**Westinghouse
Astronuclear
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August 1971

**LOW TEMPERATURE
TENSILE PROPERTIES OF
IRRADIATED ALLOY A-286**

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LOW TEMPERATURE TENSILE PROPERTIES OF IRRADIATED ALLOY A-286

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ABSTRACT

Tensile properties of A-286 sheet were measured over the temperature range 140°R to 940°R after irradiation at 140°R to fluences from 0 to 1×10^{19} n/cm², $E > 1$ MeV. Results show large increases in yield strength, small decreases in ultimate tensile strength and large decreases in uniform and total elongation after irradiation. Comparison of these results with a similar ambient irradiation indicate that cryogenic irradiation results in significantly greater property changes at comparable test temperatures.

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INTRODUCTION

The NERVA reactors present a unique environment for the component materials, which are exposed to a high neutron flux while at cryogenic to elevated temperatures. Previous tests⁽¹⁾ have shown that radiation-induced property changes are intensified at lower temperatures. While face-centered cubic structural alloys are generally selected as the structural alloys to preclude cryogenic temperature-induced embrittlement, the effect of adding a neutron fluence approaching that expected during NERVA operation has not previously been investigated for alloy A-286.

A-286 is a widely used, age-hardenable, austenitic, nickel-chromium steel developed for high temperature use. In addition, it exhibits excellent strength and ductility at cryogenic temperatures and has been found not to be embrittled in a high-pressure hydrogen environment as exists in the NERVA reactors. Therefore, it has been selected over other higher strength nickel-based alloys as the prime NERVA core support material and for various other hardware throughout the reactor.

This test is part of a series of tensile test plans intended to cover the entire reactor operating test temperature (approximately 140°R to 1500°R) and fluence⁽²⁾ (up to 3.4×10^{19} n/cm², $E < 0.4$ eV and 1.9×10^{20} n/cm², $E > 1$ MeV) ranges. The maximum fast fluence obtained at low temperature without warmup would be about 1.9×10^{19} n/cm². In this test, specimens were exposed to fluences up to 10^{19} n/cm², $E > 1$ MeV, and tested over the lower half of the temperature range. Results from a test covering the higher temperatures and maximum thermal fluence range are reported in WANL-TME-2791⁽⁶⁾. One additional test at maximum fast fluence and cryogenic temperatures is being planned.

1.0 TEST PROCEDURE

1.1 MATERIAL

Specimens were taken from 0.033 inch thick A-286 sheet with the axes in the rolling direction. Two lots of material were included. Both were purchased from Allegheny Ludlum Steel Corporation to AMS 5525-C. The chemical compositions shown in Table 1 met the specification. Grain size was ASTM No. 6 to 7.

TABLE 1

CHEMICAL COMPOSITION, w/o

	Heat No. 90456	Heat No. 82312		Heat No. 90456	Heat No. 82312
Al	0.16	0.16	S	0.003	0.003
Cr	15.1	15.1	Ti	2.12	2.05
C	0.04	0.05	Mo	1.25	1.38
Mn	1.49	1.50	B	0.006	0.006
Ni	25.4	25.7	P	<0.01	<0.01
Si	0.40	0.53	V	0.30	0.31
			Fe	Bal.	Bal.

After machining, specimens were solution treated for 30 minutes at 1800°F, then aged for 16 hours at 1325°F.

1.2 SPECIMENS

Specimen configuration is shown in Figure 1. A pin-loaded design was selected for 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 was used to determine specimen deflection, the entire one-inch reduced section was considered as the gage length.

1.3 TEST PLANS

Because of the wide range of test variables of interest, a factorial experiment test plan was designed which considered all combinations of the variable levels. The variables

considered were:

- 1) Lot-to-lot variation,
- 2) Fast fluence: 0, 5×10^{17} , 2×10^{18} and 1×10^{19} n/cm², $E > 1$ MeV, and
- 3) Test temperature: 140, 340, 540, 740 and 940°R.

One specimen was tested for each combination of the above variables with several spare specimens included as substitutes for damaged specimens. A random test order was used. In addition, specimens were included for irradiation at the highest fluence followed by annealing at 340°R, 540°R and 740°R and testing at 140°R. Annealing times of 10 minutes to 1000 minutes were used. Properties determined were 0.2% offset yield strength, ultimate tensile strength, uniform elongation and total elongation.

1.4 IRRADIATION

Fluence levels were attained in the 10 MW Ground Test Reactor (GTR) at General Dynamics, Fort Worth, Texas in reactor cycle 20C. During irradiation the specimens were immersed in boiling liquid nitrogen (LN₂, 140°R). The reactor ran a total of approximately 6000 MW-hrs.

Fluences were measured using Co, Ni, Fe and In foils. Details will be given in a subsequent General Dynamics report.

1.5 TESTING

After irradiation, specimens were stored in LN₂ at the Irradiated Materials Laboratory (IML) of the Nuclear Aerospace Research Facility of General Dynamics until tested.

A Model TT-D split console-type Instron machine was used for the tensile testing. To attain the desired test temperature the specimens were immersed in LN₂ (140°R), sprayed with a LN₂-GN₂ mixture (340°R), held at room temperature (540°R) or heated in a Marshall tube furnace (740°R and higher). Times required to heat the specimens from 140°R to the test temperature were 20 minutes to 340°R, 5 minutes to 540°R, 10 minutes to 740°R and 15 minutes to 940°R.

A temperature calibration between the specimen grip assembly and a thermocoupled specimen was made prior to testing at 740°R and above. The grip temperature was then used to control the furnace temperature. A similar procedure was used at 340°R. Here the temperature was maintained by controlling the amount of cold nitrogen gas impinging on the specimen from a perforated coil surrounding the specimen and thermocoupled grip assembly⁽³⁾.

For the annealing studies, the specimens were heated to the anneal temperatures with approximately the same heating ramps, held for the desired length of time, and returned to LN₂ for testing.

Crosshead speed during testing was 0.02 inch per minute. All data shown in the report were obtained from the Instron load-deflection charts. These are sufficiently accurate for the required data. Uniform elongations obtained are chart plastic deflections to maximum load. Bench measurements of total elongation were made but the results were very similar to the chart values and are not reported here.

Data reduction was by General Dynamics. The raw test data and details of the testing procedures are given in their report⁽⁴⁾.

2.0 TEST RESULTS AND DISCUSSION

Results were analyzed by the WANL Reliability Department to determine the response of the data to the test variables. Details and results of the analyses can be found elsewhere⁽⁵⁾. Generally, the analysis of variance method was used with responses compared at the 0.05 significance level.

Data obtained from each specimen are shown in Table 2. The predicted data values from the analysis of variance are shown for each property in Tables 3 through 6. These results will be used in the following discussion. Also shown are "pooled" standard deviations, effective sample sizes, degrees of freedom and 95/99 lower limit values. No statistical analysis was made of the annealing specimen data. The test results for these specimens are reported in Table 7.

Occasionally, in discussing the results of this test, data from a previous irradiation⁽⁶⁾ will be included. Labeled PBRF, these data were obtained on test specimens from the same lot. However, irradiation was in the 585°R Plum Brook Reactor Facility coolant water at a higher flux but similar fluence level. Testing was also by General Dynamics, Fort Worth although a slower pulling rate (0.002 in/min.) was used. The data will be compared to show the effect of irradiation temperature and to extend the characterization of the material's response to irradiation to a higher temperature.

2.1 YIELD STRENGTH

Of the properties measured, the irradiation effect was most pronounced on the yield strength (Figure 2). This property was increased up to 53% at the lowest temperature and highest fluence. The effect has been well characterized as due to the blocking of dislocation movement by defects (interstitials and vacancies) created when atoms are displaced from their normal lattice positions by the bombarding neutrons⁽⁷⁾.

TABLE 2

IRRADIATED A-286 SHEET TENSILE DATA*

Specimen Number	Lot**	Fluence E > 1 MeV (n/cm ²)	Test Temperature (°R)	0.2% Offset Yield Strength (KSI)	Ultimate Ten. Strength (KSI)	Uniform Elongation (%)	Total Elongation (%)
201	A	0	140	112.0	197.3	40.8	45.6
312	B	0	↓	115.9	199.0	39.3	44.8
205	A	4.1x10 ¹⁷		123.5	198.2	37.0	42.7
316	B	4.1x10 ¹⁷		124.6	201.5	34.9	41.4
209	A	2.6x10 ¹⁸		154.5	205.7	31.0	40.2
320	B	2.6x10 ¹⁸		147.8	201.7	31.9	38.8
213	A	1.0x10 ¹⁹		169.9	191.5	24.3	33.9
324	B	1.0x10 ¹⁹		177.5	200.6	25.8	35.3
202	A	0	340	101.2	163.2	27.6	32.1
313	B	0	↓	103.5	164.7	26.2	31.9
206	A	4.1x10 ¹⁷		112.6	163.7	25.9	31.8
317	B	4.1x10 ¹⁷		114.7	165.8	26.3	31.1
210	A	2.6x10 ¹⁸		132.9	160.4	24.4	28.6
333	B	2.6x10 ¹⁸		132.5	159.3	21.5	28.1
214	A	1.0x10 ¹⁹		143.3	153.2	15.3	24.4
325	B	1.0x10 ¹⁹		139.4	153.1	16.5	23.5
203	A	0	540	96.7	152.1	24.3	27.9
314	B	0	↓	98.9	150.3	23.6	26.9
207	A	4.1x10 ¹⁷		106.5	150.0	23.6	28.0
318	B	4.1x10 ¹⁷		110.9	153.4	23.6	27.0
211	A	2.6x10 ¹⁸		123.3	147.0	21.6	26.1
322	B	2.6x10 ¹⁸		126.6	150.2	20.9	24.7
215	A	1.0x10 ¹⁹		123.8	138.0	16.8	20.8
326	B	1.0x10 ¹⁹		120.0	136.5	16.2	21.5
204	A	0	740	90.1	144.9	22.4	24.4
315	B	0	↓	90.1	143.7	21.6	24.1
208	A	4.1x10 ¹⁷		101.0	143.3	20.0	24.6
319	B	4.1x10 ¹⁷		91.0	145.0	21.5	24.6
212	A	2.6x10 ¹⁸		102.6	136.6	19.1	21.4
323	B	2.6x10 ¹⁸		112.4	141.3	18.5	20.8
216	A	1.0x10 ¹⁹		112.2	134.1	13.5	15.9
327	B	1.0x10 ¹⁹		115.2	131.2	13.1	16.3

* Tables 2 through 4 are taken from reference (5).

** Lot A - Allegheny Ludlum Heat No. 90456.

Lot B - Allegheny Ludlum Heat No. 82312.

TABLE 2 (CONTINUED)

<u>Specimen Number</u>	<u>Lot</u>	<u>Fluence E > 1 MeV (n/cm²)</u>	<u>Test Temperature (°R)</u>	<u>0.2% Offset Yield Strength (KSI)</u>	<u>Ultimate Ten. Strength (KSI)</u>	<u>Uniform Elongation (%)</u>	<u>Total Elongation (%)</u>
218	A	0	940	81.2	138.5	21.9	23.2
328	B	0	↓	82.4	138.9	20.6	22.2
219	A	4.1x10 ¹⁷		82.0	140.2	23.6	25.0
331	B	4.1x10 ¹⁷		86.5	138.9	19.2	22.4
221	A	2.6x10 ¹⁸		88.9	132.9	20.2	21.7
332	B	2.6x10 ¹⁸		91.0	133.7	19.4	21.0
223	A	1.0x10 ¹⁹		100.6	131.4	16.3	18.1
334	B	1.0x10 ¹⁹		102.6	131.8	14.2	16.3

TABLE 3

IRRADIATED A-286 SHEET 0.2% OFFSET YIELD STRENGTH

(Average and 95/99 Lower Limit Values in KSI)

Fast Fluence (n/cm^2)

Test Temp. °R	0			41×10^{16}			26×10^{17}			10^{19}		
	$\bar{X}$	LL	N	$\bar{X}$	LL	N	$\bar{X}$	LL	N	$\bar{X}$	LL	N
140	113.73	101.32	2.282	125.10	113.29	3.322	149.86	138.05	3.322	173.48	161.07	2.282
340	102.19	90.71	4.321	115.08	103.79	5.072	133.32	122.03	5.072	142.37	130.89	4.321
540	96.42	84.92	4.243	107.69	96.50	5.600	121.51	110.32	5.600	123.35	111.85	4.243
740	91.43	79.94	4.321	97.93	86.64	5.072	109.45	98.16	5.072	111.42	100.02	4.321
940	82.24	69.75	2.282	86.0	69.04	3.322	92.16	80.35	3.322	101.63	89.22	2.282

N is the effective
sample size of $\bar{X}$.
 $s = 3.343$ with
degrees of freedom
 $f = 29$

8

TABLE 4

IRRADIATED A-286 SHEET ULTIMATE TENSILE STRENGTH

(Average and 95/99 Lower Limit Values in KSI)

Fast Fluence (n/cm^2)

Test Temp. °R	0			41×10^{16}			26×10^{17}			10^{19}		
	$\bar{X}$	LL	N	$\bar{X}$	LL	N	$\bar{X}$	LL	N	$\bar{X}$	LL	N
140	197.99	190.31	2.473	200.80	193.26	2.800	203.31	195.77	2.800	195.64	187.96	2.473
340	163.35	156.11	3.944	163.59	156.39	4.179	161.75	154.55	4.179	153.01	145.77	3.944
540	152.18	144.91	3.784	151.38	144.29	4.828	146.73	139.64	4.828	138.46	131.19	3.784
740	144.77	137.53	3.944	144.48	137.28	4.179	138.54	131.34	4.179	132.27	125.03	3.944
940	138.01	130.33	2.473	139.76	132.22	2.800	134.07	126.53	2.800	131.32	123.64	2.473

N is the effective
sample size of $\bar{X}$.
 $s = 2.083$ with
degrees of freedom
 $f = 28$

TABLE 5

A-286 SHEET UNIFORM ELONGATION
(Average and 95/99 Lower Limit Values in %)

Test Temperature $^{\circ}\text{R}$	Fast Fluence (n/cm^2)											
	0			41×10^{16}			26×10^{17}			10^{19}		
	$\bar{X}$	LL	N	$\bar{X}$	LL	N	$\bar{X}$	LL	N	$\bar{X}$	LL	N
140	38.81	34.23	3.509	36.48	32.10	6.061	31.96	27.58	6.061	25.25	20.68	3.509
340	27.63	23.16	4.598	25.98	21.61	6.349	22.14	17.77	6.349	16.11	11.64	4.598
540	24.97	20.54	5.128	24.00	19.63	6.452	20.84	16.47	6.452	15.49	11.06	5.128
740	21.34	16.87	4.598	21.05	16.68	6.349	18.57	14.20	6.349	13.90	9.43	4.598
940	20.03	16.46	3.509	21.42	17.04	6.061	19.62	15.24	6.061	15.63	11.05	3.509

N is the effective sample size of $\bar{X}$. $S = 1.155$ with degrees of freedom, $f = 12$

TABLE 6

A-286 SHEET TOTAL ELONGATION
(Average and 95/99 Lower Limit Values in %)

Test Temperature $^{\circ}\text{R}$	Fast Fluence (n/cm^2)											
	0			41×10^{16}			26×10^{17}			10^{19}		
	$\bar{X}$	LL	N	$\bar{X}$	LL	N	$\bar{X}$	LL	N	$\bar{X}$	LL	N
140	44.88	41.01	2.353	42.66	38.96	4.445	39.23	35.53	4.445	34.57	30.70	2.353
340	32.21	28.37	2.581	31.11	27.45	5.333	28.39	24.73	5.333	24.03	20.19	2.581
540	27.47	23.64	2.667	27.43	23.77	5.715	25.34	21.69	5.715	21.21	17.38	2.667
740	24.48	20.63	2.581	24.14	20.48	5.333	21.35	17.68	5.333	16.09	12.25	2.581
940	22.63	18.76	2.353	23.62	19.92	4.445	21.73	18.03	4.445	16.97	13.10	2.353

N is the effective sample size of $\bar{X}$. $S = 0.7666$ with degrees of freedom, $f = 5.79$.

TABLE 7

TENSILE DATA FOR ANNEALING SPECIMENS

Test Temperature - 140°R, Lot A

Specimen No.	Fluence (E > 1 MeV) (n/cm ²)	Annealing Time (min.)	Temperature °R	0.2% Off. Yield Str. (ksi)	Ultimate Strength (ksi)	Uniform Elongation (%)	Total Elongation (%)
301	1 x 10 ¹⁹	No Anneal		174.7	200.1	22.2	33.0
302	1 x 10 ¹⁹	No Anneal		170.6	200.0	22.2	30.7
303	1 x 10 ¹⁹	10	340	165.3	196.2	27.0	36.9
304	1 x 10 ¹⁹	100	340	168.0	201.1	27.0	33.3
305	1 x 10 ¹⁹	10	540	150.9	191.6	30.0	38.1
306	1 x 10 ¹⁹	100	540	143.2	194.6	28.6	38.8
337	1 x 10 ¹⁹	1000	540	154.0	198.3	32.6	39.8
307	1 x 10 ¹⁹	10	740	142.4	193.6	31.2	37.9
308	1 x 10 ¹⁹	100	740	140.3	194.8	31.0	38.8
339	1 x 10 ¹⁹	10	940	141.6	201.2	31.9	38.0
338	1 x 10 ¹⁹	10	1140	113.3	196.4	37.8	43.4

Figure 2. A-286 Yield Strength vs. Test Temperature

The increase of yield strength with fluence is found to follow a square root relation (see Figure 3). As predicted by Seiger⁽⁸⁾, this relationship indicates that the number of obstacles to dislocation movement is proportional to the fluence and thus that no interaction (saturation) of individual "defects" is occurring at the fluences attained.

At higher temperatures the yield strength "recovers". This effect is shown in Figures 4 and 5. In Figure 4, the percent change in yield strength is plotted versus the test temperature while Figure 5 shows the yield strength values plotted versus the annealing temperature. Time of the anneals was 10 minutes although no apparent effect of anneal times up to 1000 minutes could be detected from the limited amount of data.

The dependence of the degree of radiation-induced change in the yield strength to test temperature indicates that the number of defects blocking dislocation movement is decreasing with increasing temperature. Theories of the mechanisms of annealing of defects are treated in detail elsewhere⁽⁷⁾. Briefly, radiation produced lattice defects are thermodynamically unstable. Even at 140°R, during the irradiation, closely spaced interstitial-vacancy pairs may be combining. As the temperature is increased activation energy for movement becomes available and defects may nucleate and grow increasingly larger clusters or annihilate at impurities, dislocations or other sinks. The similarity between Figure 5 and Figure 4 indicates that the property changes are more a function of the defect state than an interaction of the defect state and test temperature. For example, in Figure 4, the rapid recovery as the temperature approaches 1140°R is not due to the ability of dislocations to break away from existing defects as might be expected, since Figure 5 shows this also occurs at the 140°R test temperature.

Another interesting feature of the annealing curve is the two broad annealing ranges: 140°R to 540°R and 940°R to 1140°R. Almost half of the property change is recovered below room temperature. In this range only interstitials are thought to be mobile. These may anneal by reactions with vacancies, sinks or each other to form clusters. The maximum slope in this portion of the curve of Figure 5 occurs at about 460°R. This temperature is very close to 0.16 times the melting point (~ 480°R) which is that predicted for interstitial migration⁽⁹⁾.

Figure 3. Yield Strength vs. Square Root of Fluence

Figure 4. Percent Increase in Yield Strength vs. Test Temperature for A-286 Sheet Irradiated at 140°R and 585°R

Figure 5. Yield Strength at 140°R vs. Anneal Temperature

The gradual recovery between 540°R and 940°R is credited to clustering of interstitials and di-vacancy migration which can occur in this range. At about 0.32 times the melting point, or 960°R, vacancies should become mobile. Their annealing along with that of larger clusters of interstitials accounts for the rapid and complete recovery of the yield strength in this range.

In comparing the GTR and PBRF data (Figure 4) it is found that the irradiation effect was greater in the GTR test, particularly at 540°R. Since the PBRF specimens received approximately 50% greater fast fluence as well as higher flux and fluence over the whole spectrum and since the control values for each test were in reasonable agreement, the difference is credited to the lower irradiation temperature in the GTR.

A possible explanation for this effect is as follows. During the 140°R irradiation, point defects are effectively "frozen in", and, when the specimen is raised to a higher test temperature, are released quite rapidly. Since the initial defect density is high, it is likely that a diffusing interstitial will meet another interstitial and combine rather than being annihilated at a sink. Defect clusters are more stable and require higher thermal energy for migration than point defects (usually).

For the case of the PBRF irradiation, however, the temperature is above that at which interstitial migration is possible. These defects are, therefore, mobile during irradiation. Since the effective annealing time (in this case the irradiation time) was several orders of magnitude longer than for the 140°R irradiation, at any given time during irradiation the point defect concentration is relatively low and migrating defects have a much greater chance of reaching a sink and being destroyed, rather than clustering and impeding dislocation movement. The larger difference between the radiation effect at 540°R is not fully understood.

2.2 ULTIMATE TENSILE STRENGTH

The sensitivity of the yield strength to radiation-produced defects makes it an interesting property to use in studying the characteristics of a material's response to irradiation. However, from a reactor designer's viewpoint, an increase in strength is

relatively unimportant. Similarly, many metals show an increase in ultimate tensile strength with irradiation⁽¹⁾. However, although a slight increase was noted at the lowest fluence level, the ultimate tensile strength of A-286 was found to decrease with fluence. A similar result was also found in the previous PBRF data (see Figure 6). The decrease occurred at temperatures above 140°R. Fortunately, the effect is small (< 5% change) and at the fluence levels obtained in this test will not affect reactor design allowable stress levels.

Although the magnitude of the changes being measured was quite small, the character of the annealing study results for the ultimate tensile strength was different than that for the yield stress. The 140°R ultimate tensile strength values are plotted versus annealing temperature in Figure 7. The interesting features of this curve are:

- 1) Although there was virtually no radiation effect at 140°R, decreases were found after annealing at higher temperatures. The characteristics of the change were similar between the "at temperature" results (Figure 6) and the "annealing" results (Figure 7) although the magnitude of the effect was significantly greater in the former.
- 2) Complete recovery should occur at about 1340°R (10 minute anneals) which is higher than found for the yield strength.
- 3) There is an apparent effect of annealing time.
- 4) The magnitude of the property change reaches a maximum after a 540°R anneal.

Although only a few data points are involved, the results indicate that the ultimate tensile strength is not affected by the finely-dispersed point defect state expected after the 140°R irradiation but that sufficient agglomerations occur at higher temperatures to effect a measurable change in the property. Above 540°R such defects begin to anneal out or grow too large to be effective.

The time dependence of annealing is not understood. Obviously, defects are present, as shown by the yield strength changes, even after long time anneals at 540°F, for example.

Fortunately, the ultimate strength decreases are very small and will not affect application of the alloy in the NERVA reactor. However, irradiation of this alloy to full 10-hour fluences is being planned to verify these conclusions.

Figure 6. Ultimate Tensile Strength vs. Test Temperature

Figure 7. Ultimate Tensile Strength vs. Annealing Temperature

2.3 TENSILE ELONGATION

The primary objective of this test was to determine the degree of embrittlement of A-286 caused by irradiation. Numerous previous tests have indicated that this class of material will lose ductility, particularly at cryogenic temperatures.

Two measures of ductility were made: the uniform and total tensile elongations. The uniform elongation is a measure of the homogeneous strain the specimen will undergo prior to necking. The difference between this value and the total elongation indicates the degree of localized strain which can occur before failure.

Both properties decreased as a function of fluence. In Figures 8 and 9, the percent reduction is plotted versus test temperature for the uniform and total elongations, respectively, for the highest fluence level. After an initial increase in radiation effect at 340°R , the change in the uniform elongation decreased slowly to about 740°R , then rapidly to complete recovery at 1140°R . The data from the GTR and PBRF tests agree at 940°R but the cryogenically irradiated GTR specimens were embrittled to a much higher degree at lower temperatures.

On the other hand, the total elongation decreased from 23% to 25% at all test temperatures except at 940°R where the decrease was $\sim 34\%$. Complete annealing is not expected in this property since at higher temperatures, embrittlement due to irradiation-produced helium has been found previously to occur⁽⁶⁾. In the case of the total elongation, cryogenic irradiation resulted in much greater change at all test temperatures.

Decreases in uniform elongation has been rationalized in the literature⁽¹⁰⁾ as due to localization of deformation to a few active slip planes where failure may occur without gross homogeneous deformation of the lattice. This appears to be a plausible explanation for the results found in this test. However, while both the uniform and total elongations decreased with fluence, the difference between the two increased. This indicates no reduction in the ability of the material to locally deform plastically. Since the extent of the necked region was not measured, no definite conclusion can be made about the deformation except that crack propagation resistance would not appear to be degraded.

Figure 8. Percent Reduction in Uniform Elongation vs. Temperature

Figure 9. Percent Reduction in Total Elongation vs. Temperature

The annealing study (Figure 10) shows the elongations recovering slowly as the anneal temperature is increased. Most of the recovery occurs in stages at 140°R to 340°R and 940°R to 1140°R . A slight effect of annealing time was noted.

Despite the large reductions in elongation found, A-286 remains sufficiently ductile to conclude that irradiation to the levels attained in this test will not be detrimental to its application in the NERVA reactor. The lowest total elongation value measured on any specimen in the test was 15.9%.

2.4 LOAD DEFLECTION CURVES

As a summary, load-deflection curves for the control and irradiated specimens at 140°R are shown in Figure 11. Most obvious affects are the increases in yield strength and reduction in uniform and total elongation. At higher temperatures the maximum load will be slightly reduced for the irradiated specimens.

The other major difference between the curves is the greatly reduced work hardening in the irradiated specimen. The reduced work hardenability is related, as was the uniform elongation, to a limiting of the number of active slip systems in irradiated material.

Figure 10. Effect of Annealing on the Tensile Elongation

Figure 11. Load-Deflection Curves at 140°R*

* Includes test machine deflection

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3.0 CONCLUSIONS

None of the effects of irradiation measured in the experiment are sufficient in magnitude to affect the application of A-286 in the NERVA reactor. The applicable ranges are 140°R to 1140°R and 0 to $1 \times 10^{19} \text{ n/cm}^2$, $E > 1 \text{ MeV}$. Reactor maximum fast fluence levels are $\sim 1.9 \times 10^{20} \text{ n/cm}^2$ (including 3σ uncertainty factor) for 10 hours of operation. However, the longest single cycle is an order of magnitude shorter so that the fluences are comparable to those attained in this test. Between cycles annealing will occur as the material soaks for a long period of time at 800°R to 1000°R . During this time most, but not necessarily all of the property changes will recover. In addition, the rate of change of the properties with fluence is reduced above $5 \times 10^{19} \text{ n/cm}^2$, $E > 1 \text{ MeV}$. Thus, a full 10 hour cyclic operation should not degrade the materials properties seriously. Because of the uncertainties involved, however, higher fluence tests seem justified and are being planned.

Another important result was the confirmation of the theory that lower temperature irradiations result in more radiation effect than higher temperature irradiations. It has always been an assumption of the NERVA materials irradiation program that irradiating at 140°R and testing at higher temperatures is more economical and more conservative than irradiating and testing at a variety of temperatures. These results tend to confirm this assumption for A-286.

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<p>Tensile properties of A-286 sheet were measured over the temperature range 140°R to 940°R after irradiation at 140°R to fluences from 0 to 1×10^{19} n/cm², E > 1 MeV. Results show large increases in yield strength, small decreases in ultimate tensile strength and large decreases in uniform and total elongation after irradiation. Comparison of these results with a similar ambient irradiation indicate that cryogenic irradiation results in significantly greater property changes at comparable test temperatures.</p>		
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