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Assessment of Radiation Effects Relating to Reactor Pressure Vessel Cladding

W. R. Corwin

Prepared for the
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CONTENTS

FOREWORD

The work prepared here was performed at Oak Ridge National Laboratory (ORNL) under sponsorship of the U.S. Nuclear Regulatory Commission's (NRC) Heavy-Section Steel Technology Program, which is directed by ORNL. The program is conducted as part of the ORNL Pressure Vessel Technology Program, of which C. E. Pugh is manager. The manager for the NRC is Milton Vagins.

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ASSESSMENT FOF RADIATION EFFECTS RELATING TO REACTOR PRESSURE VESSEL CLADDING

W. R. Corwin

ABSTRACT

Because the weld overlay cladding on the interior of light-water reactor pressure vessels was applied for corrosion resistance and not for structure, little attention has been given to the potential of mechanical property degradation due to radiation exposure. In light of the concerns recently raised regarding overcooling transients in nuclear power reactors, it has been suggested that any such degradation could adversely affect the serviceability and/or integrity of the vessel.

A literature survey assesses the current knowledge regarding the effects of neutron radiation on the mechanical and fracture properties of stainless steel weld overlay cladding under conditions relevant to light-water reactor operation. In particular, effects on the material's microstructure and tensile, fatigue, impact, and fracture properties are examined. Although information is lacking on the specific materials under the exact irradiation conditions of interest, a wealth of information is available on irradiated stainless steel weldments in general, from which basic behavioral trends can be obtained.

Some irradiation embrittlement apparently does occur in stainless steel weldments at the relatively low temperatures and fluences typical of light-water reactors. Tensile strength increases and ductility decreases. Low-cycle fatigue behavior is degraded somewhat, but high-cycle fatigue and fatigue crack growth seem largely unaffected.

Effects of δ-ferrite on fracture resistance are small in both irradiated and unirradiated materials. Notch impact and fracture toughness are both reduced by irradiation, and a dependence of toughness on testing rate, not seen in wrought material, is indicated.

INTRODUCTION

The interior of light-water reactor (LWR) pressure vessels is typically clad with a corrosion-resistant weld overlay to prevent excessive corrosion products from contaminating the reactor coolant. Historically, it has been felt that the effect of irradiation on the cladding material would not adversely affect the serviceability or integrity of the pressure vessel.[1] Recently, however, concern that this judgment may not always be conservative has been raised, so existing literature was examined to establish the current state of knowledge concerning radiation effects on the cladding of reactor pressure vessels (RPVs) of LWRs.

With the exception of a few early reactors, in which thin-gage stainless steel sheet was stitch-welded or roll-bonded to the interior of vessels, the common method of applying the protective cladding has been to use a weld overlay procedure. This was done in earlier reactor vessels by single or multiwire submerged arc techniques, but more recently submerged arc strip cladding has come into prominent use. Typical cladding materials are types 308, 309, and 312 weld metals.

In examining existing information relevant to irradiation effects on reactor pressure vessel cladding, we discovered no data specifically on types 308, 309, or 312 cladding on a ferritic plate. However, a host of information on irradiation effects in both wrought stainless steel and stainless steel weldments was compiled and will be reported here. Included are baseline data on unirradiated material and effects of irradiation on microstructure, tensile properties, fatigue and fatigue crack propagation, notched impact properties, and fracture toughness. The data indeed indicate grounds for concern because, at fluences approaching the levels seen on the interior of RPVs of pressurized-water reactors [as low as 5×10^{23} neutrons/m^2 (>0.1 MeV)], marked decreases in tensile ductility, notched impact energy, and fracture toughness in types 304, 308, and 316 weldments occur. Moreover, a strong rate dependence of fracture toughness in weld metals is seen, unlike in wrought materials, indicating that under dynamic conditions toughness is lower.

MICROSTRUCTURAL EFFECTS

Basic theory states that at relatively low temperatures and fluences, the primary cause of irradiation hardening and loss of ductility in austenitic material is the development of small vacancy or interstitial clusters in the form of loops, three-dimensional arrays, and unspecified aggregates, which, in sufficient concentration, impede dislocation motion. The result is an increase in macroscopic flow stress. As the material deforms, annihilation of the defects by moving dislocations reduces work-hardening rates and causes premature plastic instability. As the temperature increases, approaching or passing one-half the absolute melting point $T_m/2$, the defects causing the hardening become unstable, so this cause of irradiation hardening disappears at higher temperatures. Above $T_m/2$, the principal cause of loss of ductility is the formation of helium from (n,α) reactions and subsequent migration to and formation of bubbles at grain boundaries.[2-3] Although the temperature regimes in which these forms of radiation damage occur vary, the service conditions seen by RPV cladding are such that we need be primarily concerned only with lower temperature damage mechanisms for LWR applications.

Within the temperature range up to $T_m/2$, several studies have investigated the effects of irradiation temperature on microstructure and resulting mechanical properties in wrought stainless steel.[4-6] As the temperature of irradiation is increased from 24°C to about 650°C at a constant level of fluence, the size of the defect clusters grows and their number decreases. Irradiation from 300°C down to room temperature seems to create the sizes and densities of defect clusters most damaging to ductility in austenitic materials for fluences up to about 10^{26} neutrons/m^2 (>0.1 MeV). Above this temperature range the relative radiation hardening declines.

Effects in weld metal are likely affected by the duplex austenite-ferrite metallurgical structure, as is discussed below, but the basic damage mechanisms should still apply.

TENSILE PROPERTIES

In general, austenitic weld metal as deposited or stress relieved is stronger and less ductile than the corresponding base metal; hence, the problem of its response to irradiation hardening is more acute. Numerous researchers have examined the tensile properties of types 304, 308, and 316 weld metals as a function of irradiation conditions. The tensile data on unirradiated material are compiled in Tables 1 and 2. The principal variables affecting the tensile properties of irradiated weld metal are the irradiation temperature, the total fluence, the average energy of the neutrons in the irradiation, and the amount of δ-ferrite in the weld metal.

Table 1. Tensile properties of unirradiated types 304, 308, and DIN 1.4948 stainless steel weldments

(Compiled from refs. 9, 10, 12, 15, 16, 19, 24, and 25)

Temperature (°C)	Strength (MPa)		Uniform elongation (%)	Reduction of area (%)
	Yield	Ultimate tensile		
20–24	400–558	600–717	28–42	35–63
149	352–427	503–565	25–31	48–56
200	290–380	435–485	18–33	45–58
260	345–448	473–565	18–27	32–51
320	275–355	430–480	17–32	33–70
371	260–407	430–545	20–32	32–60
385	320	485	24	51
400	304	454		
427	260–350	425–475	17–33	47–58

Table 2. Tensile properties of unirradiated types 316 and 316L stainless steel weldments

(Compiled from refs. 16, 17, 24, and 25)

Temperature (°C)	Strength (MPa)		Reduction of area (%)
	Yield	Ultimate tensile	
20–24	351–478	600–680	34
260	310–352	469–496	
400	330	465	
427	327		

The temperature range in which neutron irradiation of austenitic materials is most damaging is up to about 300°C, corresponding to the production of critical size and density of defect clusters. This has been demonstrated in both wrought[4,5,7,8] and weld metals.[9] For irradiation temperatures above about 300°C, the amount of increase in strength and decrease in ductility decreases to about 600°C, above which little increase in strength is observed. Higher irradiation temperatures produce a lowering of ductility due to helium generation and coalescence, but this is well above the temperatures of interest to LWR applications. Experimental results detailing irradiation temperature dependence of tensile properties are included in Appendix A.

No noticeable change in tensile properties is observed in either austenitic wrought[2,7,8] or weld metals[10,11] until a fluence of about 5×10^{23} neutrons/m^2 (>0.1 MeV) has accumulated. Above this level, increasing fluence produces substantial tensile property degradation in the range from 50 to 350°C. In wrought types 304 and 308, tensile ductility was reduced up to 50% at 2×10^{24} neutrons/m^2 and 70% at 10×10^{24} neutrons/m^2 (>1 MeV) in irradiations at 50 and 290°C (ref. 8). At greater exposures under similar conditions (up to 5×10^{26} neutrons/m^2), tensile ductility approaches zero.[2,12]

Irradiations on AISI type 308 and DIN 1.4948 stainless steel (similar to AISI type 304) weld metals were conducted at somewhat higher temperatures,[10,11] 400 to 500°C, where embrittlement should not be as severe. Small decreases in ductility not accompanied by increases in tensile strength were observed at fast fluences as low as roughly 1×10^{23} neutrons/m^2 (> 0.1 MeV) at very low strain rates. As the fluence was increased to 5×10^{24} neutrons/m^2, decreases in ductility varying from 10 to 70% were observed.

The effect of mean energy of the neutron spectrum on irradiation embrittlement in stainless steel below 300°C has not been well documented, but, in extensive work on types 304 and 316 plate and type 308L weld metal for irradiation temperatures between 371 and 426°C, a strong effect has been demonstrated.[13] For total fluences from 0.2×10^{26} to 3.5×10^{26} neutrons/m^2 for several spectra in which the mean neutron energy ranged from 0.17 to 0.76 MeV, a significantly higher exposure was required to produce the same damage as the spectrum became softer. An empirical correlation of fluence, spectrum, and temperature effects was developed but is strictly applicable only for the experimental conditions examined.

The δ-ferrite content has been suggested as a possible factor in the strength and ductility of austenitic welds. In extensive studies on unirradiated weld metal, however, ferrite content has been shown to have, at most, a very mild strengthening effect.[14,15] In other studies where this effect has been more pronounced, compositional differences may outweigh the effects of the ferrite.[16] In irradiated stainless steel welds, the effect of δ-ferrite on the tensile properties has not been well established, but indications are that it is still not a major factor.[14,16,17]

FATIGUE AND FATIGUE CRACK PROPAGATION

A substantial amount of research has been performed on effects of irradiation on the fatigue and fatigue crack propagation characteristics of both wrought and welded stainless steel, but virtually all of it investigated at temperatures and fluences beyond applicability to LWRs. Nonetheless, some insight into irradiation effects on austenitic materials in these areas may be gained by examining previous work.

Effects of irradiation on smooth bar fatigue life of both wrought and weld metal appear to follow the general trend of unirradiated material. Increases in tensile strength and decreases in ductility tend to improve high-cycle fatigue and degrade low-cycle fatigue behavior, respectively. In very high-fluence irradiations [1.6×10^{27} neutrons/m^2 (>0.1 MeV)] on wrought type 304 stainless steel at temperatures from 370 to 470°C, fatigue life increased at lower irradiation temperatures but decreased at the higher ones, reflecting the increased strength at the lower irradiation temperatures.[18] In irradiations on type 308 weld metal at somewhat higher temperatures to fluences of 10^{21} to 10^{26} neutrons/m^2 (>0.1 MeV), a small improvement in high-cycle fatigue life and a small decrease in low-cycle fatigue life were observed.[19]

A lower fluence irradiation on DIN 1.4948 weld metal of 0.1×10^{24} to 5×10^{24} neutrons/m^2 (>0.1 MeV) at 450 to 550°C produced no significant effect on fatigue life.[10]

The effect of high fluence on the fatigue crack propagation in types 308 and 316 stainless steel welds has been shown to be minimal at an irradiation temperature of 427°C, but it becomes rather detrimental from 600 to 650°C (ref. 20). No results at temperatures and fluences more applicable to LWR cladding could be found. The effect of δ-ferrite content on the macroscopic crack growth rate of unirradiated type 308 stainless steel weld metal has been shown to be insignificant over a wide range of temperatures and ferrite contents. The only noticeable effect of increasing ferrite content in the range 260 to 427°C was the misdirection of the crack front around the ferrite particles at low stress intensities. No macroscopic effect on growth rate could be measured.[21]

Experimental results detailing irradiation effects on fatigue crack propagation behavior of austenitic weldments are included in Appendix B.

TOUGHNESS

Toughness effects of irradiation on stainless steel welds have been examined primarily by use of notched impact tests (Charpy and dynamic tear) and K from J-integral assessment procedures using precracked three-point bend specimens (both dynamic and static).

The primary variables affecting the toughness of types 304, 308, and 316 stainless steel weldments as measured by notched impact tests are δ-ferrite content, test and irradiation temperatures, and fast neutron fluence. The effect of the amount of δ-ferrite on the toughness of types 304 and 308 weldments has been extensively examined at various test temperatures in both unirradiated[14-17,22-23] and irradiated[14,16-17] material. In the unirradiated material, as the content of δ-ferrite decreases through the range typically encountered in welds (ferrite number FN from 19 to 5), only a small increase, if any, is seen in the notch toughness of types 304 and 308 welds. At very low ferrite contents (1.9 FN) a small additional increase is observed. In the temperature range over which these studies were conducted, 20 to 482°C, the toughness increased slightly with increasing temperature. These test results are summarized in Tables 3 and 4.

In weld metal irradiated over a fluence range of 8×10^{23} to 1.5×10^{25} neutrons/m^2 (>0.1 MeV) and a temperature of 260 to 482°C, only a very small increase in embrittlement was seen with increasing ferrite content.

At the fluences and temperatures at which irradiation embrittlement occurs, large decreases in both Charpy V-notch and dynamic tear energies occur at relatively low fluences. In an irradiation of type 308 stainless steel weld metal to a fluence of 8×10^{23} neutrons/m^2 (>0.1 MeV) at 260°C, Charpy energies dropped from unirradiated values of 74 to 115 J down to as low as 24 J (ref. 14). Under similar irradiation conditions, the Charpy energy of type 316 weld metal was reduced from 68 to 81 J to as low as 48 J (ref. 17).

Irradiation at higher temperatures from 371 to 449°C and higher fluences from 0.1×10^{25} to 15×10^{25} neutrons/m^2 (>0.1 MeV) produced similar effects, reducing Charpy energies to below 27 J (refs. 15, 23). This trend of marked reduction of notched impact energy due to irradiation embrittlement has been confirmed by dynamic tear testing.[17,23]

Table 3. Effects of temperature and δ-ferrite content on notched impact test results of unirradiated types 304 and 308 stainless steel weld metal

(Compiled from refs. 14, 15, 16, 17, 22, and 24)

Temperature (°C)	Ferrite number	Impact energy (J)	
		Charpy V-notch	"5/8 in. dynamic tear"
20–24	1.9	104–112	
	4.4	80–94	
	5.2	84–88	814–845
	7.2	125[a]	
	9.4	70–73	
	10.4	72–81	792–808
	15–15.7	62–72	742–816
	19.0	73–87	821–854
260	5.2	106–114	1216
	10.4	95–106	1098
	15.7	87–100	1320
	19.0	104–108	1135
371	5.2	100–110	1063–1230
	7.7	146[a]	1315[a]
	10.4	95–110	945–1124
	15.7	88–111	945–1332
	19.0	105–118	1050–1087
427	15.0	82	817
482	5.2	106–111	1250
	7.7	155[a]	1175[a]
	10.4	99–104	1110
	15.7	72–98	894–1296
	19.0	102	1094

[a] Weld metal with controlled residual elements.

Table 4. Effect of temperature on the Charpy V-notch impact results of unirradiated type 316 stainless steel weld metal

(Compiled from refs. 17 and 24. Ferrite number between 7 and 10.5)

Temperature, °C	24	260	371	427	482
Charpy energy, J	70–95	68–114	106–108	111	103–110

The qualitative material degradation obtained in notched impact tests has basically been reconfirmed in fracture toughness K_J testing using precracked three-point bend bars and a J-integral analysis. Delta-ferrite and temperature have only a small effect on the K_J of types 304, 308, and 316 stainless steel weld metal in both unirradiated and irradiated conditions for ferrite contents from 5 to 19 FN and temperatures from 24 to 482°C (refs. 14, 16, 24).

One unexpected result of fracture toughness tests on type 308 stainless steel weld metal was the revelation of a strong dependence of fracture toughness on test velocity.[14] The fracture toughness of unirradiated weld metal tested dynamically was reduced to below half of the value determined in static tests. Even within the dynamic testing regime, a large inverse dependence of fracture toughness on impact velocity was observed. However, a similar dependence of fracture toughness on temperature has not been observed in wrought stainless steel, as shown in Table 5.

Table 5. Fracture toughness of unirradiated austenitic stainless steel welds by J-integral assessment procedures

(Compiled from refs. 14, 16, and 25)

Stainless steel type	Temperature (°C)	Fracture toughness, K_J (MPa·$\sqrt{m}$)	
		Static	Dynamic, 2.4–5.1 m/s
304, 308	20–24	194–274 163[a]	121–176
	260		135–274
	400	124 137[a]	
	482		125–279
316	20	129 172[a]	
	400	104 94[a]	

[a] Specimens similar to precracked Charpy specimens but 20 × 20 × 110 mm.

The reduction of toughness in notched impact tests of type 308 stainless steel weld metal irradiated at 260°C to a fluence of 8×10^{23} neutrons/m^2 (>0.1 MeV) is paralleled by the results of fracture toughness K_J tests.[14] Fracture toughness levels of 121 to 235 MPa·$\sqrt{m}$ were reduced to as low as 76 MPa·$\sqrt{m}$. In some cases no ductility at all was observed as the specimens fractured before yielding. At temperatures to 427°C and fluences to 1.5×10^{26} neutrons/m^2 (>0.1 MeV), the toughness of types 304, 308, and 316 weld metal was reduced as low as 50 MPa·$\sqrt{m}$.[16,25]

That the toughness of austenitic weld metal is not consistently reduced by moderate level irradiation can be concluded from work on type 316 weldments. In one case, three-point bend specimens irradiated at 350°C to 2×10^{24} to 6×10^{24} neutrons/m^2 (>0.1 MeV) yielded J_{Ic} values within the scatter band of the unirradiated material, 38 to 62 kJ/m^2, and only a slight degradation of the R-curves of the irradiated material.[26] On the other hand, irradiation at 260°C to a fluence of only 5.1×10^{23} neutrons/m^2 (>0.1 MeV) dropped the unirradiated J_{Ic} of 114 kJ/m^2 to 49 kJ/m^2 and steepened the R-curve of the weld metal appreciably.[27]

Experimental results detailing irradiation effect on toughness of austenitic weldments are included in Appendix C.

SUMMARY

Although no specific information is available on the effects of neutron irradiation on thin layers of stainless steel cladding on ferritic substrates, a large body of data on such effects in types 304, 308, and 316 weldments, from which inferences relevant to RPV cladding may be drawn, does exist. It appears that the following conclusions based on available data concerning stainless steel weldments and their exposure to neutron irradiation can be made.

1. An increase in tensile strength and a decrease in tensile ductility occur with fluences as low at 5×10^{23} neutrons/m^2 (>0.1 MeV). These effects are most pronounced for irradiation temperatures below 300°C. Increasing the fluence to 5×10^{24} neutrons/m^2 can result in drops in ductility of 70%.

2. The mean energy of the neutron spectrum directly affects tensile embrittlement at a given fluence, with higher energies being the most damaging.

3. Delta-ferrite content has only a minor inverse effect on the strength, ductility, and toughness of both irradiated and unirradiated stainless steel welds.

4. Radiation-induced strengthening tends to improve smooth bar high-cycle fatigue characteristics and either slightly degrade or not affect low-cycle fatigue.

5. Effects of low- to moderate-temperature radiation exposure on the fatigue crack propagation behavior of weldments are negligible.

6. Substantial reductions in notch impact energy of stainless steel weldments have been observed at fluences as low as 8×10^{23} neutrons/m^2 (>0.1 MeV), resulting in Charpy V-notch energies as low as 24 J. No strong temperature dependence of notch impact energy in either irradiated or unirradiated material between 24 and 371°C was observed.

7. Analogous reductions in fracture toughness K_J under similar irradiation conditions were observed, with K_J dropping to as low as 76 $\mathrm{MPa}\cdot\sqrt{\mathrm{m}}$. In some cases no macroscopic ductility was observed, with specimens fracturing before to yielding. In contrast, limited results on J_{Ic} and J_R behavior showed only minor irradiation degradation.

8. A rate dependence of fracture toughness of stainless steel weldments not seen in wrought materials was observed, with high testing rates yielding the lowest values.

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APPENDIXES

Appendix A

TENSILE PROPERTIES OF AUSTENITIC STAINLESS STEEL BASE AND WELD METAL

This appendix contains excerpts of the original works from which the summary statements in the text regarding tensile properties were compiled. Since they appear in exactly the same form as in the original publication, the units of the properties are not necessarily consistent. A table for conversion factors is included in Appendix D.

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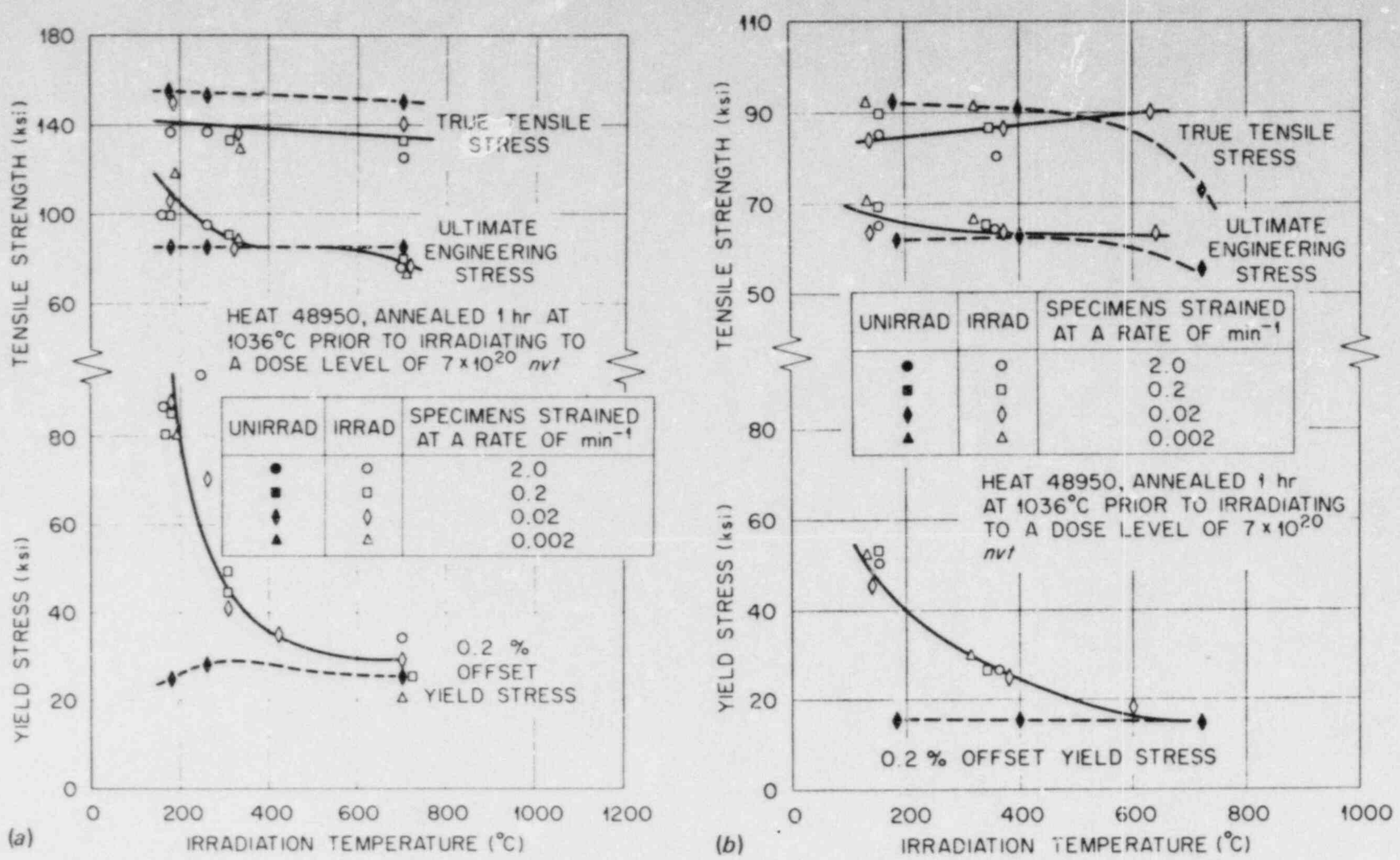

Fig. A.1. Effect of irradiation temperature on the tensile properties of wrought type 304 stainless steel. (*a*) Tested at room temperature. (*b*) Tested at 399°C. *Source*: W. R. Martin and J. R. Weir, "The Effect of Irradiation Temperature on the Postirradiation Stress Strain Behavior of Stainless Steel," pp. 251–68 in *Flow and Fracture of Metals and Alloys in Nuclear Applications*, ASTM STP 380, American Society for Testing and Materials, Philadelphia, 1964.

Table A.1. Tensile properties of type 304 wrought stainless steel irradiated to a fluence of 7×10^{24} neutrons/m^2 (fast) and 9×10^{24} neutrons/m^2 (thermal)

Tension Test Temperature, deg C	Irradiation Temperature, deg C	Strain Rate, in./in./min	Yield Stress, ksi, 0.2% Offset	Tensile Strength, ksi		Fracture Stress, ksi	True Strain, per cent		Total Engineering Elongation, measured in 1 in.
				Engineering Ultimate	True		Uniform	Fracture	
20	175	0.002	97.5	120.0	180.0	350.0	40.5	172.0	54.8
20	289	0.002	52.9	87.6	129.5	305.0	39.0	170.0	55.2
20	704	0.002	19.5	75.4	...	250.0	...	139.0	82.3
20	169	0.02	88.0	105.4	152.3	320.0	36.8	159.0	50.6
20	290	0.02	41.3	87.6	135.8	315.0	43.8	178.0	66.4
20	704	0.02	29.8	80.2	141.2	240.0	56.4	139.0	78.6
20	168	0.20	86.9	101.6	...	...	...	...	40.0
20	276	0.20	47.0	90.0	130.2	300.0	36.9	172.0	66.0
20	704	0.20	25.2	82.1	137.2	...	51.2	...	71.0
20	162	2.0	87.7	99.1	135.0	...	30.7	...	40.0
20	223	2.0	95.9	105.8	132.6	...	22.5	...	32.0
20	704	2.0	35.8	78.8	123.0	213.0	44.5	120.0	60.4
204	200	0.002	93.5	94.3	104.1	...	9.4	...	14.8
204	447	0.02	27.6	63.8	86.1	...	29.9	...	41.7
204	203	0.20	96.7	94.2	104.1	232.0	9.9	139.0	17.0
204	211	2.0	88.8	90.1	102.5	260.0	12.8	152.0	19.4
399	130	0.002	52.9	71.2	91.2	168.0	25.3	128.0	33.3
399	315	0.002	24.2	66.7	91.0	...	31.0	...	40.7
399	130	0.02	45.0	64.2	82.8	139.0	25.5	115.0	33.3
399	375	0.02	23.0	64.0	86.2	164.0	29.8	131.0	39.4
399	593	0.02	18.2	64.1	90.0	...	34.0	...	44.2
399	141	0.20	54.5	71.1	90.4	...	23.9	...	31.8
399	341	0.20	24.8	66.4	86.9	158.0	27.0	125.0	34.3
399	141	2.0	52.1	67.1	84.0	150.0	22.4	123.0	30.6
399	341	2.0	25.6	61.3	79.8	155.0	26.2	131.0	35.6
454	169	0.02	72.8	76.0	83.6	135.0	9.5	100.0	15.1
454	350	0.02	41.0	66.4	80.3	153.0	19.0	129.0	26.5
454	456	0.02	24.4	63.0	89.4	...	34.2	...	45.9
454	704	0.02	14.8	50.4	...	92.5	...	82.0	30.8
454	144	0.20	51.8	68.2	85.4	134.0	22.6	126.0	30.6
454	130	2.0	51.4	66.9	83.0	155.0	21.5	123.0	28.8

Source: W. R. Martin and J. R. Weir, "The Effect of Irradiation Temperature on the Postirradiation Stress Strain Behavior of Stainless Steel," pp. 251–68 in *Flow and Fracture of Metals and Alloys in Nuclear Applications*, ASTM STP 380, American Society for Testing and Materials, Philadelphia, 1964.

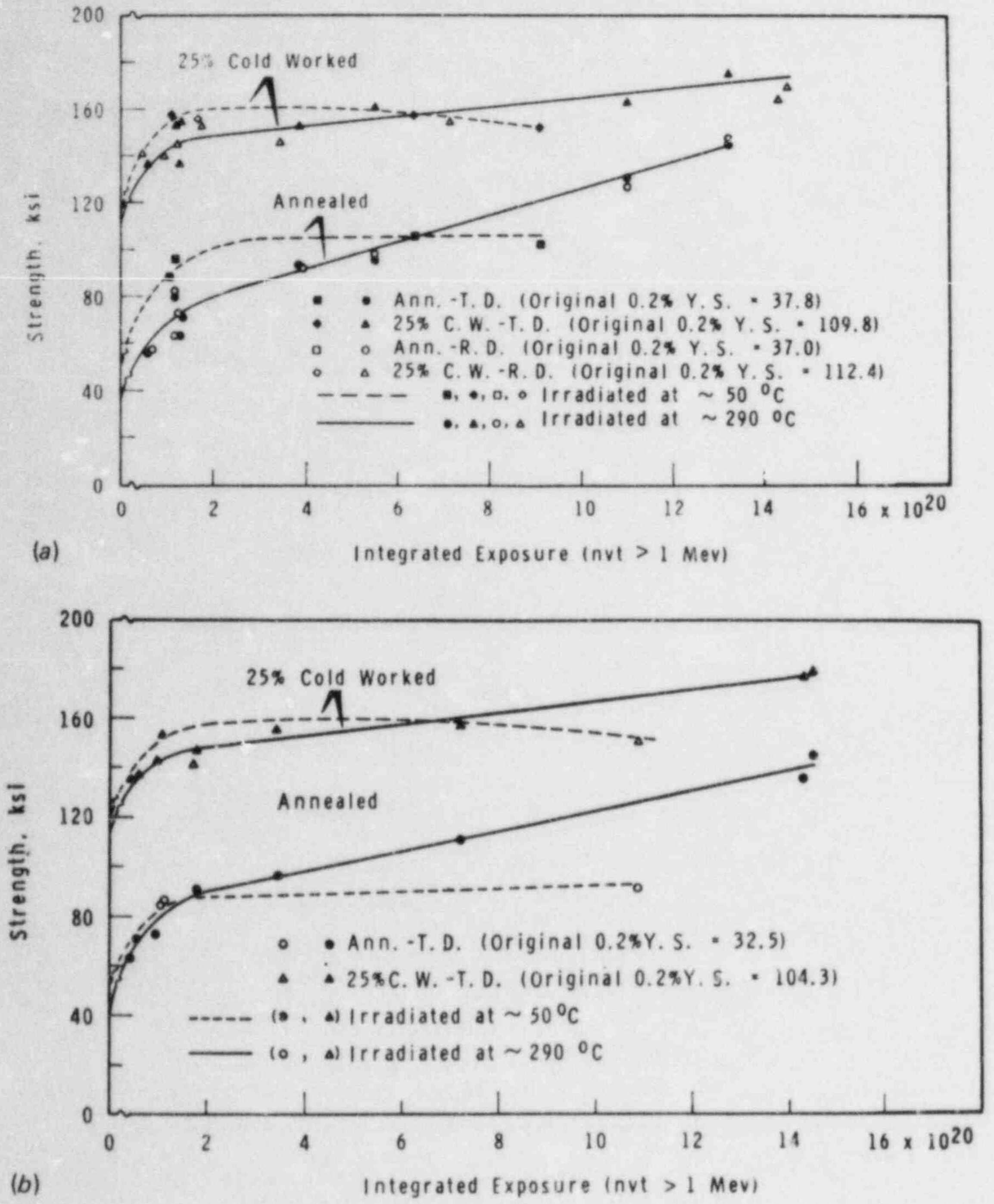

Fig. A.2. Effects of irradiation on the room-temperature yield strength of wrought stainless steel. (*a*) Type 348. (*b*) Type 304. *Source*: J. E. Irvin, A. L. Bement, and R. G. Hoagland, "The Combined Effect of Temperature and Irradiation on the Mechanical Properties of Austenitic Stainless Steels," pp. 236–50 in *Flow and Fracture of Metals and Alloys in Nuclear Applications*, ASTM STP 380, American Society for Testing and Materials, Philadelphia, 1964.

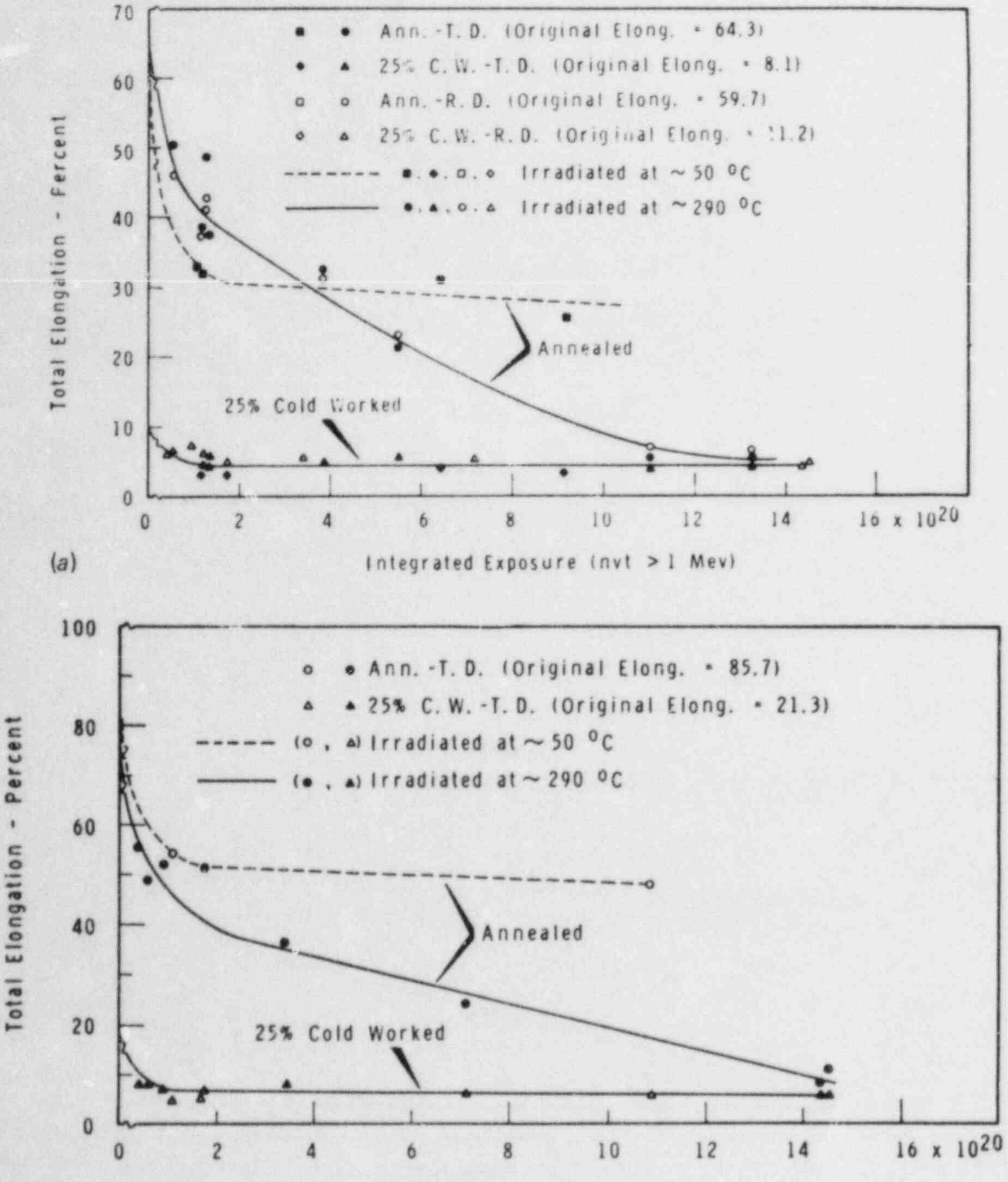

Fig. A.3. Effects of irradiation on the room-temperature tensile ductility of wrought stainless steel. (*a*) Type 348. (*b*) Type 304. *Source*: J. E. Irvin, A. L. Bement, and R. G. Hoagland, "The Combined Effect of Temperature and Irradiation on the Mechanical Properties of Austenitic Stainless Steels," pp. 236–50 in *Flow and Fracture of Metals and Alloys in Nuclear Applications*, ASTM STP 380, American Society for Testing and Materials, Philadelphia, 1964.

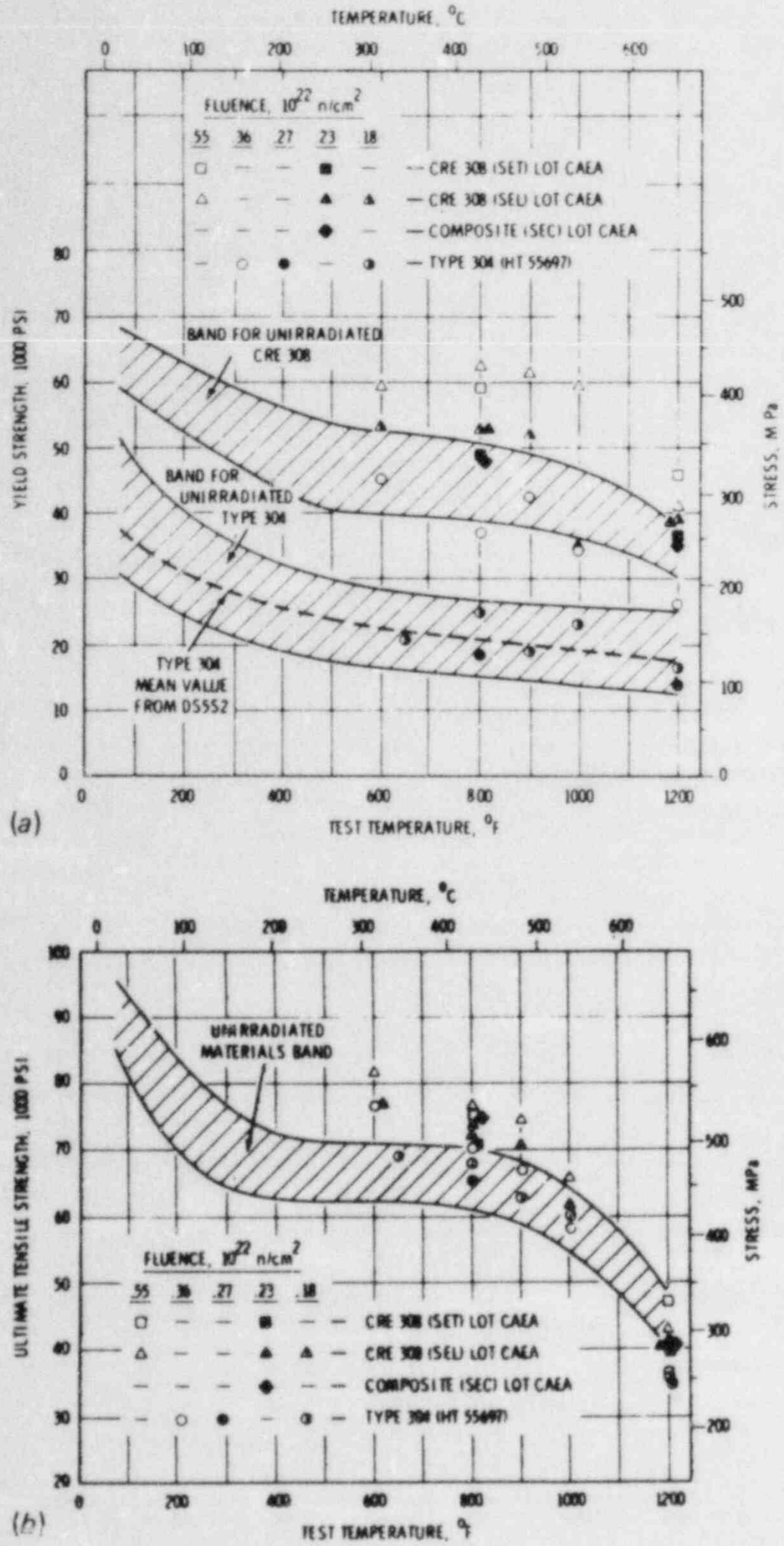

Fig. A.4. Effect of high-fluence irradiation (>1 MeV) at 426 to 482°C on the tensile strength of type 304 wrought stainless steel and type 308 stainless steel weld metal with controlled residual elements. (*a*) Yield strength. (*b*) Tensile strength. *Source*: A. L. Ward, "Irradiation Effects on Mechanical Properties of an SMAW-Deposited Type 308 Stainless Steel," *Weld. J. (Miami)* 8, 259–64-s (1975).

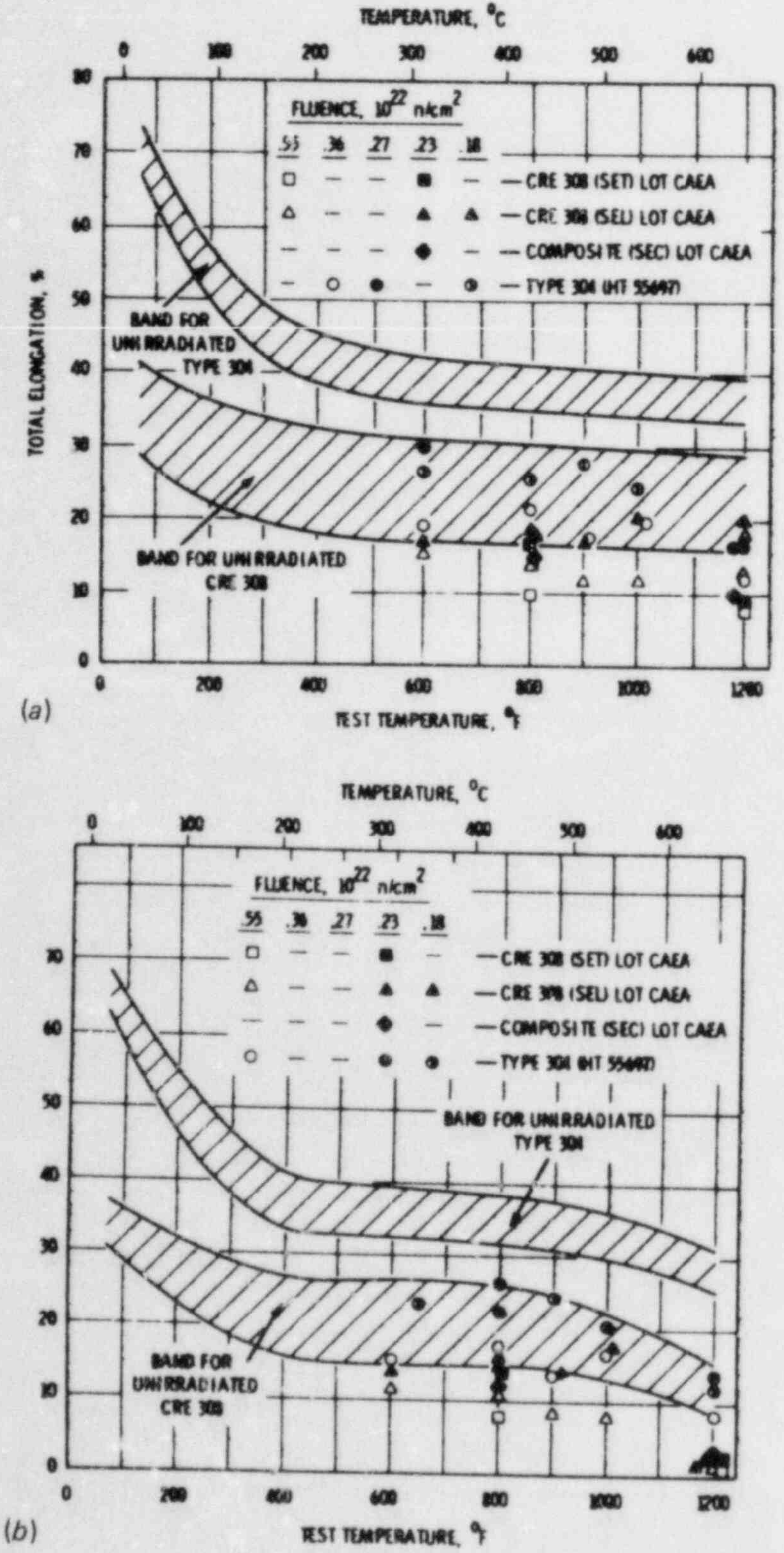

Fig. A.5. Effect of high-fluence irradiation (>1 MeV) at 426 to 482°C on the tensile elongation of type 304 wrought stainless steel and type 308 stainless steel weld metal with controlled residual elements. (*a*) Total elongation. (*b*) Uniform elongation. *Source*: A. L. Ward, "Irradiation Effects on Mechanical Properties of an SMAW-Deposited Type 308 Stainless Steel," *Weld. J. (Miami)* 8, 259–64-s (1975).

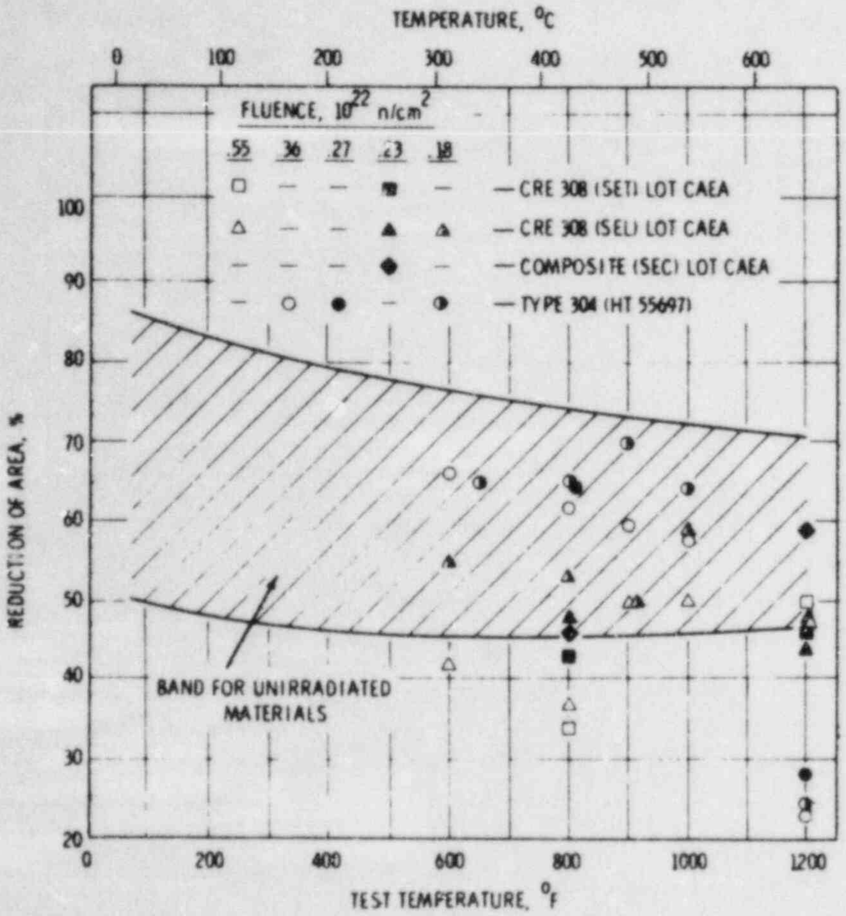

Fig. A.6. Effect of high-fluence irradiation (>1 MeV) at 426 to 482°C on the tensile reduction of area of type 304 wrought stainless steel and type 308 stainless steel weld metal with controlled residual elements. *Source*: A. L. Ward, "Irradiation Effects on Mechanical Properties of an SMAW-Deposited Type 308 Stainless Steel," *Weld. J. (Miami)* 8, 259–64-s (1975).

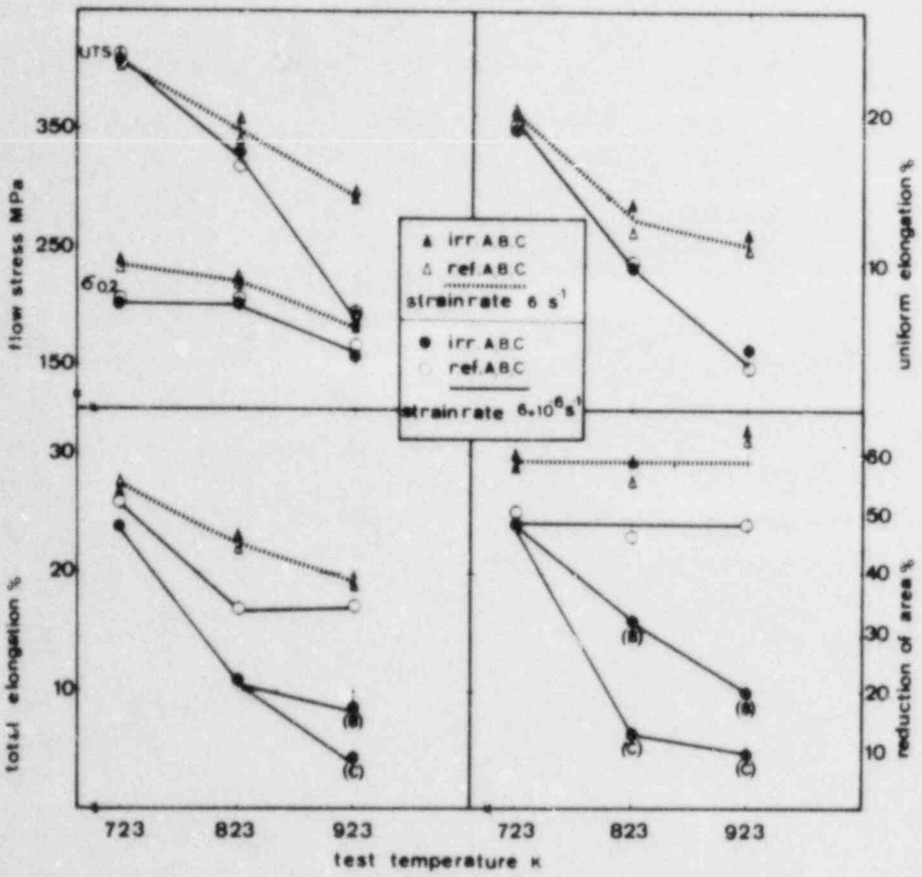

Fig. A.7. Effect of three irradiations on the tensile properties of type DIN 1.4948 stainless steel weld metal. Irradiation A was performed at 450°C to a fluence of 5×10^{24} neutrons/m^2 (>0.1 MeV). Irradiations B and C were performed at 550°C to fluences of 0.1×10^{24} and 5×10^{24} neutrons/m^2 (>0.1 MeV), respectively. *Source*: M. I. de Vries and B. von der Schaaf, "Tensile, Creep, and Fatigue Properties of Low Fluence Neutron Irradiated Welded Joints of DIN 1.4948," pp. 285–302 in *Effects of Radiation on Materials: Tenth Conference*, ASTM STP 725, American Society for Testing and Materials, Philadelphia, 1981.

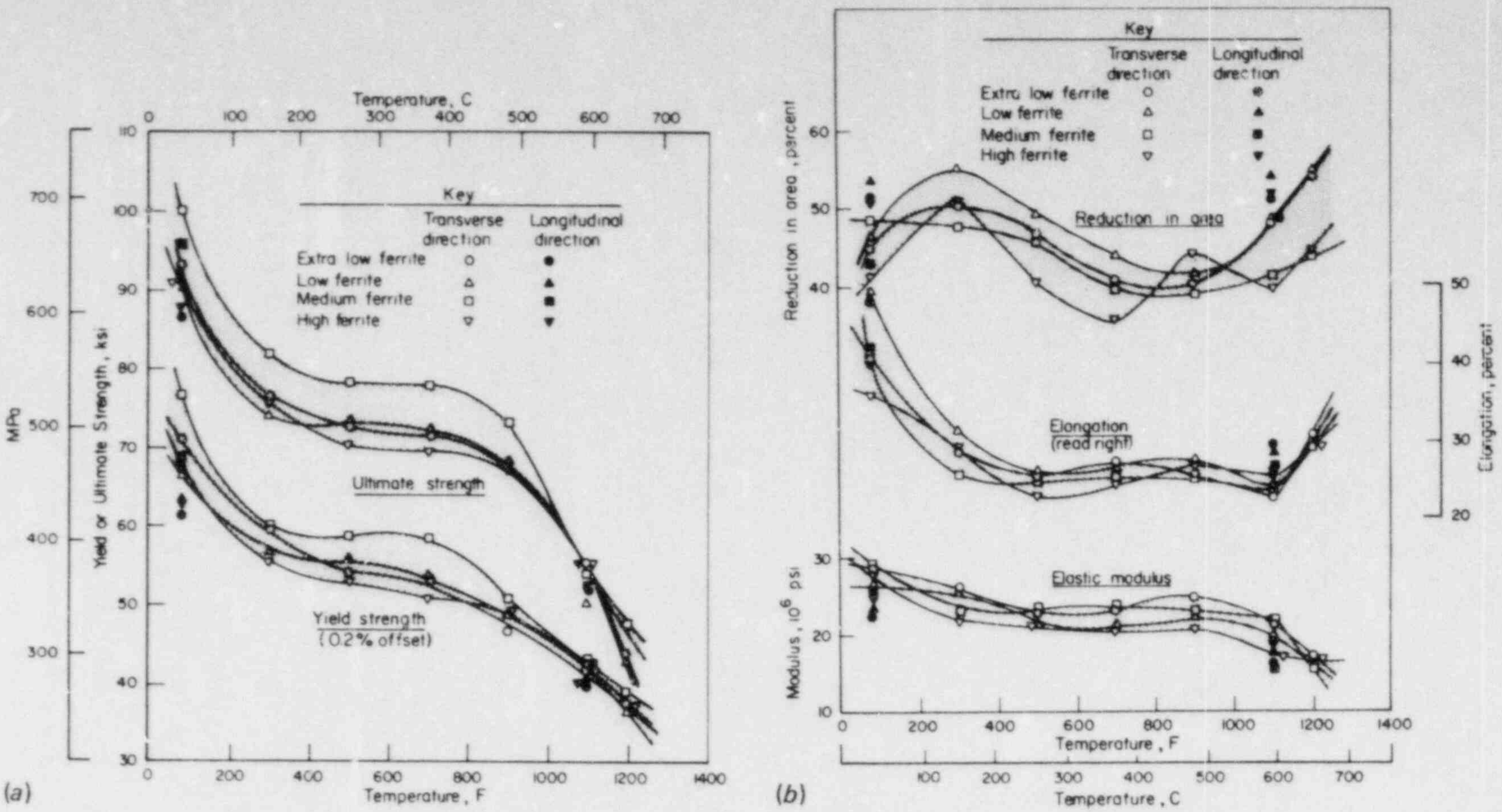

Fig. A.8. Tensile properties of unirradiated type 308 stainless steel weld metal with four δ-ferrite contents; extra low, 1.6 FN; low, 4.1 to 4.8 FN; medium, 9.2 to 9.7 FN; and high, 15.0 to 15.2 FN. (*a*) Yield strength and ultimate tensile strength. (*b*) Elastic modulus, elongation, and reduction of area. *Source*: D. Hauser and J. A. Van Echo, "Effects of Delta Ferrite Content on the Mechanical Properties of E 308-16 Stainless Steel Weld Metal: II, Mechanical Properties and Metallographic Studies," pp. 17–46 in *Properties of Steel Weldments for Elevated Temperature Pressure Containment Applications*, ed. G. V. Smith, MPC-9, American Society of Mechanical Engineers, New York, 1978.

Table A.2. Tensile properties of unirradiated type 308 stainless steel weld metal containing an extra low level of δ-ferrite, 1.6 FN

Spec.	Temperature		Yield Strength 0.2% Offset, ksi	Ultimate Strength, ksi	Elongation, percent	Reduction of Area, percent	Elastic Modulus, 10^6 psi
	F	C					
DL-1	80	27	62.2	87.1	40.0	53.2	24.9
DL-2	80	27	63.5	88.3	40.0	47.6	25.1
DT-7	80	27	66.8	89.6	29.0	32.9	28.7
DT-8	80	27	69.9	92.3	42.5	48.4	26.3
DT-9	300	149	59.5	75.1	30.0	51.4	--
DT-10	300	149	51.4	76.2	27.5	49.1	21.5
DT-11	500	260	56.7	72.2	27.0	47.1	20.9
DT-12	500	260	50.0	68.4	18.5	33.1	20.9
DT-13	700	371	49.0	68.8	23.0	32.5	20.9
DT-14	700	371	52.2	70.4	25.0	37.7	20.3
DT-15	900	482	49.1	67.4	27.0	43.4	20.2
DT-16	900	482	49.1	67.3	27.5	44.7	20.5
DL-3	1100	593	40.4	55.1	26.0	51.0	15.7
DL-4	1100	593	40.1	55.5	26.5	51.0	15.9
DT-17	1100	593	42.6	54.8	26.5	45.8	17.5
DT-18	1100	593	40.8	55.7	22.0	32.5	15.6
DT-19	1200	649	36.4	47.4	29.0	37.2	16.7
DT-20	1200	649	37.6	46.3	29.0	50.9	16.5

Note: DL are longitudinal specimens.
DT are transverse specimens.
1 ksi = 6.9 MPa

Source: D. Hauser and J. A. Van Echo, "Effects of Delta Ferrite Content on the Mechanical Properties of E 308-16 Stainless Steel Weld Metal: II, Mechanical Properties and Metallographic Studies," pp. 17–46 in *Properties of Steel Weldments for Elevated Temperature Pressure Containment Applications*, ed. G. V. Smith, MPC-9, American Society of Mechanical Engineers, New York, 1978.

Table A.3. Tensile properties of unirradiated type 308 stainless steel weld metal containing a low level of δ-ferrite, 4.1 to 4.8 FN

Spec.	Temperature F	Temperature C	Yield Strength 0.2% Offset, ksi	Ultimate Strength, ksi	Elongation, percent	Reduction of Area, percent	Elastic Modulus, 10^6 psi
AL-1	80	27	60.3	85.7	46.0	52.6	23.0
AL-2	80	27	62.8	86.9	50.0	49.5	22.5
AT-9	80	27	71.8	94.1	42.5	45.2	28.0
AT-10	80	27	70.2	92.1	39.0	44.5	29.1
AT-11	300	149	61.2	77.3	27.0	50.0	27.6
AT-12	300	149	57.1	75.5	30.0	49.7	24.0
AT-13	500	260	52.7	73.1	26.5	46.8	22.6
AT-14	500	260	55.3	72.0	24.0	46.0	22.4
AT-15	700	371	52.5	71.6	27.0	40.5	23.0
AT-16	700	371	52.3	71.5	27.0	40.2	22.8
AT-17	900	482	48.2	68.1	25.5	37.7	23.5
AT-18	900	482	45.4	67.3	25.0	41.8	25.6
AL-3	1100	593	40.3	52.0	31.0	48.6	16.6
AL-4	1100	593	39.3	52.8	27.5	52.8	15.4
AT-19	1100	593	41.3	55.2	23.5	48.2	20.1
AT-20	1100	593	42.2	55.6	22.0	46.7	21.8
AT-21	1200	649	37.7	45.1	25.5	52.0	16.9
AT-22	1200	649	37.0	42.5	35.0	55.4	16.5

Note: AL are longitudinal specimens.
AT are transverse specimens.
1 ksi = 6.9 MPa

Source: D. Hauser and J. A. Van Echo, "Effects of Delta Ferrite Content on the Mechanical Properties of E 308-16 Stainless Steel Weld Metal: II, Mechanical Properties and Metallographic Studies," pp. 17–46 in *Properties of Steel Weldments for Elevated Temperature Pressure Containment Applications*, ed. G. V. Smith, MPC-9, American Society of Mechanical Engineers, New York, 1978.

Table A.4. Tensile properties of unirradiated type 308 stainless steel weld metal containing a medium level of δ-ferrite, 9.2 to 9.7 FN

Spec.	Temperature F	Temperature C	Yield Strength 0.2% Offset, ksi	Ultimate Strength, ksi	Elongation, percent	Reduction of Area, percent	Elastic Modulus, 10^6 psi
BL-1	80	27	61.5	89.0	48.0	56.0	22.2
BL-2	80	27	65.3	91.4	49.0	50.7	24.8
BT-9	80	27	66.3	90.8	47.5	44.2	26.0
BT-10	80	27	66.2	91.2	51.0	48.4	26.4
BT-11	300	149	57.0	72.9	31.5	55.7	27.6
BT-12	300	149	56.2	74.8	30.5	56.3	24.0
BT-13	500	260	52.7	72.8	24.0	46.4	22.4
BT-14	500	260	58.9	73.2	27.0	51.2	19.5
BT-15	700	371	53.2	71.4	26.5	43.9	24.7
BT-16	700	371	53.8	71.4	26.5	43.5	18.6
BT-17	900	482	51.0	67.6	26.0	39.6	19.7
BT-18	900	482	47.1	69.0	29.0	42.9	21.9
BL-3	1100	593	39.9	50.7	27.5	52.8	17.5
BL-4	1100	593	40.3	50.1	29.0	55.3	17.1
BT-19	1100	593	40.8	55.6	22.5	46.6	20.5
BT-20	1100	593	44.2	54.7	25.0	48.7	19.2
BT-21	1200	649	35.6	44.5	30.8	52.2	16.2
BT-22	1200	649	37.2	41.3	28.5	56.0	16.7

Note: BL are longitudinal specimens.
BT are transverse specimens.
1 ksi = 6.9 MPa

Source: D. Hauser and J. A. Van Echo, "Effects of Delta Ferrite Content on the Mechanical Properties of E 308-16 Stainless Steel Weld Metal: II, Mechanical Properties and Metallographic Studies," pp. 17–46 in *Properties of Steel Weldments for Elevated Temperature Pressure Containment Applications*, ed. G. V. Smith, MPC-9, American Society of Mechanical Engineers, New York, 1978.

Table A.5. Tensile properties of unirradiated type 308 stainless steel weld metal containing a high level of δ-ferrite, 15.0 to 15.2 FN

Spec.	Temperature F	 C	Yield Strength 0.2% Offset, ksi	Ultimate Strength, ksi	Elongation, percent	Reduction of Area, percent	Elastic Modulus, 10^6 psi
CL-1	80	27	65.1	94.7	43.0	42.3	25.9
CL-2	80	27	71.0	96.7	41.0	43.0	25.8
CT-9	80	27	76.4	99.9	41.0	51.5	28.5
CT-10	80	27	76.9	99.6	41.0	44.9	28.9
CT-11	300	149	62.4	82.3	26.6	48.3	25.8
CT-12	300	149	56.2	81.4	25.0	46.3	20.2
CT-13	500	260	56.2	78.3	25.0	44.1	26.7
CT-14	500	260	61.6	78.4	23.5	46.7	19.7
CT-15	700	371	58.0	79.1	24.0	39.3	23.3
CT-16	700	371	58.9	76.8	26.0	39.3	23.6
CT-17	900	482	53.6	74.1	23.5	38.1	20.4
CT-18	900	482	48.1	72.3	26.0	39.7	24.7
CL-3	1100	593	42.0	51.7	24.0	47.7	15.2
CL-4	1100	593	43.3	54.2	29.0	48.5	15.9
CT-20	1100	593	45.0	55.0	24.0	41.5	20.2
CT-21	1100	593	41.0	54.0	22.0	40.2	22.1
CT-22	1200	649	38.9	48.3	30.5	43.4	15.8
CT-23	1200	649	39.3	47.1	28.0	43.5	15.3

Note: CL are longitudinal specimens.
CT are transverse specimens.
1 ksi = 6.9 MPa

Source: D. Hauser and J. A. Van Echo, "Effects of Delta Ferrite Content on the Mechanical Properties of E 308-16 Stainless Steel Weld Metal: II, Mechanical Properties and Metallographic Studies," pp. 17–46 in *Properties of Steel Weldments for Elevated Temperature Pressure Containment Applications*, ed. G. V. Smith, MPC-9, American Society of Mechanical Engineers, New York, 1978.

Table A.6. Effect of irradiation on the tensile and hardness properties of type 308 stainless steel weld metal

Weld Code	Ferrite Number	Unirradiated Condition[a]						427°C Irradiated Condition[b]			
		Yield Strength (MPa)			Tensile Strength (MPa)			Yield Strength	Tensile Strength	Elongation (%)[c]	Hardness (Rc)[d]
		260°C	371°C	482°C	260°C	371°C	482°C	427°C	427°C	427°C	24°C
V41	5.2	382 (365)[e]	350	325 (310)[f]	473 (485)[e]	476	430 (412)[f]	—	—	—	30.4
V42	10.4	420 (403)[e]	394	358 (329)[f]	521 (519)[e]	514	478 (425)[f]	679	703	7.1	32.9
V43	15.7	415 (415)[e]	378	362 (342)[f]	520 (522)[e]	494	482 (447)[f]	—	—	—	—
V44	19.0	447 (416)[e]	378	376 (362)[f]	563 (564)[e]	535	517 (475)[f]	811	811	5.8	33.9

[a] 1 MPa = 0.145 ksi.

[b] ~1.5 × 10^{22} n/cm^2, $E > 0.1$ MeV (5.74-mm gage diameter specimens).

[c] Elongation in 25.4 mm.

[d] Average of duplicate specimens.

[e] Thermally conditioned at 260° C for 2500 h.

[f] Thermally conditioned at 482° C for 2500 h.

Source: J. R. Hawthorne, *Fatigue and Fracture Resistance of Stainless Steel Weld Deposition After Elevated Temperature Irradiation*, NRL-8451, Naval Research Laboratory, Washington, D. C., November 1980.

Table A.7. Tensile properties of unirradiated type 316 stainless steel submerged-arc test welds

Weld Code	Thickness (in.)	Temperature		Yield Strength[a] (ksi)	Tensile Strength[b] (ksi)
		(°F)	(°C)		
V23	1	75	24	65.3	88.3
		500	260	50.8	72.3
V24	1	75	24	65.8	90.1
V25	1	75	24	65.8	87.5[c]
		500	260	50.6	70.8[c]
S83	1	75	24	60.1	87.0[c]
		500	260	44.6	68.3[c]

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[a] 0.226-in. diam x 1.125-in. gage length specimens.
[b] average of duplicate tests except where noted.
[c] single test determination.

Source: J. R. Hawthorne and B. H. Menke, "Influence of Delta Ferrite Content and Welding Variables on Notch Toughness of Austenitic Stainless Steel Weldments," pp. 351–63 in *Structural Materials for Service at Elevated Temperatures in Nuclear Power Generation*, MPC-1, American Society of Mechanical Engineers, New York, 1975.

Table A.8. Tensile properties of irradiated and unirradiated type 308 stainless steel weld metal

Specimen	Condition[a]	Yield Strength, MPa	Ultimate Strength, MPa	Total Elongation in 10 mm, %	RA, %	Test Temperature, °C
WT-49	weld 2a-T-S	243.4	356.5	44	45	593
WP-61	weld 2a-P-S	211.0	333.7	50	48	593
D2B9 (4.66)	weld 2I-F-S	282.7	380.6	32	33	593
WT-57	weld 2a-T-S	284.1	439.9	52	39	482
WT-34	weld 2a-T-C	319.2	438.5	40	42	482
WP-80	weld 2a-P-C	325.4	427.5	42	50	482
D285 (1.16)	weld 2i-T-S	408.9	492.3	28	38	482
D2C4 (0.96)	weld 2i-T-C	467.5	501.9	33	32	482

[a] 2 = base metal Heat 600414,
a = as welded condition,
T = specimen taken transverse to weld seam,
P = specimen taken parallel to weld seam,
FL = transverse specimens across fusion line,
S = taken from section near surface of weldment,
C = taken from section near center of weldment,
I = irradiated to fluence shown in parentheses in units of 10^{21}n/cm^2 (E >0.1 MeV) at 580 to 610°C, and
i = irradiated to fluence shown in parentheses in units of 10^{21}n/cm^2 (E >0.1 MeV) at 410 to 450°C.

Source: G. E. Korth and M. D. Harper, "Fatigue and Creep-Fatigue Behavior of Irradiated and Unirradiated Type 308 Stainless Steel Weld Metal at Elevated Temperature," pp. 172–90 in *Properties of Reactor Structural Alloys After Neutron or Particle Irradiation*, ASTM STP-570, American Society for Testing and Materials, Philadelphia, 1975.

Table A.9. Effect of irradiation at 400°C on the room-temperature tensile properties of two types of stainless steel weld and base metals

(Fluence at $E > 0.1$ MeV is about one-half the total shown)

Material		σ_u, MN/m^2		σ_y, MN/m^2		ϵ_r, %		Fluence	
								dpa	n/m^2 (total)
AISI 304	base	602 627 614	614	264 262 264	263	68 73 71	71	nonirradiated	
	welded	700 665 675	680	472 462 473	469	41 31 32	35		
AISI 316L	base	582 578 577	579	239 247 230	239	68 63 65	65		
	welded	689 665 685	680	505 432 497	478	36 31 34	34		
AISI 304	base	662 675	668	372 394	383	62 62	62	2.39	8.22×10^{25}
	welded	674 684	679	487 498	492	30 33	31	2.34	8.05
AISI 316L	base	624 641	632	324 342	333	65 57	61	2.01	7.35
	welded	693 683	688	514 482	498	30 30	30	2.15	7.72

Source: J. Dufresne, B. Henry, and H. Larsson, "Fracture Toughness of AISI 304 and 316L Stainless Steel," pp. 511–28 in *Effects of Radiation on Structural Materials*, ASTM STP 683, American Society for Testing and Materials, Philadelphia, 1979.

Table A.10. Effect of irradiation at 400°C on the tensile properties of two types of stainless steel base and weld metals at 400°C

(Fluence at $E > 0.1$ MeV is about one-half the total shown)

Material		σ_u, MN/m^2		σ_y, MN/m^2		ϵ_r, %		Fluence	
								dpa	n/m^2 (total)
AISI 304	base	467 468 462	466	136 159 140	145	45 45 46	45		nonirradiated
	welded	439 466 456	454	306 310 296	304	14 18 18	17		
AISI 316L	base	426 432 427	428	106 110 134	117	40 41 36	39		
	welded	476 480 439	465	345 339 307	330	17 19 15	17		
AISI 304	base	508 508	508	292 295	294	33 33	33	2.39	8.22 × 10^{25}
	welded	509 500	505	386	386	16	16	2.34	8.05
AISI 316L	base	465 470	467	229 225	227	33 34	33	2.01	7.35
	welded	520 526	523	381 413	397	17 16	17	2.15	7.72

Source: J. Dufresne, B. Henry, and H. Larsson, "Fracture Toughness of AISI 304 and 316L Stainless Steel," pp. 511–28 in *Effects of Radiation on Structural Materials*, ASTM STP 683, American Society for Testing and Materials, Philadelphia, 1979.

Appendix B

FATIGUE CRACK PROPAGATION BEHAVIOR OF AUSTENITIC WELD METAL

This appendix contains excerpts of the original works from which the summary statements in the text on fatigue and fatigue crack propagation were compiled. Since they appear in exactly the same form as in the original publication, the units of the properties are not necessarily consistent. A table for conversion factors is included in Appendix D.

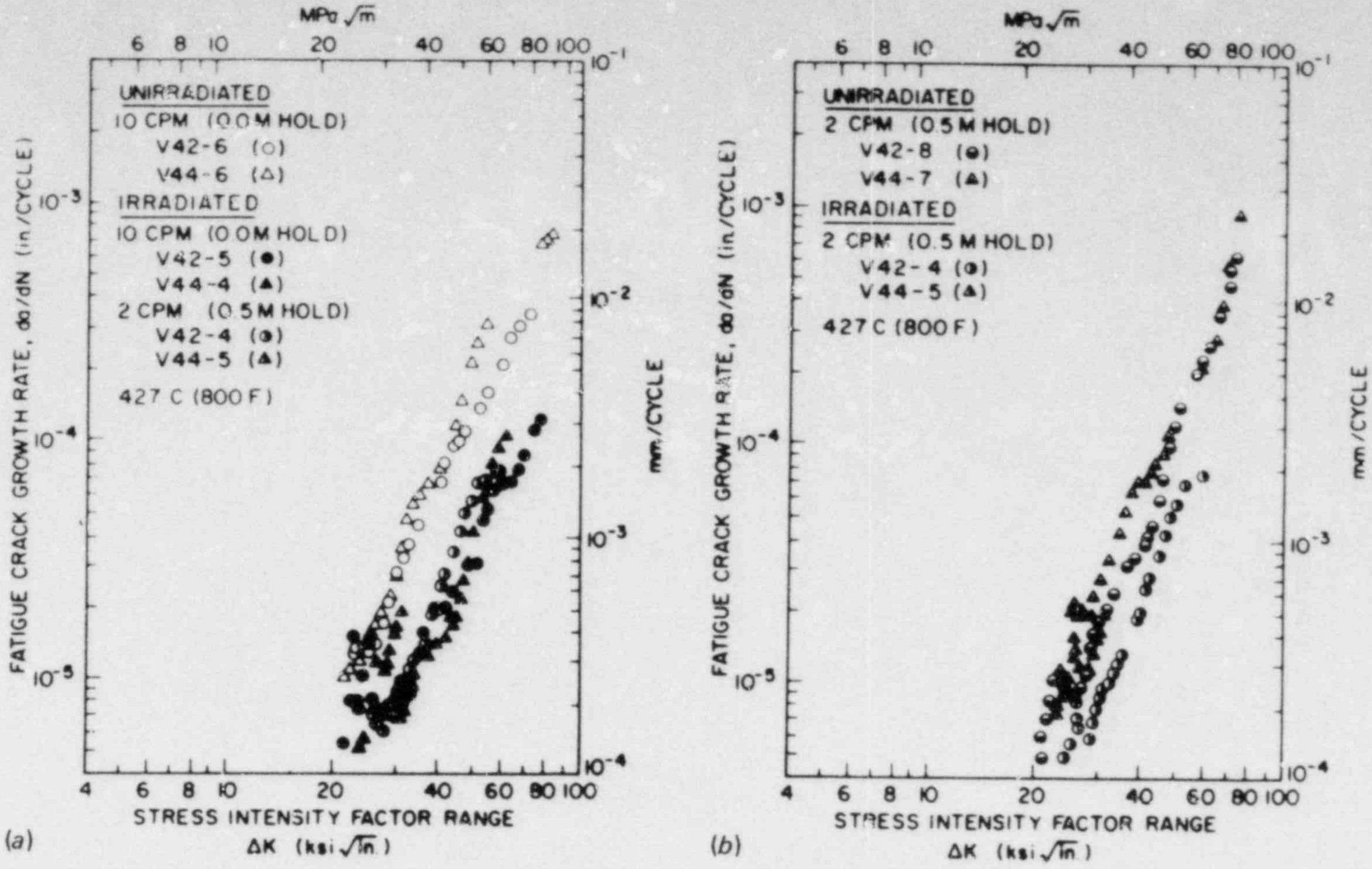

Fig. B.1. Effect of irradiation at 427°C to a fluence of 1.5×10^{26} neutrons/m^2 (>0.1 MeV) on the fatigue crack propagation behavior of type 308-16 weld metal at 427°C. (308-16 is the designation of type 308 stainless steel shielded metal arc welding rods with a particular coating.) Ferrite numbers for specimens V42-*X* and V44-*X* are 10.4 and 19 FN, respectively. (*a*) Continuously cycling and cycling with a tension hold time. (*b*) Cycling with tension hold time only. *Source:* J. R. Hawthorne, *Fatigue and Fracture Resistance of Stainless Steel Weld Deposition After Elevated Temperature Irradiation*, NRL-8451, Naval Research Laboratory, Washington, D.C., November 1980.

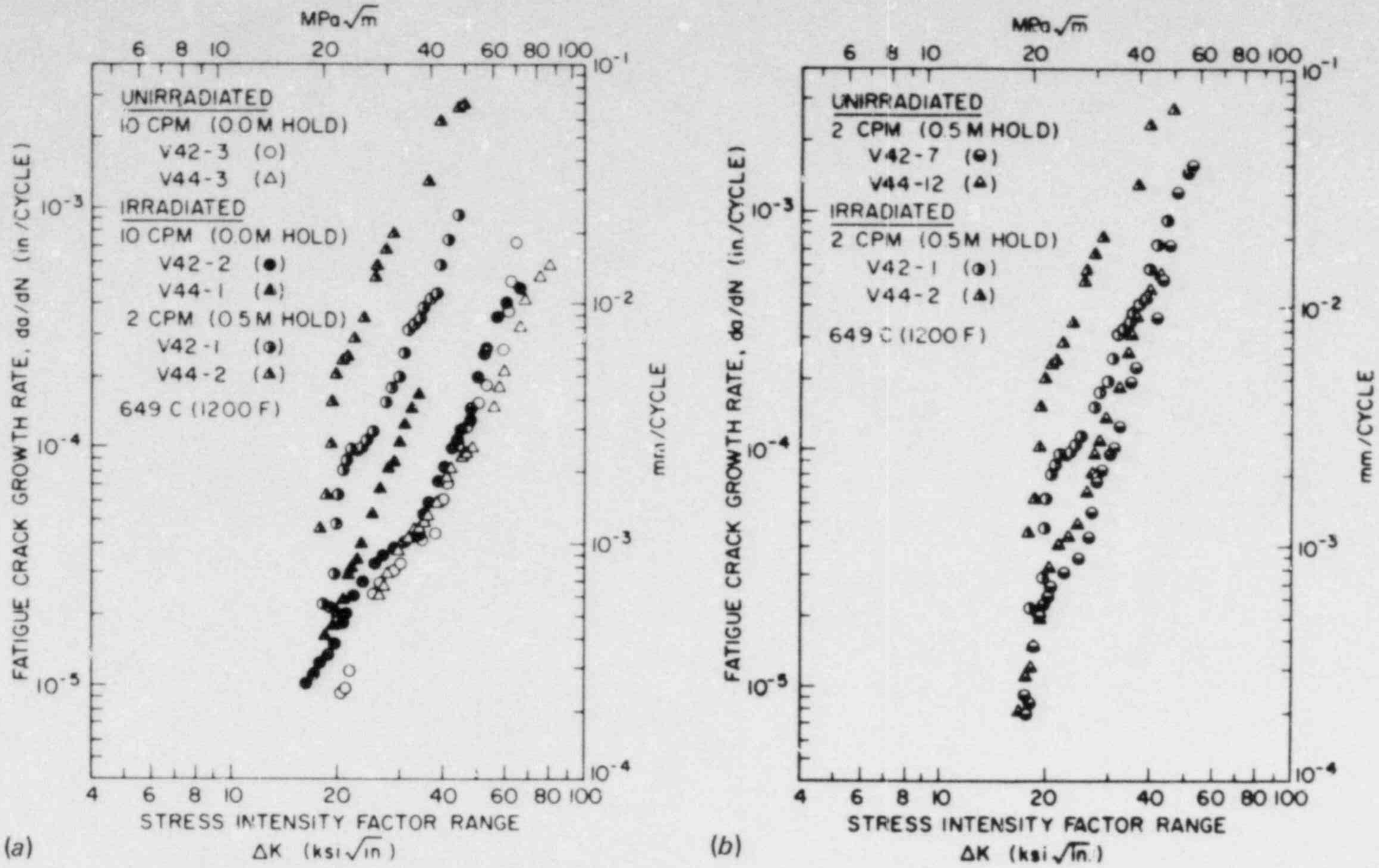

Fig. B.2. Effect of irradiation at 649°C to a fluence of 1.5×10^{26} neutrons/m^2 (>0.1 MeV) on the fatigue crack propagation behavior of type 308-16 weld metal at 649°C. Ferrite numbers for specimens V42-*X* and V44-*X* are 10.4 and 19 FN, respectively. (*a*) Continuously cycling and cycling with a tension hold time. (*b*) Cycling with tension hold time only. *Source*: J. R. Hawthorne, *Fatigue and Fracture Resistance of Stainless Steel Weld Deposition After Elevated Temperature Irradiation*, NRL-8451, Naval Research Laboratory, Washington, D.C., November 1980.

Appendix C

FRACTURE TOUGHNESS AND NOTCH IMPACT PROPERTIES OF AUSTENITIC WELD METAL

This appendix contains excerpts of the original works from which the summary statements in the text on toughness were compiled. Since they appear in exactly the same form as in the original publication, the units of the properties are not necessarily consistent. A table for conversion factors is included in Appendix D.

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Table C.1. Charpy-V (C_V) and dynamic tear (DT) notch ductility of unirradiated type 308 stainless steel weld metal over a range of δ-ferrite contents

Weld Code	Delta Ferrite Content[a]		C_V Energy (ft-lb)				DT Energy (ft-lb)		
			75F (24C)	500F (260C)	900F (482C)	1100F (593C)	75F (24C)	500F (260C)	900F (482C)
V41	5.2		62	78	78	82	637	832	-
			65	84	82	87	662	963	-
		(avg)	(64)	(81)	(80)	(85)	(650)	(897)	
V42	10.4		53	70	-	-	620	740	-
			60	78	-	-	633	880	-
			(57)	(74)			(627)	(810)	
V43	15.7		47	68	64	75	581	904	949
			50	74	72	77	639	1043	-
			(49)	(71)	(68)	(76)	(610)	(974)	(949)
V44	19.0		54	77	75	78	643	822	-
			64	80	-	90	669	851	-
			(59)	(79)	(75)	(84)	(656)	(837)	

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[a] Ferrite number; Magne-Gage determination

Source: J. R. Hawthorne and B. H. Menke, "Influence of Delta Ferrite Content and Welding Variables on Notch Toughness of Austenitic Stainless Steel Weldments," pp. 351–63 in *Structural Materials for Service at Elevated Temperatures in Nuclear Power Generation*, MPC-1, American Society of Mechanical Engineers, New York, 1975.

Table C.2. Charpy V-notch ductility of unirradiated type 316 stainless steel submerged arc weld metal

Weld Code	Charpy-V Energy (ft-lb)					
	-100°F (- 73°C)	75°F (24°C)	500°F (260°C)	700°F (371°C)	900°F (482°C)	1100°F (593°C)
V23	-	70 70 63	81 84	-	80	72
V24	-	55 56 57	66 74	-	-	-
V25	-	57 52	75 54 70	-	59 64	58
S83	-	52	58	-	-	-
S85 (ac weld)	43	50 54	55 50	-	65	48
Q55 [1] (ac weld)	-	-	-	78 80	76 81	-

Source: J. R. Hawthorne and B. H. Menke, "Influence of Delta Ferrite Content and Welding Variables on Notch Toughness of Austenitic Stainless Steel Weldments," pp. 351–63 in *Structural Materials for Service at Elevated Temperatures in Nuclear Power Generation*, MPC-1, American Society of Mechanical Engineers, New York, 1975.

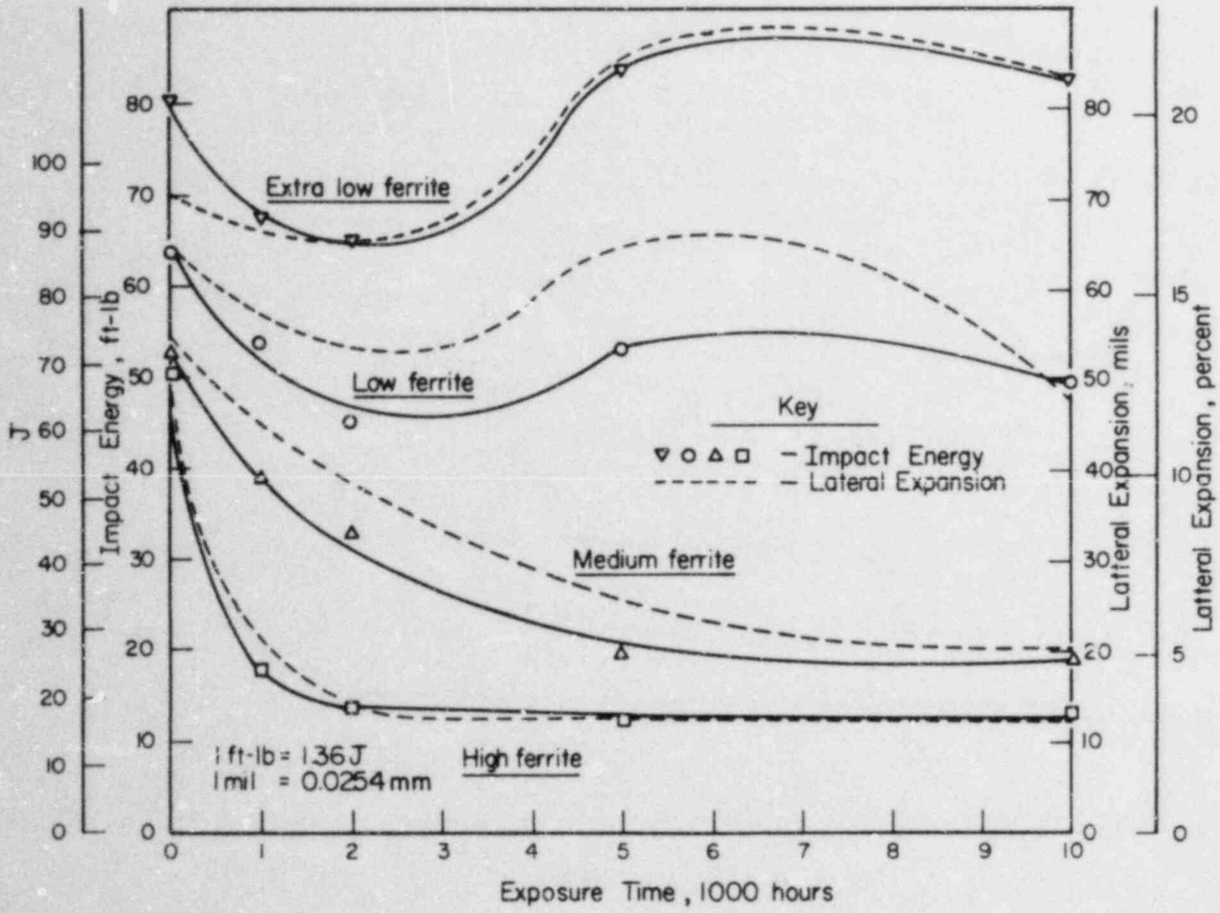

Fig. C.1. Effects of δ-ferrite content and aging at 593°C on the Charpy impact properties of unirradiated type 308 stainless steel weld metal. Ferrite numbers for extra low, low, medium, and high are 1.6, 4.1 to 4.8, 9.2 to 9.7, and 15.0 to 15.2 FN, respectively. *Source*: D. Hauser and J. A. Van Echo, "Effects of Delta Ferrite Content on the Mechanical Properties of E 308-16 Stainless Steel Weld Metal: II, Mechanical Properties and Metallographic Studies," pp. 17–46 in *Properties of Steel Weldments for Elevated Temperature Pressure Containment Applications*, ed. G. V. Smith, MPC-9, American Society of Mechanical Engineers, New York, 1978.

Table C.3. Effects of δ-ferrite content and aging at 593°C on the Charpy impact properties of unirradiated type 308 stainless steel weld metal. Ferrite numbers for extra low, low, medium, and high ferrite levels are 1.6, 4.1 to 4.8, 9.2 to 9.7, and 15.0 to 15.2 FN, respectively

Material[(a)]	Exposure Time, hr	Impact Energy,[(b)] ft-lbs (J)	Lateral Expansion,[(b)] mils (mm)
663-3	0	80.0 (108.5)	70 (1.78)
178-3	0	63.7 (86.4)	64 (1.63)
179-3	0	52.8 (71.6)	55 (1.40)
180-3	0	50.2 (68.1)	54 (1.37)
663-1	1000	67.3 (91.3)	65 (1.65)
178-2	1000	54.0 (73.2)	60 (1.52)
179-2	1000	38.8 (52.6)	43 (1.09)
180-2	1000	17.8 (24.1)	20 (0.51)
663-2	2000	66.5 (90.2)	66 (1.68)
178-2	2000	45.2 (61.3)	53 (1.35)
179-2	2000	32.8 (44.5)	41 (1.04)
180-2	2000	13.5 (18.3)	14 (0.36)
663-2	5000	84.0 (113.9)	86 (2.18)
178-2	5000	53.2 (72.1)	64 (1.63)
179-2	5000	19.7 (26.7)	25 (0.64)
180-2	5000	12.5 (17.0)	12 (0.30)
663-1	10,000	83.2 (112.8)	83 (2.11)
178-2	10,000	49.3 (66.8)	48 (1.22)
179-2	10,000	18.8 (25.5)	20 (0.51)
180-2	10,000	12.7 (17.2)	18 (0.33)

(a) The first three numbers represent the ferrite level: 663 - extra low ferrite, 178 - low ferrite, 179 - medium ferrite, 180 - high ferrite; the third number designates the plate in the series.

(b) Average of three measurements unless otherwise noted.

Source: D. Hauser and J. A. Van Echo, "Effects of Delta Ferrite Content on the Mechanical Properties of E 308-16 Stainless Steel Weld Metal: II, Mechanical Properties and Metallographic Studies," pp. 17–46 in *Properties of Steel Weldments for Elevated Temperature Pressure Containment Applications*, ed. G. V. Smith, MPC-9, American Society of Mechanical Engineers, New York, 1978.

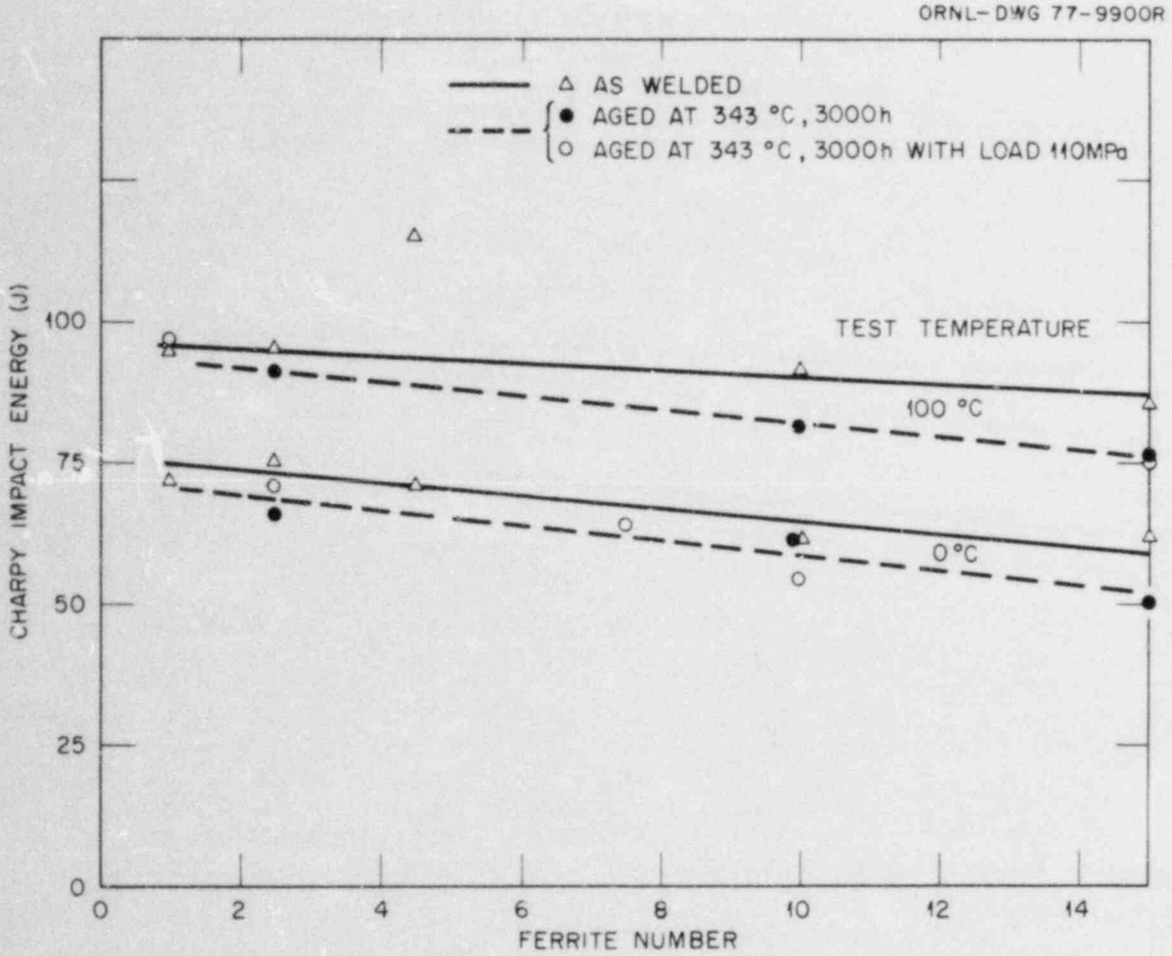

Fig. C.2. Charpy V-notch energy versus ferrite number for unirradiated type 308 stainless steel weld metal. The 110-MPa load refers to the design stress intensity value permitted in Sect. III, Div. 1, Subsect. NB, ASME Code, at 343°C for welded pipe such as SA-358, type 304. *Source*: R. K. Nanstad et al., *Effect of Ferrite Content and Aging at 343°C on Fatigue and Impact Toughness of Type 308 Stainless Steel Weld Metals for LWR Applications*, to be published at Oak Ridge National Laboratory.

Table C.4. Effects of irradiation and thermal conditioning on the Charpy-V (C_VE) and dynamic tear (DTE) notch ductility of type 308 stainless steel weld metal for four δ-ferrite contents

Weld	FN[a]	Temp. °C	C_VE Unirrad. J	C_VE Unirrad. ft-lb	C_VE Irrad. 260°C[b] J	C_VE Irrad. 260°C[b] ft-lb	DTE Unirrad. J	DTE Thermal Cond. J[c]
V41	5.2	24	84	62	38	28		
			88	65	38	28		
		260	106	78	45	33	1216[d]	1156
			114	84	56	41		
		371[d]	105	78				
		482[d]	109	80			1254	1391[e]
		593[d]	115	85				
V42	10.4	24	72	53	33	24		
			81	60	38	28		
		260	95	70	39	29	1098[d]	995
			106	78	46	34		
		371[d]	107	79				
		482[d]	102	75			1110	997
		593[d]	115	85				
V43	15.7	24	64	47	26	19		
			68	50	29	21		
		260	92	68	41	30	1320[d]	942[d]
			100	74	48	35		
		371[d]	106	78				
		482[d]	93	68			1296	980
		593[d]	103	76				
V44	19.0	24	73	54	24	18		
			87	64				
		260	104	77	41	30	1135[d]	1005[d]
			108	80	42	31		
					53	39		
		371[d]	115	85				
		482[d]	102[e]	75			1094	910
		593[d]	114	84				

[a] Ferrite number (Magne-Gage determination)

[b] Fluence: ~8.7×10^{19} n/cm^2 >0.1 MeV (UCRR)

[c] Thermally conditioned 2400 hrs at test temp. (260 or 482°C)

[d] Duplicate test avg.

[e] Single determination

Source: J. R. Hawthorne and H. E. Watson, "Exploration of the Influence of Welding Variables on Notch Ductility of Irradiated Austenitic Stainless Steel Welds," pp. 327–36 in *Radiation Effects in Breeder Reactor Structural Materials*, American Institute of Mining, Metallurgical, and Petroleum Engineers, New York, 1977.

Table C.5. Effects of irradiation and thermal conditioning on the Charpy V-notch ductility of type 308 stainless steel weld metal with controlled residual elements

Temperature		Unirrad.		Irradiated 288°C (550°F)[b]		Irradiated ~371°C (700°F)[c]		Irradiated 449°C (840°F)[c]		Thermally Conditioned[d]			
										371°C (700°F)		482°C (900°F)	
(°C)	(°F)	(J)	(ft-lb)	(J)	(ft-lb)	(J)	(ft-lb)	(J)	(ft-lb)	(J)	(ft-lb)	(J)	(ft-lb)
24	75	125	92	-	-	-	-	-	-	-	-	-	-
260	500	-	-	117 111	82 86	30	22	54	40	-	-	-	-
371	700	146	108	-	-	27	20	45	33	149 160	110 118	-	-
482	900	155	114	-	-	34	25	46	34	-	-	123 126	91 93
593	1100	151	111	-	-	95	70	84	62	-	-	-	-

[a] Ferrite number 7.7

[b] 6.7×10^{19} n/cm^2>0.1 MeV (UCRR)

[c] 2.5×10^{22} n/cm^2>0.1 MeV (EBR-II)

[d] 2400 hour thermalconditioning

Source: J. R. Hawthorne and H. E. Watson, "Exploration of the Influence of Welding Variables on Notch Ductility of Irradiated Austenitic Stainless Steel Welds," pp. 327–36 in *Radiation Effects in Breeder Reactor Structural Materials*, American Institute of Mining, Metallurgical, and Petroleum Engineers, New York, June 1977.

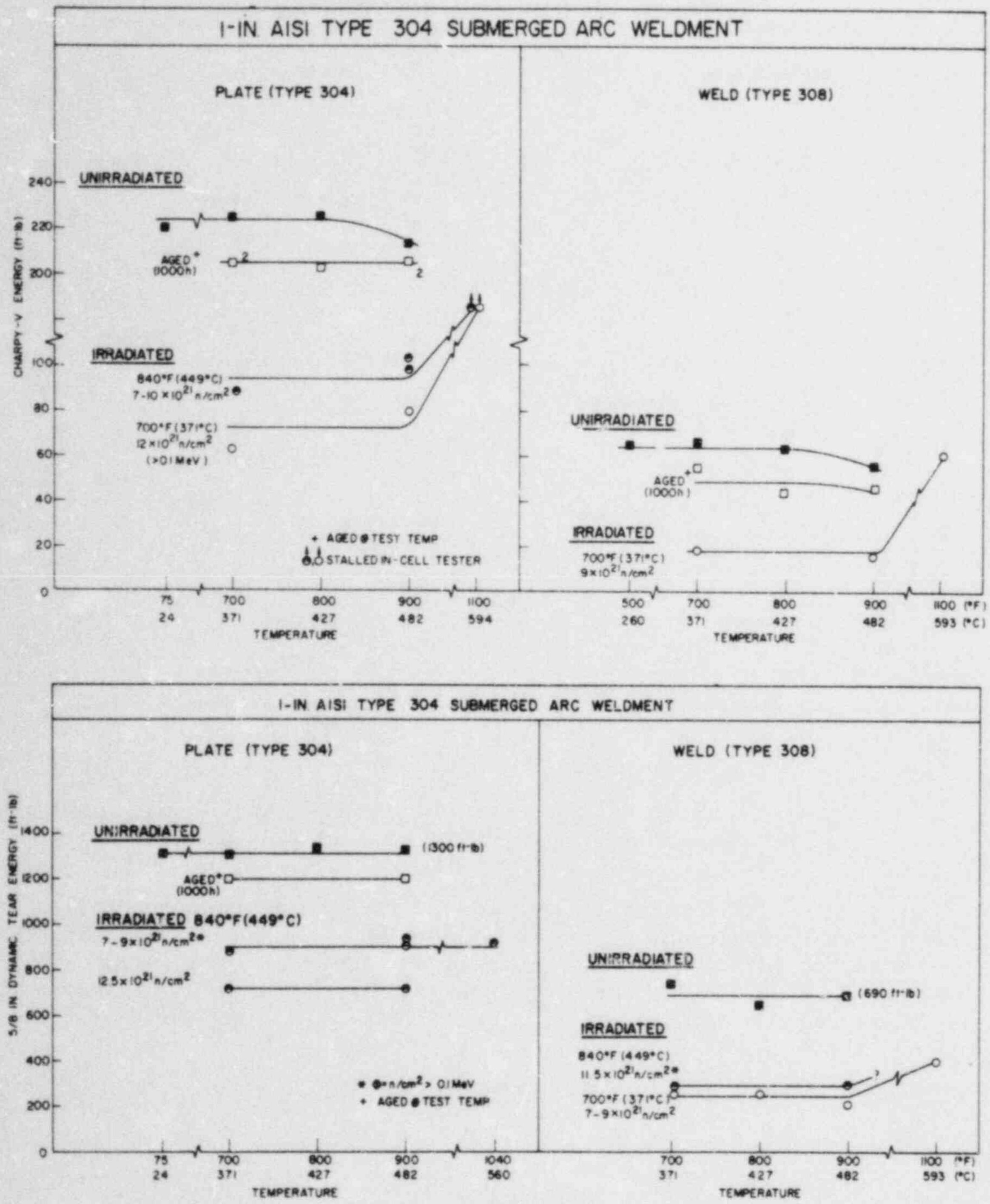

Fig. C.3. Effects of irradiation on the Charpy-V and dynamic tear notch ductilities of type 304 stainless steel plate and type 308 stainless steel weld metal. Results of unirradiated specimens tested at their aging temperatures are shown for comparison. *Source*: J. R. Hawthorne and H. E. Watson, "Notch Toughness of Austenitic Stainless Steel Weldments with Nuclear Irradiation," *Weld. J. (Miami)* 6, 255–60-s (1973).

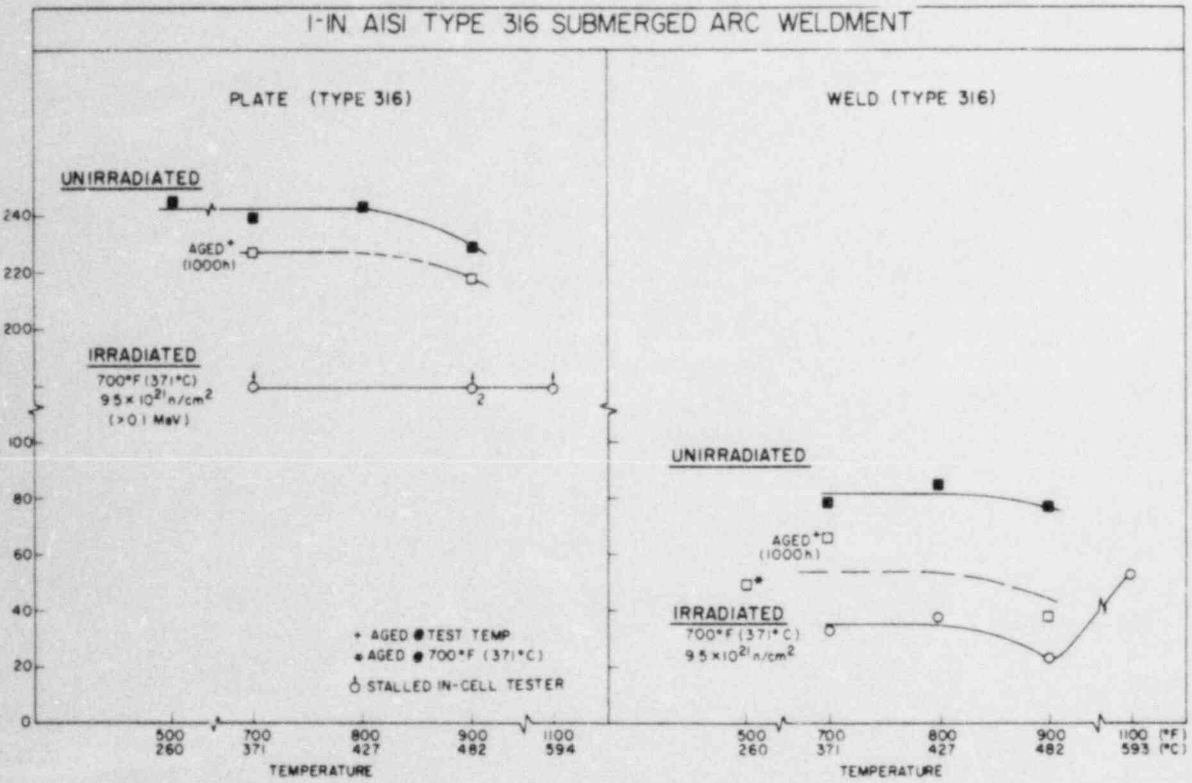

Fig. C.4. Effects of irradiation on the Charpy V-notch ductility of type 316 stainless steel plate and weld metal. Results of unirradiated specimens tested at their aging temperatures are shown for comparison. *Source*: J. R. Hawthorne and H. E. Watson, "Notch Toughness of Austenitic Stainless Steel Weldments with Nuclear Irradiation," *Weld. J. (Miami)* 6, 255–60 (1973).

Table C.6. Effect of irradiation on the Charpy V-notch ductility of type 308 stainless steel weld metal for four δ-ferrite contents

Weld Code	Ferrite Number	C_v Energy Absorption (J)[a]					
		Unirradiated Condition				427°C Irradiated Condition[b]	
		260°C	371°C	482°C	593°C	371°C	482°C
V41	5.2	106	100	106	111	24	24
		114	110	111	118	24	30
V42	10.4	95	104	99	—[c]	19	23
		106	110	104	—[c]	23	26
V43	15.7	92	100	87	102	—	—
		100	111	98	104	—	—
V44	19.0	104	111	102	106	20	26
		108	118	—[c]	122	23	30

[a] 1 J = 0.738 ft·lb.

[b] ~1.5 × 10^{22} n/cm^2, $E > 0.1$ MeV.

[c] Not determined.

Source: J. R. Hawthorne, *Fatigue and Fracture Resistance of Stainless Steel Weld Deposition After Elevated Temperature Irradiation*, NRL-8451, Naval Research Laboratory, Washington, D.C., November 1980.

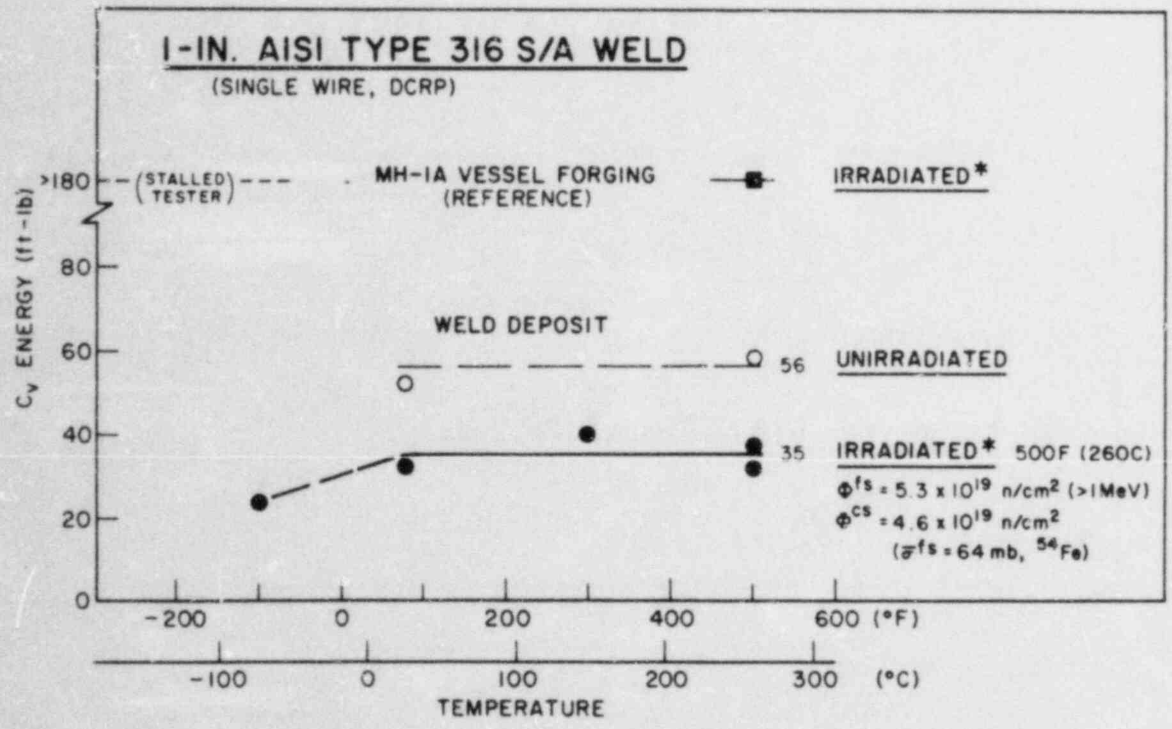

Fig. C.5. Effect of irradiation on the Charpy V-notch ductility of type 316 stainless steel submerged arc weld metal. *Source*: J. R. Hawthorne and B. H. Menke, "Influence of Delta Ferrite Content and Welding Variables on Notch Toughness of Austenitic Stainless Steel Weldments," pp. 351–63 in *Structural Materials for Service at Elevated Temperatures in Nuclear Power Generation*, MPC-1, American Society of Mechanical Engineers, New York, 1975.

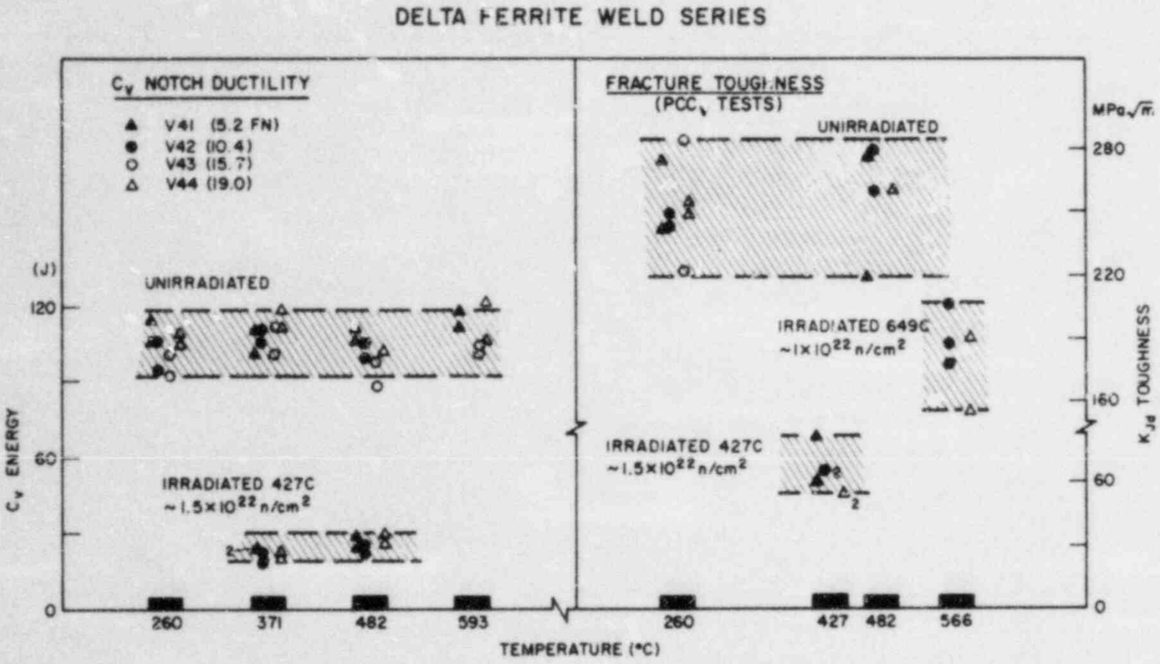

Fig. C.6. Effect of irradiation on the notch ductility and dynamic fracture toughness of type 308-16 weld metal with four levels of delta ferrite. Fluences shown are for $E > 0.1$ MeV. *Source*: J. R. Hawthorne, *Fatigue and Fracture Resistance of Stainless Steel Weld Deposition After Elevated Temperature Irradiation*, NRL-8451, Naval Research Laboratory, Washington, D.C., November 1980.

Table C.7. Effect of irradiation on the fracture toughness K_J and yield strength of type 308 stainless steel weld metal

(K_J is determined by J-integral assessment procedures for four δ-ferrite contents and three loading rates)

Weld No.	FN	Temp. °C	Tup[a] Velocity	K_J[b]		Yield Strength[c]	
				MPa√m	ksi√in.	MPa	ksi
I. Unirradiated Condition							
V41	5.2	24	1	127	115	752	109
			2	176	160	634	92
			3	274	250	497	72
V42	10.4	24	1	132	120	745	108
			2	148	135	703	102
			3	248	226	600	87
V43	15.7	24	1	121	110	662	96
			2	173	157	724	105
			3	207	188	531	77
V44	19.0	24	1	137	125	821	119
			3	238	217	511	74
V41	5.2	260	1	145	132	717	104
			2	224	204	600	87
V42	10.4	260	1	151	137	676	98
			2	200	182	593	86
V43	15.7	260	1	135	123	703	102
			2	234	213	641	93
V44	19.0	260		153	139	579	84
			2	204	186	607	88
V41	5.2	482	1	125	114	428	62
			2	226	206	386	56
V42	10.4	482	1	155	141	496	72
			2	227	207	434	63
V44	19.0	482	2	211	192	441	64
II. Irradiated: 260°C, ~8.7×10^{19} n/cm >0.1 MeV (UCRR)							
V42	10.4	24	1	76[d]	69[d]	952[e]	138[e]
V43	15.7	24	2	85	77	972	141
V44	19.0	24	2	80[d]	73[d]	999[e]	145[e]
V42	10.4	260	2	133	121	738	107
				100	91	848	123
				93	85	952	138
V43	15.7	260	2	123	112	717	104
				108	98	889	129
V44	19.0	260	2	130	118	807	117
				105	96	917	133
III. Irradiated: 649°C, ~0.9×10^{22} n/cm^2 >0.1 MeV (EBR-II)							
V42	10.4	482	1	109	99	441	64
V42	10.4	566	1	124	113	448	65
			2	151	137	428	62
V44	19.0	560	1	114	104	428	62
			2	123	112	372	54

[a] Velocity 1: 512 cm/sec (16.8 ft/sec) (dynamic).
Velocity 2: 244 cm/sec (8.0 ft/sec) (dynamic).
Velocity 3: .0042 cm/sec (.00014 ft/sec) (static).

[b] $K_J = (EJ_M)^{1/2}$ where J_M = J-integral at maximum load.

[c] $\sigma_{ys} = 3.3\ PL/(W-a)^2$ (4)

[d] $K_J \cong K_{Id}$ (fracture before general yield).

[e] fracture before general yield.

Source: J. R. Hawthorne and H. E. Watson, "Exploration of the Influence of Welding Variables on Notch Ductility of Irradiated Austenitic Stainless Steel Welds," pp. 327–36 in *Radiation Effects in Breeder Reactor Structural Materials*, American Institute of Mining, Metallurgical, and Petroleum Engineers, New York, June 1977.

Table C.8. Effect of irradiation on the dynamic fracture toughness of type 308 stainless steel weld metal as determined with precracked Charpy specimens and *J*-integral assessment procedures

Weld Code	Ferrite Number	Dynamic Fracture Toughness K_J (MPa$\sqrt{m}$)[a]			
		Unirradiated Condition		427° C Irradiated Condition[b]	649° C Irradiated Condition[c]
		260°C	482°C	427°C	566°C
V41	5.2	242	211	62[d]	—
		274	278	85	—
V42	10.4	243	259	65	185
		249	279	68	207
					177[e]
V44	19.0	248	257	54[d]	152
		255	--	56[d]	189

[a] 1 MPa$\sqrt{m}$ = 0.91 ksi $\sqrt{in.}$

[b] ~1.5 × 10^{22} n/cm^2, $E > 0.1$ MeV.

[c] ~1.0 × 10^{22} n/cm^2, $E > 0.1$ MeV.

[d] Specimen fractured before general yielding.

[e] 482° C test.

Source: J. R. Hawthorne, *Fatigue and Fracture Resistance of Stainless Steel Weld Deposition After Elevated Temperature Irradiation*, NRL-8451, Naval Research Laboratory, Washington, D.C., November 1980.

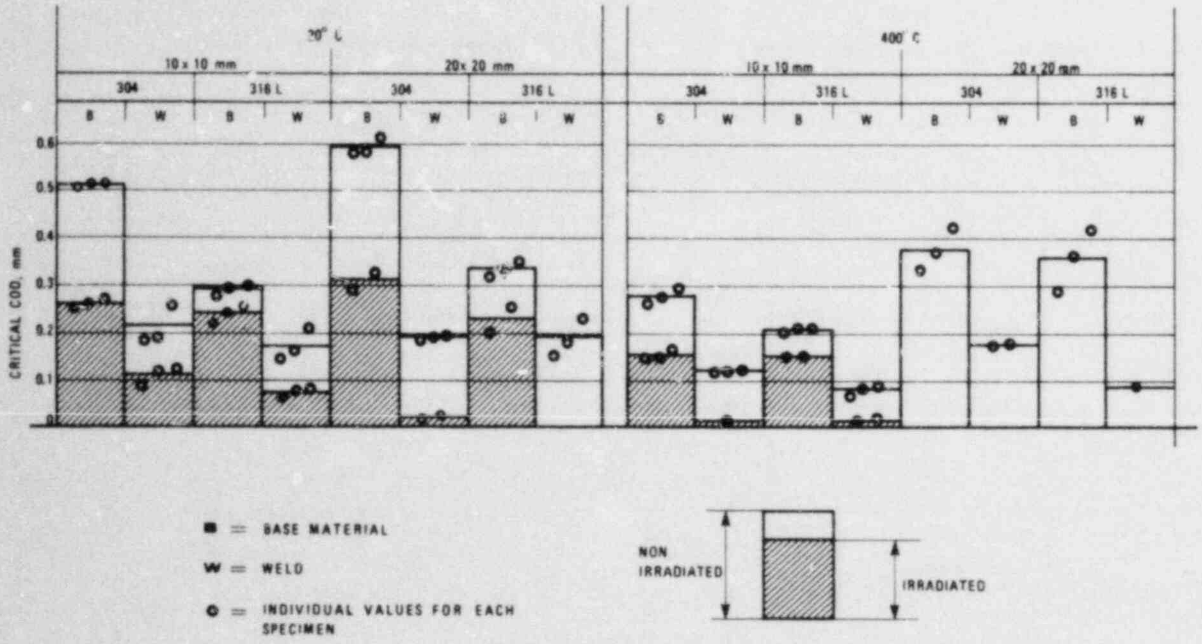

Fig. C.7. Effect of 400°C irradiation on the critical COD values (initiation of stable crack growth) for stainless steel weldments for fluence levels of 3 to 4.5×10^{25} neutrons/m^2 (>0.1 MeV). *Source*: J. Dufresne, B. Henry, and H. Larsson, "Fracture Toughness of AISI 304 and 316L Stainless Steel," pp. 511–28 in *Effects of Radiation on Structural Materials*, ASTM STP 683, American Society for Testing and Materials, Philadelphia, 1979.

Table C.9. Effect of 400°C irradiation on the room-temperature fracture toughness J_c and critical COD δ_c of stainless steel weldments determined on 10- by 10- and 20- by 20-mm-cross-section bend specimens. Fluence with E > 0.1 MeV is about one-half of total.

Specimen		Nonirradiated						Irradiated							
														Fluence	
		δ_c, mm		J_c, kN/m		$J_c/\sigma_u\delta_c$		δ_c, mm		J_c, kN/m		$J_c/\sigma_u\delta_c$		dpa	n/m^2 (total)
AISI 304 10 × 10	base	0.513 0.503 0.511	0.509	404 388 392	395^a	1.27 1.26 1.24	1.26	0.259 0.253 0.270	0.261	258 251 254	254^a	1.49 1.48 1.41	1.46	2.36	8.22 × 10^{25}
	welded	0.185 0.264 0.193	0.214	168 243 172	194	1.33 1.38 1.31	1.34	0.090 0.123 0.115	0.109	102 133 111	116	1.68 1.59 1.43	1.57	2.37	8.18
AISI 316L 10 × 10	base	0.294 0.281 0.299	0.291	197 172 199	189^a	1.16 1.06 1.15	1.12	0.256 0.216 0.244	0.239	196 170 185	183	1.21 1.25 1.19	1.22	1.75	6.67
	welded	0.207 0.144 0.162	0.171	204 141 153	166	1.46 1.45 1.39	1.43	0.076 0.080 0.064	0.073	91 92 77	87	1.74 1.68 1.75	1.72	2.08	7.27
AISI 304 20 × 20	base	0.615 0.579 0.583	0.592	456 411 448	438^a	1.20 1.15 1.24	1.20	0.292 0.325	0.309	241 296	268	1.24 1.36	1.30	1.91	7.10
	welded	0.193 0.185 0.192	0.190	145 140 129	138	1.12 1.11 0.99	1.07	0.020 0.015	0.018	25 17	21	1.86 1.71	1.78	2.39	8.26
AISI 316L 20 × 20	base	0.327 0.316 0.356	0.333	206 195 229	210	1.09 1.07 1.11	1.09	0.202 0.259	0.231	183 207	195	1.43 1.26	1.35	1.93	6.86
	welded	0.232 0.181 0.159	0.191	195 149 114	153	1.24 1.22 1.06	1.17	...	...	...	...	...	...	...	...

^{a}Values not satisfying the criterion $B > 25J_c/\bar{\sigma}$.

Source: J. Dufresne, B. Henry, and H. Larsson, "Fracture Toughness of AISI 304 and 316L Stainless Steel," pp. 511–28 in *Effects of Radiation on Structural Materials*, ASTM STP 683, American Society for Testing and Materials, Philadelphia, 1979.

Table C.10. Effect of 400°C irradiation on the fracture toughness J_c and critical COD δ_c of stainless steel weldments determined at 400°C on 10- by 10- and 20- by 20-mm-cross-section bend specimens. Fluence with $E > 0.1$ MeV is about one-half of total.

Specimen		Nonirradiated						Irradiated							
		δ_c, mm		J_c, kN/m		$J_c/\sigma_u\delta_c$		δ_c, mm		J_c, kN/m		$J_c/\sigma_u\delta_c$		Fluence	
														dpa	n/m^2(total)
AISI 304 10 × 10	base	0.261 0.277 0.292	0.277	133 152 144	143[a]	1.09 1.18 1.06	1.11	0.167 0.149 0.149	0.155	150 120 136	135	1.76 1.57 1.80	1.71	2.36	8.22×10^{25}
	welded	0.113 0.120 0.121	0.118	82 77 [illegible]	80	1.61 1.41 1.46	1.49	0.011	0.011	11	11	1.95	1.95	2.37	8.18
AISI 316L 10 × 10	base	0.208 0.202 0.210	0.207	81 77 99	86	0.91 0.89 1.11	0.97	0.153 0.151	0.152	117	114	1.64 1.58	[illegible]	1.74	6.31
	welded	0.089 0.068 0.079	0.079	62 50 56	56	1.51 1.57 1.53	1.54	0.015 0.009	0.012	17 14	15	2.13 2.92	2.52	2.06	7.51
AISI 304 20 × 20	base	0.423 0.371 0.333	0.376	232 173 148	184	1.18 1.01 0.95	1.05	...	...	...	...	...	...	...	...
	welded	0.177 0.176	0.177	98 97	98	1.23 1.22	1.22	...	...	...	...	...	...	...	...
AISI 316L 20 × 20	base	0.418 0.289 0.367	0.358	170 111 206	162	0.95 0.91 1.32	1.06	...	...	...	...	...	...	...	...
	welded	0.086	0.086	46	46	1.16	1.16	...	...	...	...	...	...	...	...

[a] Values not satisfying the criterion $B > 25J_c/\bar{\sigma}$

Source: J. Dufresne, B. Henry, and H. Larsson, "Fracture Toughness of AISI 304 and 316L Stainless Steel," pp. 511–28 in *Effects of Radiation on Structural Materials*, ASTM STP-683, American Society for Testing and Materials, Philadelphia, 1979.

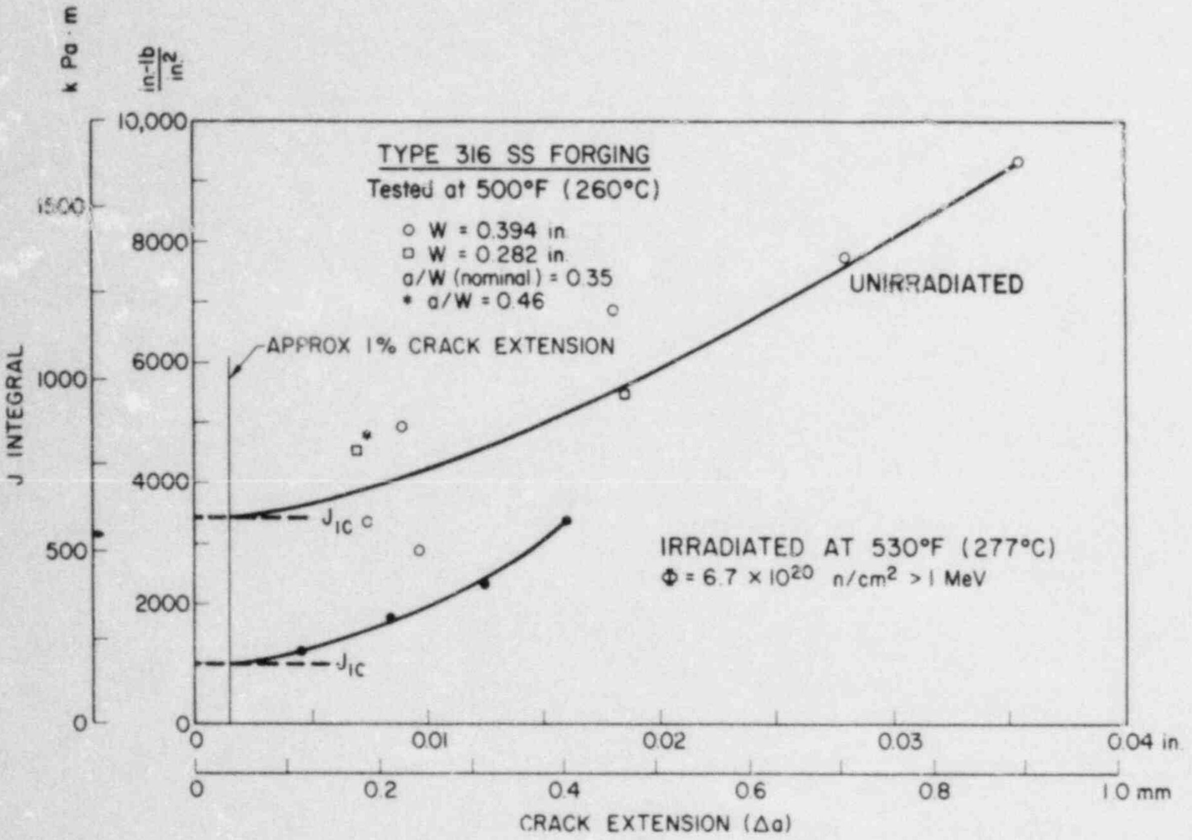

Fig. C.8. Effect of irradiation on the *J*-integral values of type 316 stainless steel weld metal. *Source*: F. J. Loss and R. A. Gray, Jr., "Toughness of Irradiated Type 316 Forging and Weld Metal Using the J-Integral," pp. 23–30 in *Irradiation Effects on Reactor Structural Materials, February–July 1974*, NRL Memorandum Report 2875, Naval Research Laboratory, Washington, D.C., August 1974.

Appendix D

CONVERSION FACTORS

SI unit	English unit	Factor[a]
mm	in.	0.0393701
cm	in.	0.393701
m	ft	3.28084
m/s	ft/s	3.28084
kN	lb$_f$	224.809
kPa	psi	0.145038
MPa	ksi	0.145038
MPa$\cdot\sqrt{m}$	ksi $\sqrt{in.}$	0.910048
J	ft-lb	0.737562
K	°F or °R	1.8
kJ/m^2	in.-lb/in.^{2}	5.71015
$W\cdot m^{-2}\cdot K^{-1}$	Btu/h-ft^2-°F	0.176110
kg	lb	2.20462
kg/m^3	lb/in.^{3}	3.61273×10^{-5}
mm/N	in./lb$_f$	0.175127
$T(°F) = 1.8T(°C) + 32$		

[a] Multiply SI quantity by given factor to obtain English quantity.

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16. ABSTRACT (200 words or less)

Because the weld overlay cladding on the interior of light-water reactor pressure vessels was applied for corrosion resistance and not for structure, little attention has been given to the potential of mechanical property degradation due to radiation exposure. In light of the concerns recently raised regarding overcooling transients in nuclear power reactors, it has been suggested that any such degradation could adversely affect the serviceability and/or integrity of the vessel.

A literature survey assesses the current knowledge regarding the effects of neutron radiation on the mechanical fracture properties of stainless steel weld overlay cladding under conditions relevant to light-water reactor operation. In particular, effects on the material's microstructure and tensile, fatigue, impact, and fracture properties are examined. Although information is lacking on the specific materials under the exact irradiation conditions of interest, a wealth of information is available on irradiated stainless steel weldments in general, from which basic behavioral trends can be obtained.

Some irradiation embrittlement apparently does occur in stainless steel weldments at the relatively low temperatures and fluences typical of light-water reactors. Tensile strength increases and ductility decreases. Low-cycle fatigue behavior is degraded somewhat, but high-cycle fatigue and fatigue crack growth seem largely unaffected. Effects of δ-ferrite on fracture resistance are small in both irradiated and unirradiated materials. Notch impact and fracture toughness are both reduced by irradiation, and a dependence of toughness on testing rate, not seen in wrought material, is indicated.

17. KEY WORDS AND DOCUMENT ANALYSIS

17a. DESCRIPTORS

Radiation Effects	Tensile Properties
Stainless Steel Welds	Charpy Impact Properties
Weld Overlay Cladding	Fracture Toughness

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