Effects of Thermal Aging and Neutron Irradiation on the Mechanical Properties of Three-Wire Stainless Steel Weld Overlay Cladding

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Abstract

Thermal aging of three-wire series-arc stainless steel weld overlay cladding at 288°C for 1605 h resulted in an appreciable decrease (16%) in the Charpy V-notch (CVN) upper-shelf energy (USE), but the effect on the 41-J transition temperature shift was very small (3°C). The combined effect of aging and neutron irradiation at 288°C to a fluence of 5×10^{19} neutrons/cm² (> 1 MeV) was a 22% reduction in the USE and a 29°C shift in the 41-J transition temperature. The effect of thermal aging on tensile properties was very small. However, the combined effect of irradiation and aging was an increase in the yield strength (6 to 34% at test temperatures from 288 to -125°C) but no apparent change in ultimate tensile strength or total elongation. Neutron irradiation reduced the initiation fracture toughness (J_{Ic}) much more than did thermal aging alone. Irradiation slightly decreased the tearing modulus, but no reduction was caused by thermal aging alone. Other results from tensile, CVN, and fracture toughness specimens showed that the effects of thermal aging at 288 or 343°C for 20,000 h each were very small and similar to those at 288°C for 1605 h. The effects of long-term thermal exposure time (50,000 h and greater) at 288°C will be investigated as the specimens become available in 1996 and beyond.

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Previous Reports in Series

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Effects of Thermal Aging and Neutron Irradiation on the Mechanical Properties of Three-Wire Stainless Steel Weld Overlay Cladding*

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1. Introduction

Thermal aging at a relatively low temperature (343°C) has been shown to significantly degrade the Charpy impact toughness of type 308 stainless steel shielded metal-arc (SMA) welds.¹ The stainless steel cladding applied to the inner surface of some reactor pressure vessels (RPVs) is similar to this material, although the cladding is a submerged arc (series-arc) weld overlay. Hence, an experimental program was initiated at Oak Ridge National Laboratory (ORNL) to evaluate the effects of thermal aging on stainless steel cladding as well as its contribution to toughness degradation during irradiation experiments. Neutron irradiation effects on three-wire stainless steel cladding were studied, and detailed results are given elsewhere²⁻⁴ and briefly summarized here. The goals of the thermal aging studies were to quantify and separate the damage contributions of thermal aging and neutron irradiation for short-term exposures and to evaluate the effects of aging for long-term exposures. Since the irradiation to the highest fluence of 5×10^{19} neutrons/cm² (> 1 MeV) was conducted at 288°C for 1605 h, tensile, Charpy V-notch (CVN), and compact fracture toughness specimens were thermally aged as discussed in the thermal aging plan described below. This report summarizes the experimental plan and presents the results of short-term thermal aging at 288°C for 1605 h, together with comparisons to neutron irradiation effects. Also, results of tensile, CVN, and compact fracture toughness specimens, thermally aged for 20,000 h at 288 or 343°C, are presented here. Additional material is currently being aged at 288°C for longer times (50,000 h and greater).

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2. Experimental Procedures

Stainless steel weld overlay cladding was fabricated using the three-wire series-arc method. The three-wire cladding material was produced by Combustion Engineering, Inc., Chattanooga, Tennessee. Various combinations of types 304, 308, and 309 stainless steel wires were used to produce three layers of cladding (approximately 20 mm total thickness). Details of the three-wire series-arc cladding procedure, postweld heat treatment (PWHT) etc., are given in reference 4. Three layers of cladding were applied to a pressure vessel plate to provide adequate thickness (approximately 20 mm) for the fabrication of test specimens. The chemical composition of the cladding is given in Table 1. After a PWHT (40 h at 621°C), the cladding material was thermally aged at 288°C for 1605 and 20,000 h. Another set of cladding specimens was aged at 343°C for 20,000 h. Testing of tensile, CVN, and 12.7-mm-thick compact [0.5T C(T)] fracture toughness specimens was conducted according to American Society for Testing and Materials (ASTM) Standards E 8-89, E 184-79, and E 813-89, respectively. Precracked CVN (PCVN) specimens were also thermally aged; the dynamic fracture toughness (K_{Ic}) test results will be reported in another report. The thermal aging plan that describes aging temperatures and times is given below. Irradiation conditions [2×10^{19} neutrons/cm² (> 1 MeV), 288°C] are given in references 4 and 5.

2.1 Thermal Aging Plan

Pieces and specimens from three-wire series-arc stainless steel cladding were thermally aged in air in two separate furnaces as discussed below. Several thermocouples were spot welded to the specimens, and aging temperatures were recorded daily:

1. Aging temperature of 288°C (550°F) for times of 1605, 20,000, 50,000 h, and greater. The aging time of 1650 h is equal to the irradiation time of the high-fluence [5×10^{19} neutrons/cm² (> 1 MeV)] specimens to enable us to separate the effects of thermal aging from those of neutron embrittlement. Also, the various aging times will provide data on effects of thermal aging versus time. The 1605- and 20,000-h aging sets were completed, and their test results are presented in this report while the 50,000-h and greater agings are still in progress.
2. Aging temperature of 343°C (650°F) for 20,000 h to compare with specimens from type 308 stainless steel welds thermally aged and tested earlier.¹ Additional pieces from type 308 stainless steel welds were also aged for 50,000 h. Results of aged three-wire cladding specimens are presented in this report, while the results of type 308 stainless steel weld specimens will be presented in another report.

Both thermal aging series above included several round tensile, CVN impact, PCVN, and 12.7-mm-thick compact [0.5T C(T)] fracture toughness specimens. All specimens have an L-S orientation (L is the welding direction).

3. Results and Discussion

The effects of neutron irradiation and thermal aging alone at 288°C for 1605 h on impact, tensile, and fracture toughness properties are described and discussed first. The effects of thermal aging for 20,000 h at 288 and 343°C are presented later.

3.1 Effects of Neutron Irradiation and Thermal Aging at 288°C for 1605 h

3.1.1 Charpy Impact Properties

All cladding exhibited ductile-to-brittle transition behavior during Charpy impact testing due to the dominance of δ -ferrite failures at low temperatures.⁶ The CVN test results fitted with a hyperbolic tangent function for the

Table 1. Chemical composition of the three-wire stainless steel weld clad overlay used in Phase 2 of the Seventh Irradiation Series

Layer	Content ^a (wt %)										
	C	Cr	Ni	Mo	Mn	Si	Co	Cu	V	P	S
Lower	0.052	19.75	9.75	0.18	1.59	0.63	0.03	0.07	0.03	0.016	0.014
Middle	0.049	19.38	9.18	0.23	1.28	0.78	0.07	0.36	0.06	0.023	0.017
Upper	0.049	19.34	9.04	0.23	1.34	0.82	0.08	0.39	0.06	0.023	0.017

^aBalance Fe, with Nb < 0.01%, Ti < 0.01%, and N < 0.057% for all layers.

as-received (unirradiated), thermally aged at 288°C, and irradiated specimens are summarized in Table 2. Comparisons of the CVN impact energy and lateral expansion of the three material conditions (as-received, thermally aged, and irradiated) are shown in Figures 1 and 2, respectively. The drop in the upper-shelf energy (USE) for the irradiated specimens [fluence of 5×10^{19} neutrons/cm² (> 1 MeV), irradiation temperature of 288°C] was 22% due to the combined effect of neutron irradiation and thermal aging. The USE was reduced by 16% due to thermal aging exposure. Hence, it appears that the contribution of thermal aging to the CVN upper-shelf drop is large compared to the irradiation damage (16 vs 6%, assuming that the effects of irradiation and thermal aging can simply be added together). Additionally, thermal aging resulted in essentially no shift (3°C measured shift) of the Charpy impact transition temperature at the 41-J level. This effect of thermal aging on the 41-J transition temperature shift is very small compared to the combined effect during neutron irradiation (3 vs 29°C). Also, the lateral expansion upper and lower shelves were lowered due to the thermal aging by 4 and 48%, respectively, compared to the as-received material. However, due to the small number of specimens tested at the lower shelf, the percentage drop of the lateral expansion lower shelf is not rigorous. The drops in the lateral expansion upper and lower shelves after irradiation were 42 and 93%, respectively, compared to the as-received material.

Table 2. Charpy impact test results for stainless steel three-wire series-arc cladding (L-S orientation)

Material condition	Transition temperature (°C)			Energy (J)		Lateral expansion (mm)	
	41 J	68 J	0.38 mm	Upper shelf	Lower shelf	Upper	Lower ^a
As-received	-43	6	-51	83	14	1.146	0.229
Aged ^b	-40	34	-65	70	11	1.098	0.119
Irradiated ^c	-14		-9	65	14	0.666	0.015

^aFew CVN specimens were tested at the lower shelf; additional specimens could improve the uncertainty of lateral expansion values at the lower shelf.

^b288°C, 1605 h.

^c288°C, 5×10^{19} neutrons/cm² (> 1 MeV), 1605-h exposure.

Figure 1. Effects of thermal aging at 288°C and neutron irradiation on the Charpy impact energy of three-wire series-arc stainless steel cladding, L-S orientation.

Figure 2. Effects of thermal aging at 288°C and neutron irradiation on the Charpy impact lateral expansion of three-wire series-arc stainless steel cladding, L-S orientation.

3.1.2 Tensile Properties

The effect of thermal aging at 288°C for 1605 h on the tensile properties (yield strength, ultimate strength, and total elongation) was very small or negligible. The tensile data for unirradiated, thermally aged (at 288°C for 1605 h), and irradiated specimens [at 288°C to a fluence of 5×10^{19} neutrons/cm² (> 1 MeV)] are given in Tables 3 through 5. The uniaxial tensile data (yield strength, ultimate strength, and total elongation) for the cladding material in those three conditions are shown in Figures 3 through 5. The tables and figures show that the increase (6 to 34%) in yield strength of the three-wire stainless steel cladding was due to the neutron irradiation with no appreciable contribution due to short-term thermal aging. The ultimate strength and the total elongation were not affected by irradiation and/or thermal aging.

Table 3. Tensile properties of unirradiated specimens in the L orientation

Specimen	Test temperature (°C)	Tensile strength (MPa)		Total elongation (%)
		Yield	Ultimate	
A16A	-125	357	1169	39
A16B	-125	338	1150	39
A26A	21	301	574	47
A26B	21	297	577	47
A20A	288	218	409	23
A20B	288	252	402	20

Table 4. Tensile properties of thermally aged (1605 h at 288°C) specimens in the L orientation

Specimen	Test temperature (°C)	Tensile strength (MPa)		Total elongation (%)
		Yield	Ultimate	
A18D	-125	360	1061	38
A24B	-125	371	1054	38
A18A	25	291	590	47
A18B	25	^a	582	45
A18C	288	197	406	28
A24A	288	213	401	23

^a Paper chart recorder of the test machine temporarily stalled in the earlier part of the test.

Table 5. Tensile properties of irradiated specimens [at 288°C to 5×10^{19} neutrons/cm² (> 1 MeV)] in the L orientation

Specimen	Test temperature (°C)	Tensile strength (MPa)		Total elongation (%)
		Yield	Ultimate	
A20C	-125	466	1072	41
A25A	27	333	609	46
B12A	27	329	591	47
A25C	288	238	433	28
B12C	288	242	417	29

Figure 3. Effects of thermal aging at 288°C and neutron irradiation on the yield strength of three-wire series-arc stainless steel cladding.

Figure 4. Effects of thermal aging at 288°C and neutron irradiation on the ultimate strength of three-wire series-arc stainless steel cladding.

Figure 5. Effects of thermal aging at 288°C and neutron irradiation on the total elongation of three-wire series-arc stainless steel cladding.

3.1.3 Fracture Toughness

The test results of 12.7-mm-thick compact [0.5TC(T)] fracture toughness specimens are summarized in Table 6 for the unirradiated, thermally aged (1605 h at 288°C), and irradiated [637 h at 288°C to a fluence of 2.4×10^{19} neutrons/cm² (> 1 MeV)] material conditions. All specimens were 10% side-grooved on each side and tested using a computerized single-specimen unloading-compliance technique. The deformation J-integral values of J_{Ic} and tearing modulus at various test temperatures are also shown in Figures 6 and 7, respectively. These results indicate that thermal aging reduced the initiation fracture toughness (J_{Ic}) at room temperature and at 120°C; however, there was no apparent effect at 288°C. This lack of an effect of thermal aging at 288°C for 1605 h on J_{Ic} at the test temperature of 288°C was also repeated for the J_{Ic} tests following the 20,000-h aging, as will be shown later. The effect of thermal aging on the tearing modulus was insignificant (no reduction) for all test temperatures (room temperature, 120, and 288°C). The low values of J_{Ic} and tearing modulus for the irradiated cladding (comparable to low upper-shelf ferritic steels sensitive to irradiation)⁷ raise concern about the potential adverse impact of stainless steel cladding on the integrity of a pressure vessel during an overcooling transient (e.g., pressurized thermal shock) in which the growth of small surface flaws can have a significant effect on the probability of vessel failure. This is particularly important since cladding failures have occurred in several pressure vessels.⁸ An evaluation of the effects of irradiated stainless steel cladding on the fracture behavior of shallow flaws under pressurized-thermal-shock (PTS) loading has been reported by Keeney-Walker et al.⁹ For pressure and temperature loading histories of the RPV, the authors used an idealization of the Rancho Seco PTS transient. The ductile fracture toughness properties for irradiated cladding (see Figure 6), a relatively low clad yield stress, and the assumption of stress-free cladding at the RPV operating temperature were used to analyze the potential for ductile tearing of the cladding. Under those conditions, results were presented which indicate ductile tearing of the cladding is unlikely to occur for the conditions assumed in the model.

Table 6. Unloading compliance J-R test results of 12.7-mm-thick three-wire stainless steel cladding fracture toughness specimens (10% side-grooved on each side)

Test temperature (°C)	Unirradiated			Irradiated ^a			Aged ^b		
	Specimen	J_{Ic} (kJ/m ²)	Tearing modulus	Specimen	J_{Ic} (kJ/m ²)	Tearing modulus	Specimen	J_{Ic} (kJ/m ²)	Tearing modulus
-75	A13G	116	62	A15F	79	29			
-75	H2	145	35	A15G	60	31			
20	A13D	132	203				H7	104	166
20	A10G	169	159				H8	144	182
30				A13A	157	158			
50				A15C	121	147			
120	A10E	136	233				H9	119	248
120	H5	129	207	A10F	108	161	AA03	94	282
120	H3	114	214						
200	H6	95	220						
200	H4	100	221						
288	A15D	76	278				H10	85	218
288	A13C	70	171	A15A	25	226	AA04	93	209
288	H1	83	185				AA02	59	230

^aIrradiated 637 h at 288°C to a fluence of 2.4×10^{19} neutrons/cm² (>1 MeV).

^bThermally aged at 288°C for 1605 h.

Figure 6. Effects of neutron irradiation and thermal aging at 288°C on the initiation fracture toughness, J_{IC} , of three-wire stainless steel cladding at various test temperatures.

Figure 7. Effects of neutron irradiation and thermal aging at 288°C on the deformation J-integral tearing modulus of three-wire stainless steel cladding at various test temperatures.

3.2 Effects of Thermal Aging for 20,000 h at 288 or 343°C

3.2.1 Charpy Impact Properties

The CVN test results shown in Table 7 indicate that: (1) thermal aging at 288°C slightly increased the 41-J transition temperature, slightly decreased the upper-shelf impact energy, and increased the 68-J transition temperature; and (2) increasing the thermal aging time from 1605 to 20,000 h at 288°C did not affect the impact properties. The effects of thermal aging on lateral expansion were small and showed a relatively larger scatter.

The effects of thermal aging at 343°C on the upper and lower shelves (for both impact energy and lateral expansion) were similar to those due to aging at 288°C for 1605 or 20,000 h. However, the 343°C aging caused much greater increases in the 41- and 68-J transition temperatures compared to aging at 288°C, as shown in Table 7 and Figures 8 through 11. A comparison of the effects of thermal aging on the Charpy impact energy and lateral expansion is shown in Figures 12 and 13.

3.2.2 Tensile Properties

The effects of thermal aging at 288 or at 343°C on the yield and ultimate tensile strength were negligible (small measured increases), as can be seen from Table 8. However, the total elongation decreased approximately 40 to 49% at -125°C, did not change at room temperature, and increased 19 to 37% at 288°C. Figures 14 through 16 show a comparison of the tensile test results for the three cladding conditions (as-received, aged 20,000 h at 288°C, and aged 20,000 h at 343°C).

3.2.3 Fracture Toughness

The effects of thermal aging at 288 or 343°C for 20,000 h are summarized in Tables 9 and 10 and shown in Figures 17 through 20. Thermal aging at these temperatures decreased the tearing modulus. However, the effects of thermal aging on the initiation fracture toughness, J_{Ic} , were very small but inconsistent. The small number of specimens tested showed both higher and lower J_{Ic} toughness values at the three test temperatures of 20, 120, and 288°C, indicating that thermal aging up to 20,000 h did not significantly degrade the initiation fracture toughness, J_{Ic} , of this three-wire stainless steel cladding material.

4. Conclusions and Description of Future Work

Thermal aging of three-wire stainless steel weld overlay cladding at 288°C for 1605 h resulted in an appreciable decrease (16%) in the CVN USE, but the effect on the 41-J transition temperature shift was negligible (3°C). The combined effect following neutron irradiation at 288°C to a fluence of 5×10^{19} neutrons/cm² (> 1 MeV) was a 22% reduction in the CVN USE and a 29°C shift at the 41-J level. The effect of thermal aging on tensile properties was very small or negligible. However, the combined effect after neutron irradiation was an increase (6 to 34% at test temperatures for 288 to -125°C) in the yield strength and no apparent change in ultimate strength and total elongation. Neutron irradiation reduced the initiation fracture toughness (J_{Ic}) much more than did thermal aging. Furthermore, irradiation slightly reduced the tearing modulus, but no reduction was caused by thermal aging alone.

The effects of short-term thermal aging on dynamic fracture toughness values will be reported separately. The effects of long-term thermal exposure (50,000 h and more) will be investigated when the specimens become available. Future work will include examining cladding from decommissioned reactors (such as the German Gundremmingen Reactor) using miniature specimen techniques to compare to ORNL's three-wire cladding.

Table 7. Charpy impact test results for stainless steel three-wire series-arc cladding (L-S orientation)

Material condition	Transition temperature (°C)			Energy (J)		Lateral expansion (mm)	
	41 J	68 J	0.38 mm	Upper shelf	Lower shelf	Upper	Lower ^a
As-received	−43	6	−51	83	14	1.146	0.229
Aged at 288°C for 1605 h	−40	34	−65	70	11	1.098	0.119
Aged at 288°C for 20,000 h	−40	38	−69	75	9	1.208	0.174
Aged at 343°C for 20,000 h	−27	61	−55	71	10	1.223	0.137

^aFew CVN specimens were tested at the lower shelf; additional specimens could improve the uncertainty of lateral expansion values at the lower shelf.

Figure 8. Effect of thermal aging at 288°C for 20,000 h on the Charpy impact energy of three-wire series-arc stainless steel cladding, L-S orientation.

Figure 9. Effect of thermal aging at 288°C for 20,000 h on the Charpy impact lateral expansion of three-wire series-arc stainless steel cladding, L-S orientation.

Figure 10. Effect of thermal aging at 343°C for 20,000 h on the Charpy impact energy of three-wire series-arc stainless steel cladding, L-S orientation.

Figure 11. Effect of thermal aging at 343°C for 20,000 h on the Charpy impact lateral expansion of three-wire series-arc stainless steel cladding, L-S orientation.

Figure 12. Comparison of the effects of thermal aging at 288 or 343°C for 20,000 h on the Charpy impact energy of three-wire series-arc stainless steel cladding, L-S orientation.

Figure 13. Comparison of the effects of thermal aging at 288 or 343°C for 20,000 h on the Charpy impact lateral expansion of three-wire series-arc stainless steel cladding, L-S orientation.

Table 8. Tensile properties of three-wire series-arc cladding specimens in the L orientation

Specimen	Test temperature (°C)	Tensile strength (MPa)		Total elongation (%)
		Yield	Ultimate	
As-received				
A16A	-125	357	1169	39
A16B	-125	338	1150	39
A26A	21	301	574	47
A26B	21	297	577	47
A20A	288	218	409	23
A20B	288	252	402	20
Aged at 288°C for 20,000 h				
BAT02	-127	386	1215	23
BAT05*	-127			
BAT01	21	309	579	47
BAT04	21	315	562	49
BAT03	288	230	396	32
BAT06	288	232	391	27
Aged at 343°C for 20,000 h				
T302	-127	399	1073	20
T305*	-127			
T301	25	315	576	47
T304	25	322	576	48
T303	288	240	409	29
T306	288	241	430	23

*Specimen broke at shoulder.

Figure 14. Comparison of the effects of thermal aging at 288 or 343°C for 20,000 h on the yield strength of three-wire series-arc stainless steel cladding.

Figure 15. Comparison of the effects of thermal aging at 288 or 343°C for 20,000 h on the ultimate strength of three-wire series-arc stainless steel cladding.

Figure 16. Comparison of the effects of thermal aging at 288 or 343°C for 20,000 h on the total elongation of three-wire series-arc stainless steel cladding.

Table 9. Unloading compliance J-R test results of as-received and thermally aged 12.7-mm-thick three-wire stainless steel cladding fracture toughness specimens (10% side-grooved on each side)

Test temperature (°C)	As-received			Thermally aged at 288°C for 1605 h			Thermally aged at 288°C for 20,000 h		
	Specimen	J _{IC} (kJ/m ²)	Tearing modulus	Specimen	J _{IC} (kJ/m ²)	Tearing modulus	Specimen	J _{IC} (kJ/m ²)	Tearing modulus
-75	A13G	116	62						
-75	H2	145	35						
20	A13D	132	203	H7	104	166	AA05	159	143
20	A10G	169	159	H8	144	182	AA07	153	149
120	A10E	136	233	H9	119	248	AA09	147	198
120	H5	120	207	AA03	94	282	AA11	175	174
120	H3	114	214						
200	H6	95	220						
200	H4	100	221						
288	A15D	76	278	H10	85	218	AA13	91	173
288	A13C	70	171	AA04	93	209	AA15	77	142
288	H1	83	185	AA02	59	230			

Table 10. Unloading compliance J-R test results of as-received and thermally aged 12.7-mm-thick three-wire stainless steel cladding fracture toughness specimens (10% side-grooved on each side)

Test temperature (°C)	As-received			Thermally aged at 288 °C for 20,000 h			Thermally aged at 343 °C for 20,000 h		
	Specimen	J _{lc} (kJ/m ²)	Tearing modulus	Specimen	J _{lc} (kJ/m ²)	Tearing modulus	Specimen	J _{lc} (kJ/m ²)	Tearing modulus
-75	A13G	116	62						
-75	H2	145	35						
20	A13D	132	203	AA05	159	143	H11	152	134
20	A10G	169	159	AA07	153	149	H12	112	119
120	A10E	136	233	AA09	147	198	H13	135	175
120	H5	120	207	AA11	175	174	H14	134	156
120	H3	114	214						
200	H6	95	220						
200	H4	100	221						
288	A15D	76	278	AA13	91	173	H15	111	147
288	A13C	70	171	AA15	77	142	H16	110	153
288	H1	83	185

Figure 17. Effect of thermal aging at 288°C for 1605 or 20,000 h on the initiation fracture toughness (J_{IC}) of three-wire series-arc stainless steel cladding.

Figure 18. Effect of thermal aging at 288°C for 1605 or 20,000 h on the tearing modulus of three-wire series-arc stainless steel cladding.

Figure 19. Comparison of the effects of thermal aging at 288 or 343°C for 20,000 h on the initiation fracture toughness (J_{Ic}) of three-wire series-arc stainless steel cladding.

Figure 20. Comparison of the effects of thermal aging at 288 or 343°C for 20,000 h on the tearing modulus of three-wire series-arc stainless steel cladding.

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11. ABSTRACT (200 words or less)

Thermal aging of three-wire series-arc stainless steel weld overlay cladding at 288°C for 1605 h resulted in an appreciable decrease (16%) in the Charpy V-notch (CVN) upper-shelf energy (USE), but the effect on the 41-J transition temperature shift was very small (3°C). The combined effect of aging and neutron irradiation at 288°C to a fluence of 5×10^{19} neutrons/cm² (> 1 MeV) was a 22% reduction in the USE and a 29°C shift in the 41-J transition temperature. The effect of thermal aging on tensile properties was very small. However, the combined effect of irradiation and aging was an increase in the yield strength (6 to 34% at test temperatures from 288 to -125°C) but no apparent change in ultimate tensile strength or total elongation. Neutron irradiation reduced the initiation fracture toughness (J_{Ic}) much more than did thermal aging alone. Irradiation slightly decreased the tearing modulus, but no reduction was caused by thermal aging alone. Other results from tensile, CVN, and fracture toughness specimens showed that the effects of thermal aging at 288 or 343°C for 20,000 h each were very small and similar to those at 288°C for 1605 h. The effects of long-term thermal exposure time (50,000 h and greater) at 288°C will be investigated as the specimens become available in 1996 and beyond.

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