×10^{16} 1.2×10^{18}	4.5×10^{16} 0.8×10^{19}	1.0×10^{19} 1.3×10^{20}	
1140	23.2	25.1	23.8	16.9	
1340	21.6	23.2	21.9	15.6	
1540	13.6	14.0	13.8	7.38	
1740	1.70	1.77	1.73	0.55	

 $\bar{X}$ has sample size of $n = 8$ s (on log scale) = 0.098 with degrees of freedom $f = 25$

TABLE 19

WASPALLOY SHEET TOTAL ELONGATION AVERAGE VALUES

(Values were Obtained Using $\log_{10} (\% + 1.0)$, then Converted to %)

Test Temperature °R	Fluence (n/cm^2)				E > 1 MeV E < 0.48 eV
	0	1.9×10^{16} 1.2×10^{18}	4.5×10^{16} 0.8×10^{19}	1.0×10^{19} 1.3×10^{20}	
1140	23.2	25.1	23.8	21.6	
1340	21.6	23.2	21.9	19.0	
1540	21.5	19.4	18.0	7.38	
1740	11.4	5.30	2.69	0.55	

 $\bar{X}$ has sample size of $n = 2$ s (on log scale) = 0.065 with degrees of freedom $f = 16$

TABLE 20

A-286 SHEET 0.2% OFFSET YIELD STRENGTH

95/99 Lower Limit Values in KSI

Test Temperature °R	Fluence (n/cm ²)				E > 1 MeV E < 0.48 eV
	0	2.2×10^{16} 1.48×10^{18}	0.9×10^{17} 1.11×10^{19}	1.5×10^{19} 1.58×10^{20}	
540	83.42	81.62	87.77	98.97	
740	78.62	76.87	82.07	97.82	
940	74.97	74.27	73.22	95.47	
1140	77.82	73.92	73.52	79.57	
1340	78.12	69.97	73.07	78.12	
1540	70.77	71.37	70.02	67.67	
1740	62.17	51.67	60.32	60.97	
1940	14.27	13.42	16.62	11.97	

TABLE 21

A-286 SHEET ULTIMATE STRENGTH

95/99 Lower Limit Values in KSI

Test Temperature °R	Fluence (n/cm ²)				E > 1 MeV E < 0.48 eV
	0	2.2×10^{16} 1.48×10^{18}	0.9×10^{17} 1.11×10^{19}	1.5×10^{19} 1.58×10^{20}	
540	142.77	140.82	138.37	123.67	
740	129.62	131.87	130.72	121.17	
940	129.62	128.22	129.22	122.97	
1140	128.27	127.12	125.02	125.67	
1340	122.97	119.32	121.17	121.32	
1540	103.37	104.07	100.12	100.12	
1740	69.22	65.47	66.62	67.32	
1940	20.07	21.37	23.32	18.22	

TABLE 22

A-286 SHEET UNIFORM ELONGATION

(95/99 Lower Limit Values)

(Values were Obtained Using $\log_{10} (\%+1.0)$, then Converted to %)

Test Temperature °R	Fluence (n/cm ²)				E > 1 MeV E < 0.48 eV
	0	2.2×10^{16} 1.5×10^{18}	0.9×10^{17} 1.1×10^{19}	1.5×10^{19} 1.6×10^{20}	
540	6.20	6.30	5.19	5.56	
740	5.22	5.47	5.67	4.21	
940	5.78	6.00	6.26	4.27	
1140	5.68	5.52	5.67	5.65	
1340	5.71	5.41	5.47	5.04	
1540	4.37	2.45	1.69	1.47	
1740	0.00	0.00	0.00	0.00	
1940	0.00	0.13	0.00	0.00	

TABLE 23

A-286 SHEET TOTAL ELONGATION

(95/99 Lower Limit Values)

(Values were Obtained Using $\log_{10} (\%+1.0)$, then Converted to %)

Test Temperature °R	Fluence (n/cm ²)				E > 1 MeV E < 0.48 eV
	0	2.2×10^{16} 1.5×10^{18}	0.9×10^{17} 1.1×10^{19}	1.5×10^{19} 1.6×10^{20}	
540	4.85	4.97	4.03	4.48	
740	3.77	4.03	4.46	3.24	
940	4.13	4.20	4.59	3.48	
1140	4.32	4.25	4.17	3.98	
1340	4.08	3.97	4.10	3.66	
1540	5.55	1.81	1.34	0.84	
1740	4.82	0.00	0.00	0.00	
1940	6.75	1.86	0.02	0.00	

Note: Due to the greater variability in the data, some of these values are lower than the corresponding values of uniform elongation in Table 22.

TABLE 24
INCONEL 718 SHEET 0.2% OFFSET YIELD STRENGTH
95/99 Lower Limit Values in KSI

Test Temperature °R	1750°F Heat Treatment				
	Fluence (n/cm ²)				
	0	3.7×10^{16}	7.3×10^{16}	6.8×10^{18}	E > 1 MeV
	0	3.7×10^{18}	1.1×10^{19}	1.5×10^{20}	E < 0.48 eV
540	160.40	156.79	157.49	151.21	
740	155.01	151.41	152.11	145.82	
940	149.91	146.31	147.01	140.72	
1140	143.38	139.77	140.47	134.18	
1340	142.19	138.58	139.28	133.00	
1540	137.88	134.27	134.97	128.68	

Test Temperature °R	1950°F Heat Treatment				
	Fluence (n/cm ²)				
	0	3.7×10^{16}	7.3×10^{16}	6.8×10^{18}	E > 1 MeV
	0	3.7×10^{18}	1.1×10^{19}	1.5×10^{20}	E < 0.48 eV
540	156.30	152.69	153.39	147.11	
740	150.91	147.30	148.00	141.72	
940	145.81	142.20	142.90	136.62	
1140	139.27	135.66	136.36	130.08	
1340	138.08	134.48	135.18	128.89	
1540	133.77	130.16	130.86	124.58	

TABLE 25

INCONEL 718 SHEET ULTIMATE STRENGTH

95/99 Lower Limit Values in KSI

1750°F Heat Treatment

Test Temperature °R	Fluence (n/cm ²)				E > 1 MeV E < 0.48 eV
	0	3.7×10^{16}	7.3×10^{16}	6.8×10^{18}	
	0	3.7×10^{18}	1.1×10^{19}	1.5×10^{20}	
540	197.10	192.80	191.30	177.30	
740	189.00	187.80	184.55	169.20	
940	185.40	180.15	182.55	164.80	
1140	178.00	173.45	176.55	164.75	
1340	172.00	173.70	170.25	171.40	
1540	160.25	155.75	158.85	156.05	

1950°F Heat Treatment

Test Temperature °R	Fluence (n/cm ²)				E > 1 MeV E < 0.48 eV
	0	3.7×10^{16}	7.3×10^{16}	6.8×10^{18}	
	0	3.7×10^{18}	1.1×10^{19}	1.5×10^{20}	
540	188.84	184.54	183.04	169.04	
740	180.74	179.54	176.29	160.94	
940	177.14	171.89	174.29	156.54	
1140	169.74	165.19	168.29	156.43	
1340	163.74	165.44	161.99	163.14	
1540	151.99	147.49	150.59	147.79	

TABLE 26

INCONEL 718 SHEET UNIFORM ELONGATION

95/99 Lower Limit Values in %

(Values were Obtained Using $\log_{10} (\%+1.0)$, then Converted to %)

Test Temperature °R	1750°F Heat Treatment				
	Fluence (n/cm^2)				
	0	3.7×10^{16}	7.3×10^{16}	6.8×10^{18}	E > 1 MeV
	0	3.7×10^{18}	1.1×10^{19}	1.5×10^{20}	E < 0.48 eV
540	11.0	9.83	9.39	8.80	
740	10.5	9.33	8.91	8.35	
940	11.7	10.5	10.0	9.38	
1140	12.0	10.7	10.2	9.57	
1340	10.7	9.54	9.12	8.54	
1540	3.04	2.64	2.50	2.30	

Test Temperature °R	1950°F Heat Treatment				
	Fluence (n/cm^2)				
	0	3.7×10^{16}	7.3×10^{16}	6.8×10^{18}	E > 1 MeV
	0	3.7×10^{18}	1.1×10^{19}	1.5×10^{20}	E < 0.48 eV
540	10.1	8.96	8.56	8.02	
740	9.54	8.50	8.12	7.60	
940	10.7	9.55	9.13	8.55	
1140	10.9	9.74	9.32	8.73	
1340	9.76	8.70	8.31	7.78	
1540	2.72	2.35	2.22	2.04	

TABLE 27

IRRADIATED INCONEL 718 SHEET TOTAL ELONGATION

95/99 Lower Limit Values in %

(Values were Obtained Using $\log_{10} (\% + 1.0)$, then Converted to %)

Test Temperature °R	1750°F Heat Treatment				
	Fluence (n/cm ²)				
	0	3.7×10^{16}	7.3×10^{16}	6.8×10^{18}	E > 1 MeV
	0	3.7×10^{18}	1.1×10^{19}	1.5×10^{20}	E < 0.48 eV
540	11.5	10.4	10.3	9.73	
740	11.2	10.1	10.1	9.48	
940	13.0	11.7	11.7	11.0	
1140	13.7	12.3	12.3	11.6	
1340	12.2	11.0	10.9	10.3	
1540	3.83	3.39	3.38	3.15	

Test Temperature °R	1950°F Heat Treatment				
	Fluence (n/cm ²)				
	0	3.7×10^{16}	7.3×10^{16}	6.8×10^{18}	E > 1 MeV
	0	3.7×10^{18}	1.1×10^{19}	1.5×10^{20}	E < 0.48 eV
540	9.13	8.20	8.19	7.70	
740	8.90	7.99	7.97	7.50	
940	10.4	9.32	9.30	8.76	
1140	10.9	9.81	9.80	9.02	
1340	9.69	8.71	8.69	8.18	
1540	2.92	2.56	2.55	2.36	

Note: Due to the greater variability in the data, some of these values are lower than the corresponding values of uniform elongation in Table 26.

TABLE 28
WASPALLOY SHEET 0.2% OFFSET YIELD STRENGTH*
95/99 Lower Limit Values in KSI

Test Temperature °R	Yield Strength KSI
1140	87.24
1340	89.48
1540	90.04
1740	83.89

* Test results were not affected by fluence

TABLE 29
WASPALLOY SHEET ULTIMATE STRENGTH
95/99 Lower Limit Values in KSI

Test Temperature °R	Fluence (n/cm²)				
	0	1.9×10^{16}	4.5×10^{16}	1.0×10^{19}	
	0	1.2×10^{18}	0.8×10^{19}	1.3×10^{20}	E > 1 MeV E < 0.48 eV
1140	161.43	160.88	161.78	155.15	
1340	157.55	157.00	157.90	151.25	
1540	149.85	149.30	150.20	143.55	
1740	95.53	94.98	95.58	89.23	

TABLE 30

WASPALLOY SHEET UNIFORM ELONGATION

95/99 Lower Limit Values in %

(Values were Obtained Using $\log_{10} (\% + 1.0)$, then Converted to %)

Test Temperature °R	Fluence (n/cm ²)				E > 1 MeV E < 0.48 eV
	0	1.9×10^{16}	4.5×10^{16}	1.0×10^{19}	
	0	1.2×10^{18}	0.8×10^{19}	0.8×10^{19}	
1140	11.1	11.4	11.2	7.51	
1340	10.2	10.5	10.3	6.85	
1540	5.93	6.10	6.00	3.59	
1740	0.28	0.31	0.29	0.00	

TABLE 31

WASPALLOY SHEET TOTAL ELONGATION

95/99 Lower Limit Values in %

(Values were Obtained Using $\log_{10} (\% + 1.0)$, then Converted to %)

Test Temperature °R	Fluence (n/cm ²)				E > 1 MeV E < 0.48 eV
	0	1.9×10^{16}	4.5×10^{16}	1.0×10^{19}	
	0	1.2×10^{18}	0.8×10^{19}	1.3×10^{20}	
1140	12.2	12.0	12.6	11.4	
1340	11.4	11.1	11.5	10.0	
1540	11.3	10.2	9.40	3.59	
1740	5.82	2.45	1.02	0.00	

TABLE 32

INCONEL 718 TUBE TEST RESULTS

Specimen Number	Test Temp. (°R)	Thermal Fluence (E < 0.48 eV) (n/cm ²)	Fast Fluence (E > 1 MeV) (n/cm ²)	0.2% Offset Yield Strength (ksi)	Ultimate Strength (ksi)	Uniform Elongation (%)	Total Elongation (%)
10	1140	0	0	158.6	192.1	11.1	11.8
4	1140	2.2 (18)	3.4 (16)	153.6	187.1	11.2	11.2
3	1240	8.0 (18)	5.4 (16)	150.7	185.0	7.6	12.9
11	1340	0	0	156.4	190.7	9.5	10.8
8	1340	7.0 (18)	7.1 (16)	154.3	195.7	5.7	10.4
5	1440	1.0 (19)	9.2 (16)	145.7	185.7	8.2	12.9
12	1540	0	0	140.7	173.6	5.6	10.6
1	1540	2.2 (18)	3.0 (16)	140.7	167.1	4.4	6.7
2	1640	7.6 (17)	1.8 (16)	122.9	130.0	5.7	9.2
9	1740	0	0	107.1	110.0	5.1	8.0
6	1740	4.7 (18)	5.0 (16)	96.4	105.0	3.1	6.1

TABLE 33

TEMPERATURE CONVERSION CHART

$^{\circ}\text{R}$	$^{\circ}\text{F}$	$^{\circ}\text{K}$	$^{\circ}\text{C}$
1940	1480	1078	805
1740	1280	967	694
1540	1080	856	583
1340	880	744	471
1140	680	633	360
940	480	522	249
740	280	411	138
540	80	300	27

TITLE Neutron Irradiation Effects on the Tensile Properties of Inconel 718, Waspaloy, and A-286	
DOCUMENT NO. WANL-TME-2791		DATE June, 1971
ABSTRACT <p>Results of tensile tests of irradiated Inconel 718, Waspaloy and A-286 are reported. Test temperatures ranged from 540°R to 1940°R and thermal fluences to 10²⁰ n/cm². At the lower test temperatures, yield strengths increased while ultimate strengths and elongations decreased. Above 1340°R all materials exhibited severe embrittlement. None appeared to be superior in resistance to high temperature irradiation embrittlement</p>		
DATA ITEM NO.	SECURITY CLASSIFICATION OF DOCUMENT Unclassified	
CDRL LINE NO.	TOTAL NO. OF PAGES 52	
KEY WORDS <p style="text-align: center;">Irradiation Inconel 718 Waspaloy A-286 Tensile Test</p>		
AUTHOR/EDITOR R. P. Shogan		PREPARING DEPT. Materials
W Form 59943 DOCUMENT INFORMATION SUMMARY		

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