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Long-Term Embrittlement of Cast Duplex Stainless Steels in LWR Systems

Semiannual Report
October 1990–March 1991

Prepared by O. K. Chopra

Argonne National Laboratory

Prepared for
U.S. Nuclear Regulatory Commission

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Long-Term Embrittlement of Cast Duplex Stainless Steels in LWR Systems

by

O. K. Chopra

Abstract

This progress report summarizes work performed by Argonne National Laboratory on long-term thermal embrittlement of cast duplex stainless steels in LWR systems during the six months from October 1990 to March 1991. Charpy-impact, tensile, and fracture toughness data are presented for several heats of cast stainless steel that were aged up to 58,000 h at temperatures of 290–400°C. The results indicate that thermal aging increases the tensile stress and decreases the fracture toughness of the materials. In general, CF-3 steels are the least sensitive to thermal aging embrittlement and CF-8M steels are the most sensitive. The increase in flow stress of fully aged cast stainless steels is ≈10% for CF-3 steels and ≈20% for CF-8 and CF-8M steels. The fracture toughness J_{IC} and average tearing modulus for heats that are sensitive to thermal aging (e.g., CF-8M steels) are as low as ≈90 kJ/m^2 and ≈60, respectively.

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Executive Summary

Cast stainless steels used in pump casings, valve bodies, piping, and other components in coolant systems of light water nuclear reactors (LWRs) suffer a loss in toughness after many years of service at temperatures in the range of 280–320°C (≈536–608°F). A program is being conducted at Argonne National Laboratory to investigate the low-temperature thermal embrittlement of cast duplex stainless steels under LWR operating conditions and to evaluate possible remedies for the thermal embrittlement problem in existing and future plants. The scope of the investigation includes the following goals: (1) characterize and correlate the microstructure of in-service reactor components and laboratory-aged material with loss of fracture toughness to establish the mechanism of aging and validate the simulation of in-reactor degradation by accelerated aging, (2) establish the effects of key compositional and metallurgical variables on the kinetics and extent of thermal embrittlement, and (3) develop the methodology and correlations necessary for predicting the toughness loss suffered by cast stainless steel components during the normal and extended life of LWRs.

Microstructural and mechanical-property data have been obtained on 25 experimental heats (static-cast keel blocks and slabs) and 6 commercial heats (centrifugally cast pipes, a static-cast pump impeller, and a static-cast pump casing ring), as well as on reactor-aged material of CF-3, CF-8, and CF-8M grades of cast stainless steel. The ferrite content of the cast materials ranges from 3 to 30%. Ferrite morphology for the castings containing >5% ferrite is either lacy or acicular.

Charpy-impact, tensile, and J-R curve tests have been conducted on several experimental and commercial heats of cast stainless steel that were aged up to 58,000 h at temperatures of 290–400°C (554–752°F). Results indicate that thermal aging at these temperatures increases the tensile strength and decreases the impact energy and fracture toughness of the steels. The Charpy transition curve shifts to higher temperatures. Different heats exhibit different degrees of thermal embrittlement; in general, the low-carbon CF-3 steels are the most resistant, and the molybdenum-bearing, high-carbon CF-8M steels are the least resistant to thermal embrittlement. Embrittlement of cast stainless steels results in brittle fracture associated with either cleavage of the ferrite or separation of the ferrite/austenite phase boundary. A predominantly brittle failure occurs when either the ferrite phase is continuous, e.g., in cast material with a high ferrite content, or the ferrite/austenite phase boundary provides an easy path for crack propagation, e.g., in high-carbon grades of cast steels with phase-boundary carbides. Consequently, the amount, size, and distribution of the ferrite phase in the duplex structure and the presence of phase-boundary carbides are important parameters in controlling the degree or extent of thermal embrittlement.

Thermal aging of cast stainless steels at temperatures <500°C (<932°F) leads to precipitation of additional phases in the ferrite matrix, e.g., formation of a chromium-rich α' phase by spinodal decomposition; nucleation and growth of α'; precipitation of a nickel- and silicon-rich G phase, $M_{23}C_6$ carbide, and γ_2 (austenite); and additional precipitation and/or growth of existing carbides at the ferrite/austenite phase boundaries. The additional phases provide the strengthening mechanisms that increase strain hardening and the local tensile stress. Consequently, the critical stress level for brittle fracture is achieved at higher tem-

peratures. The effects of material variables on the thermal embrittlement of cast stainless steels have been evaluated.

Tensile and fracture toughness J-R curve data are presented for several experimental and commercial heats of cast stainless steel that were aged up to 58,000 h at temperatures of 290–450°C (554–842°F). The results indicate that thermal aging increases tensile stress and decreases fracture toughness of cast stainless steels. The increase in flow stress of fully aged cast stainless steels is ≈10% for CF-3 steels and ≈20% for CF-8 and CF-8M steels. The values of fracture toughness J_{IC} and average tearing modulus for heats that are sensitive to thermal aging (e.g., CF-8M steels) are as low as ≈90 kJ/m² and ≈60, respectively. The results also indicate that the fracture toughness of cast stainless steels can be lower than that of the wrought stainless steels.

1 Introduction

Cast duplex stainless steels used in LWR systems for primary pressure-boundary components such as valve bodies, pump casings, and primary coolant piping are susceptible to thermal embrittlement at reactor operating temperatures, i.e., 280–320°C (536–608°F). Aging of cast stainless steels at these temperatures causes an increase in hardness and tensile strength and a decrease in ductility, impact strength, and fracture toughness of the material. Most studies on thermal embrittlement of cast stainless steels involve simulation of end-of-life reactor conditions by accelerated aging at higher temperatures, viz., 400°C (752°F), because the time period for operation of power plants (≈40 y) is far longer than can generally be considered for laboratory studies. Thus, estimates of the loss of fracture toughness suffered by cast stainless steel components are based on an Arrhenius extrapolation of high-temperature data to reactor operating conditions.

A program is being conducted at Argonne National Laboratory (ANL) to investigate the significance of low-temperature embrittlement of cast duplex stainless steels under light water reactor (LWR) operating conditions and to evaluate possible remedies for thermal embrittlement problems in existing and future plants. The scope of the program includes the following goals: (1) characterize and correlate the microstructure of in-service reactor components and laboratory-aged material with loss of fracture toughness to establish the mechanism of aging and validate the simulation of in-reactor degradation by accelerated aging, (2) establish the effects of key compositional and metallurgical variables on the kinetics and extent of thermal embrittlement, and (3) develop the methodology and correlations for predicting the toughness loss suffered by cast stainless steel components during normal and extended life of LWRs.

Microstructural and mechanical-property data are being obtained on 25 experimental heats (19 in the form of static-cast keel blocks and 6 in the form of 76-mm slabs) and 6 commercial heats (centrifugally cast pipes and a static-cast pump impeller and pump casing ring), as well as on reactor-aged material of grades CF-3, CF-8, and CF-8M cast stainless steel. Specimen blanks for Charpy-impact, tensile, and J-R curve tests have been aged at 290, 320, 350, 400, and 450°C (554, 608, 662, 752, and 842°F) for times up to 58,000 h. The reactor-aged material is from the recirculating-pump cover plate assembly of the KRB reactor, which was in service in Gundremmingen, Germany, for ≈8 yr at 284°C (543°F). Fractured impact test bars from five heats of aged cast stainless steel were obtained from the Georg Fischer Co. (GF) of Switzerland for microstructural characterization. The materials from GF are from a previous study of long-term aging behavior of cast stainless steel.[1] Data on chemical composition, ferrite content, hardness, ferrite morphology, and grain structure of the experimental and commercial heats have been reported earlier.[2] The chemical composition, hardness, and ferrite content and distribution of the cast materials are given in Table 1. Results of microstructural characterization and mechanical-property data from Charpy-impact, tensile, and J-R curve tests on 16 heats of cast stainless steel aged up to 30,000 h at temperatures between 290 and 450°C have been presented earlier.[2-11]

Work at ANL and elsewhere[1,12-17] has shown that embrittlement of cast stainless steel components will occur during the reactor lifetime of 40 y. Thermal aging at reactor temperatures increases the tensile strength and decreases the impact energy and fracture tough-

Table 1. Product form, chemical composition, hardness, and ferrite morphology of various heats of cast stainless steel

Heat	Grade	Chemical Composition (wt.%)									Ferrite[a] (%)		Hardness	Ferrite Spacing
		Mn	Si	P	S	Mo	Cr	Ni	N	C	Calc.	Meas.	R_B	(μm)
						Keel Blocks[b]								
50	CF-3	0.60	1.10	0.016	0.007	0.33	17.8[illegible]	9.14	0.079	0.034	3.0	4.4	80.1	194
49	CF-3	0.60	0.95	0.010	0.007	0.32	19.41	10.69	0.065	0.010	4.[illegible]	7.2	76.6	185
48	CF-3	0.60	1.08	0.009	0.006	0.30	19.55	10.46	0.072	0.011	5.1	8.7	78.1	127
47	CF-3	0.60	1.06	0.007	0.006	0.59	19.81	10.63	0.028	0.018	8.4	16.3	79.7	68
52	CF-3	0.57	0.92	0.012	0.005	0.35	19.49	9.40	0.052	0.009	10.3	13.5	81.6	69
51	CF-3	0.63	0.86	0.014	0.005	0.32	20.13	9.06	0.058	0.010	14.3	18.0	83.8	52
58	CF-8	0.62	1.12	0.010	0.005	0.33	19.53	10.89	0.040	0.056	3.2	2.9	77.1	303
54	CF-8	0.55	1.03	0.011	0.005	0.35	19.31	9.17	0.084	0.063	4.1	1.8	83.3	317
57	CF-8	0.62	1.08	0.009	0.004	0.34	18.68	9.27	0.047	0.056	4.4	4.0	80.2	138
53	CF-8	0.64	1.16	0.012	0.009	0.39	19.53	9.23	0.049	0.065	6.3	8.7	83.1	92
56	CF-8	0.57	1.05	0.007	0.007	0.34	19.65	9.28	0.030	0.066	7.3	10.1	82.5	84
59	CF-8	0.60	1.08	0.008	0.007	0.32	20.33	9.34	0.045	0.062	8.8	3.5	83.2	75
61	CF-8	0.65	1.01	0.007	0.007	0.32	20.65	8.86	0.080	0.054	10.0	13.1	85.3	82
60	CF-8	0.67	0.95	0.008	0.006	0.31	21.05	8.34	0.058	0.064	15.4	[illegible]	86.7	63
62	CF-8M	0.72	0.56	0.007	0.005	2.57	18.29	12.39	0.030	0.063	2.8	4.5	78.1	140
63	CF-8M	0.61	0.58	0.007	0.006	2.57	19.37	11.85	0.031	0.055	6.4	10.4	81.6	81
66	CF-8M	0.60	0.49	0.012	0.007	2.39	19.45	9.28	0.029	0.047	19.6	19.8	85.3	41
65	CF-8M	0.50	0.48	0.012	0.007	2.57	20.78	9.63	0.064	0.049	20.9	23.4	89.0	43
64	CF-8M	0.60	0.63	0.006	0.005	2.46	20.75	9.40	0.038	0.038	29.0	28.4	89.7	41
						76-mm Slabs[c]								
69	CF-3	0.63	1.13	0.015	0.005	0.34	20.18	8.59	0.028	0.023	21.0	23.6	83.7	35
	CF-8	0.72	1.09	0.028	0.016	0.25	19.43	8.54	0.053	0.070	7.0	7.[illegible]	78.8	253
68	CF-8	0.64	1.07	0.021	0.014	0.31	20.64	8.08	0.062	0.063	14.9	23.4	84.6	87
70	CF-8M	0.55	0.72	0.021	0.016	2.30	19.17	9.01	0.049	0.066	14.2	18.9	86.5	96
74	CF-8M	0.54	0.73	0.022	0.016	2.51	19.11	9.03	0.048	0.064	15.5	18.4	85.8	90
75	CF-8M	0.53	0.67	0.022	0.012	2.58	20.86	9.12	0.052	0.065	24.8	27.8	89.5	60
						Reactor Components[d]								
P3	CF-3	1.06	0.88	0.017	0.014	0.01	[illegible]	8.45	0.168	0.02[illegible]	2.8	1.9	82.2	–
P2	CF-3	0.74	0.94	0.010	0.006	0.16	20.20	9.38	0.040	0.019	12.5	15.6	83.8	69
I	CF-3	0.47	0.83	0.030	0.011	0.45	20.20	8.70	0.032	0.019	20.4	17.1	81.0	65
C1	CF-8	1.22	1.18	0.033	0.008	0.65	19.00	9.37	0.040	0.039	7.8	2.2	79.5	–
P1	CF-8	0.59	1.12	0.026	0.013	0.04	20.49	8.10	0.056	0.036	17.7	24.1	84.9	90
P4	CF-8M	1.07	1.02	0.019	0.01[illegible]	2.05	19.64	10.00	0.151	0.040	5.9	10.0	83.1	182
205	CF-8M	0.93	0.63	0.019	–	3.37	17.88	8.80	–	0.040	21.0	15.9	–	79
758	CF-8M	0.91	0.62	0.018	–	3.36	17.91	8.70	–	0.030	24.2	19.2	–	62
						Reactor-Aged[e]								
KRB	CF-8	0.31	1.17	–	–	0.17	21.99	8.03	0.038	0.062	27.7	34.0	–	–

Table 1. (Contd.)

Heat	Grade	Chemical Composition (wt.%) Mn	Si	P	S	Mo	Cr	Ni	N	C	Ferrite[a] (%) Calc.	Meas.	Hardness R_B	Ferrite Spacing (μm)
						Laboratory-Aged[f]								
280	CF-3	0.50	1.37	0.015	0.006	0.25	21.60	8.00	0.038	0.028	36.3	40.0	–	186
278	CF-8	0.28	1.00	0.008	0.019	0.13	20.20	8.27	0.030	0.038	18.5	15.0	–	174
292	CF-8	0.34	1.57	0.018	0.016	0.13	21.60	7.52	0.039	0.090	23.9	28.0	–	–
286	CF-8M	0.40	1.33	0.044	0.015	2.44	20.20	9.13	0.062	0.072	18.9	22.0	–	201

[a] Calculated from the composition with Hull's equivalent factor.
Measured by ferrite scope AUTO Test FE, Probe Type FSP-1.
[b] *Static Cast Keel Blocks*: Foundry ESCO; Size 180 x 120 x 90-30 mm.
[c] *Static Cast Slabs*: Foundry ESCO; Size 610 x 610 x 76 mm.
[d] *Centrifugally Cast Pipes*:
P3 Foundry SANDUSKY; Size 580 mm O.D., 76 mm wall.
P2 Foundry FAM, France; Size 930 mm O.D., 73 mm wall.
P1 Foundry ESCO; Size 890 mm O.D., 63 mm wall.
P4 Foundry SANDUSKY; Size 580 mm O.D., 32 mm wall.
205 Size 305 mm O.D., 25 mm wall.
Static Cast:
Elbow 758: Size 305 mm O.D., 30 mm wall.
Pump Impeller I: Foundry ESCO; Size 660 mm diameter.
Pump Casing C1: Foundry ESCO; Size 600 mm O.D., 57 mm wall.
[e] *KRB Reactor Pump Cover Plate*: Foundry GF; Size 890 mm diameter.
[f] Aged Material from Georg Fischer Co., Switzerland.

ness of the steels. The Charpy transition curve shifts to higher temperatures. Different heats exhibit different degrees of thermal embrittlement: the low-C CF-3 steels are the most resistant, and the Mo-bearing, high-C CF-8M steels are the least resistant to thermal embrittlement. The extent of thermal embrittlement increases with increased ferrite content.

The mechanisms of thermal embrittlement of cast duplex stainless steel have been discussed earlier.[5-7] Thermal aging of cast stainless steels at <500°C (<932°F) leads to precipitation of additional phases in the ferrite, e.g., formation of a Cr-rich α' phase by spinodal decomposition; nucleation and growth of α'; precipitation of an Ni- and Si-rich G phase, $M_{23}C_6$, and γ_2; and additional precipitation and/or growth of existing carbides at the ferrite/austenite phase boundaries.[8-10,18,19] The formation of Cr-rich regions by spinodal decomposition is the primary strengthening mechanism for ferrite, which increases strain hardening and local tensile stress. Consequently, the critical stress for brittle fracture, i.e., either cleavage of the ferrite or separation of the ferrite/austenite phase boundary, is achieved at higher temperatures.

The degree or extent of thermal embrittlement is controlled by the amount of brittle fracture. A predominantly brittle failure occurs when either the ferrite phase is continuous, e.g., in cast material with a large ferrite content, or the ferrite/austenite phase boundary provides an easy path for crack propagation, e.g., in high-C or high-N steels that contain phase-boundary carbides or nitrides. Consequently, the amount, size, and distribution of the ferrite in the duplex structure and phase-boundary precipitates are important parameters that control the extent of thermal embrittlement.

Current assessments of thermal embrittlement of cast stainless steels involve simulation of end-of-design-life reactor conditions by accelerated aging at higher temperatures, viz., 400°C (752°F), because the time period for operation of power plants (≈40 y) is far longer than can generally be considered for laboratory studies. Estimates of mechanical-property degradation of cast stainless steel components are based on an Arrhenius extrapolation of high-temperature data to reactor operating conditions.

The temperature dependence of thermal embrittlement is controlled primarily by the kinetics of ferrite strengthening, i.e., the size and spacing of Cr fluctuations produced by spinodal decomposition of ferrite. Small changes in the constituent elements of the material can cause the kinetics of thermal embrittlement to vary significantly. Activation energies of thermal embrittlement can range from 65 to 230 kJ/mole. Also, aging behavior at 400°C (752°F) shows significant heat-to-heat variation. Production heat treatment, and possibly the casting process, influence aging behavior at 400°C and therefore the kinetics of thermal embrittlement. The log of the aging time at 400°C for a 50% reduction in Charpy-impact energy has been shown to be a useful parameter for characterizing the kinetics of thermal embrittlement.[20,21] Activation energy for thermal embrittlement is high for steels that show fast embrittlement at 400°C and low for those that show slow embrittlement at 400°C.

Mechanical-property results from the present study and data from other investigations have been analyzed to develop the procedure and correlations for predicting the kinetics and extent of thermal embrittlement of reactor components from known material parameters. An initial assessment of the mechanisms and significance of low-temperature thermal embrittlement of cast stainless steels in LWR systems has been presented.[20,21] This report presents mechanical-property data on several heats of cast stainless steel aged up to 58,000 h at 290, 320, 350, and 400°C (554, 608, 662, and 752°F).

2 Impact Energy

2.1 Kinetics of Thermal Embrittlement

The Charpy-impact data for various experimental and commercial heats, aged up to 30,000 h at 290-450°C (554-842°F), have been presented earlier.[2] The variation of the room-temperature Charpy-impact energy C_V (J/cm^2) with time can be expressed as

$$\log_{10}C_V = \log_{10}C_{V_{sat}} + \beta\{1 - \tanh[(P - \theta)/\alpha]\}, \quad (1)$$

where P is the aging parameter, $C_{V_{sat}}$ is the minimum impact energy reached after long-term aging, β is half the maximum decrease in $\log C_V$, θ is the log of the time to achieve β reduction in impact energy, and α is a shape factor. The aging parameter P is the log of the time at 400°C and is defined by

$$P = \log_{10}(t) - \frac{1000Q}{19.143}\left(\frac{1}{T_s + 273} - \frac{1}{673}\right), \quad (2)$$

where Q is the activation energy (kJ/mole) and t and T_s are, respectively, the time (h) and

Table 2. Activation energies for kinetics of thermal embrittlement of cast stainless steels

Heat	Cv_{sat} (J/cm²)	Constants			Q [kJ/mole (kcal/mole)]	
		β	θ	α	Average	95% Confidence Limit
47	151.4	0.086	2.68	1.200	193 (46.1)	103-275 (24.5-65.7) [a]
51	115.9	0.139	3.53	1.152	205 (48.9)	129-281 (30.8-67.0) [a]
69	89.1	0.214	3.21	1.070	176 (42.5)	151-204 (36.2-48.8)
P2	141.3	0.258	2.83	1.094	219 (52.2)	173-264 (41.4-63.1)
59	75.0	0.224	3.48	1.200	247 (59.1)	195-299 (46.7-71.5)
60	44.8	0.327	3.09	1.026	212 (50.7)	177-247 (42.3-59.1)
61	93.3	0.214	3.48	1.200	198 (47.3)	146-250 (34.8-59.7)
68	56.8	0.301	2.88	0.680	161 (38.5)	140-182 (33.4-43.6)
P1	54.1	0.305	2.57	0.748	253 (60.4)	209-296 (50.0-70.8)
63	115.1	0.150	2.98	1.609	154 (36.8)	100-208 (24.0-49.6)
64	41.1	0.338	2.81	0.597	147 (35.2)	133-161 (31.9-38.6)
65	50.1	0.319	3.01	0.965	162 (38.6)	137-186 (32.7-44.4)
66	87.9	0.208	3.16	1.566	164 (39.2)	118-210 (28.1-50.2) [a]
74	63.1	0.269	3.44	0.700	95 (22.7)	54-136 (12.8-32.6) [a]
75	32.1	0.436	2.82	0.509	139 (33.2)	122-156 (29.2-37.2)
P4	62.7	0.289	2.70	0.615	159 (37.9)	140-177 (33.5-42.4)

[a] Standard deviation is large because of the relatively small decrease in impact energy and a large scatter in data.

temperature (°C) of aging. The values of the constants in Eqs. 1 and 2, obtained from best fit of the Charpy data for various heats of cast stainless steel aged up to 30,000 h at 320, 350, and 400°C (608, 662, and 752°F) were presented earlier.[2,5-7,20,21] The 450 and 290°C aging results were excluded from the analyses, since the former are not representative of reactor operating conditions and the latter showed a slight increase instead of a decrease in impact energy after aging up to 30,000 h. The relatively short-time-aging data at 290°C tend to bias the analyses to yield higher values of activation energies.

Charpy-impact data for materials that were aged for 30,000 h or longer are given in Appendix A, Table A-1. The room-temperature Charpy data were reanalyzed to determine the kinetics of thermal embrittlement; the 290°C aging results were included in these analyses. Values of the constants in Eqs. 1 and 2 are given in Table 2. The change in Charpy-impact energy, as well as the best-fit curves for the various heats of cast stainless steel, is shown in Figs. 1-5. Activation energies for thermal embrittlement of the various heats, with minor differences, are comparable to the values reported earlier.[5-7,20,21]

Material was also obtained from the Electric Power Research Institute (EPRI) heat of CF-3 steel.[17] Charpy-impact specimen blanks were obtained from fractured CT specimens of the unaged material. The material was aged up to 17,000 h at 320 and 350°C (608 and 662°F) to determine the kinetics of embrittlement. The results are given in Appendix A, Table A-2. Best-fit curves to Eq. 1 and 2 are shown in Fig. 6; the data for 400°C aging from the earlier study are also included in the figure. Results from GF[1] and Framatome (FRA)[15] studies were also fitted to Eqs. 1 and 2 to obtain a consistent set of values for activation energy. The chemical composition and the constants in Eq. 1 and 2 for the EPRI, GF, and FRA heats are given in Table 3.

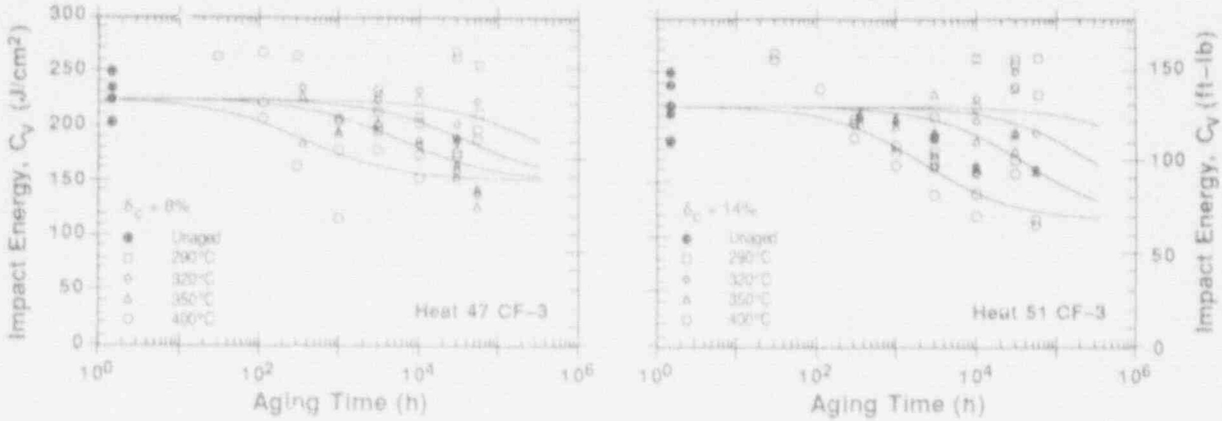
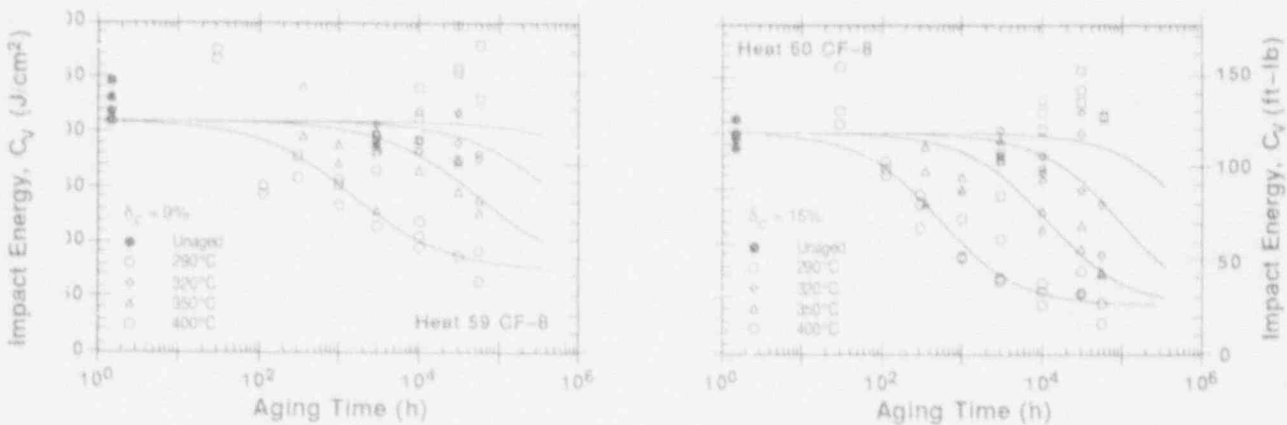


Figure 1. Effect of aging time and temperature on the room-temperature Charpy-impact energy of static-cast CF-3 keel blocks



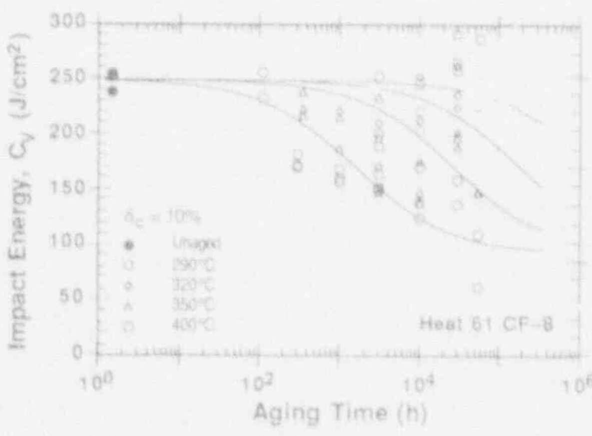


Figure 2. Effect of aging time and temperature on the room-temperature Charpy-impact energy of static-cast CF-8 keel block

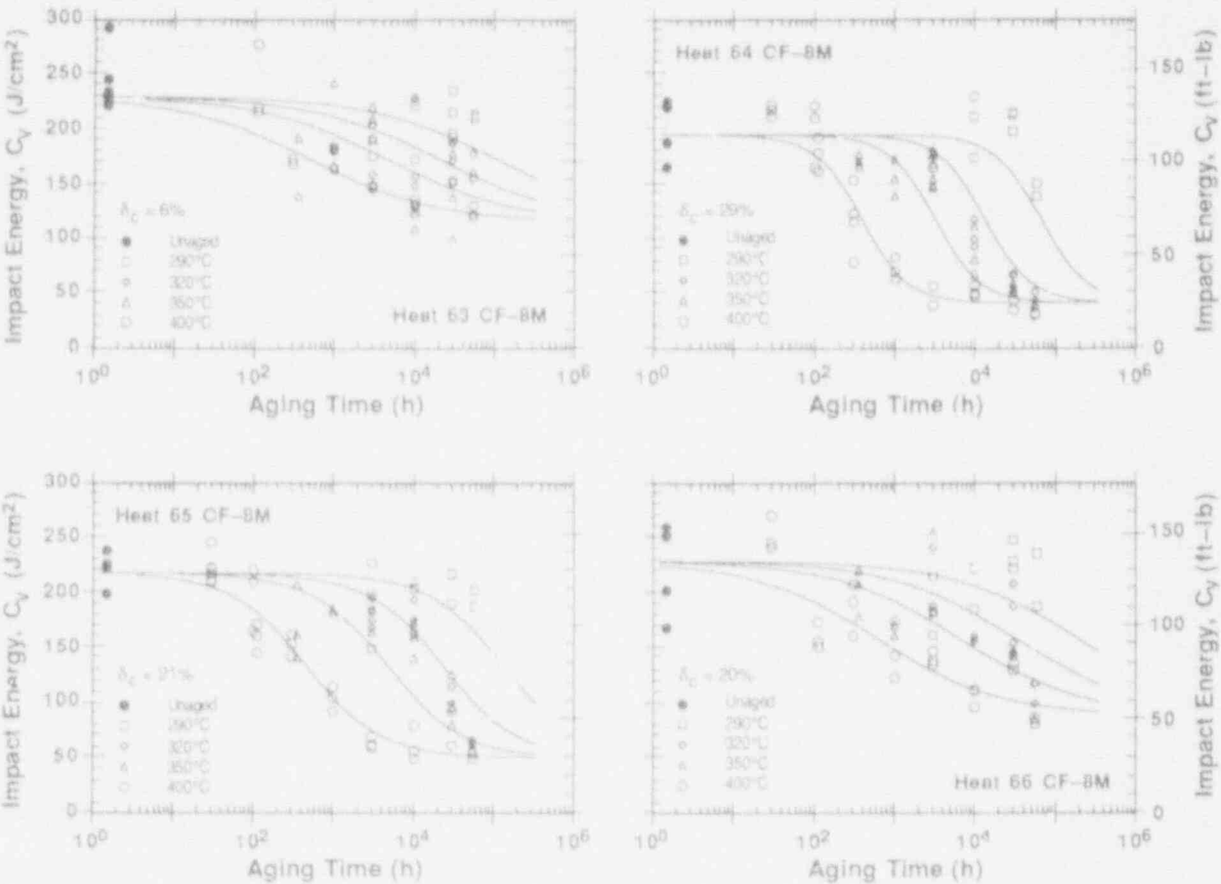


Figure 3. Effect of aging time and temperature on the room-temperature Charpy-impact energy of static-cast CF-8M keel block

The Charpy-impact data obtained at ANL and elsewhere indicate that all cast stainless steels reach a "saturation" impact energy, i.e., a minimum value that would be achieved by the material after long-term aging. The actual value of saturation impact energy for a specific cast stainless steel is independent of aging temperature but depends strongly on the chemical composition of the steel. In general, it is lower for the Mo-bearing CF-8M steels than that for the Mo-free CF-3 or CF-8 steels, and decreases with an increase in ferrite content or the concentration of C or N in the steel. The effect of ferrite content is obvious in Figs. 1-5 for all grades of steel. Influence of C content is seen by comparing the results for Heats 47 and 59 or Heats 51 and 60 in Figs. 1 and 2, and of N content by comparing the results for Heats 63 and P4 in Figs. 3 and 5. These compositional factors promote a predominantly brittle failure. An increase in ferrite content provides a continuous path for crack propagation via cleavage of ferrite. The presence of carbides or nitrides at the ferrite/austenite phase boundary provides an easy path for crack propagation via phase boundary separation. Similar trends are observed in the data from GF,[1] Electricité de France (EdF),[13] and FRA[15] studies.

The results also indicate that the time to reach saturation, i.e., the kinetics of thermal embrittlement, also shows significant heat-to-heat variation. The decrease in Charpy-im-

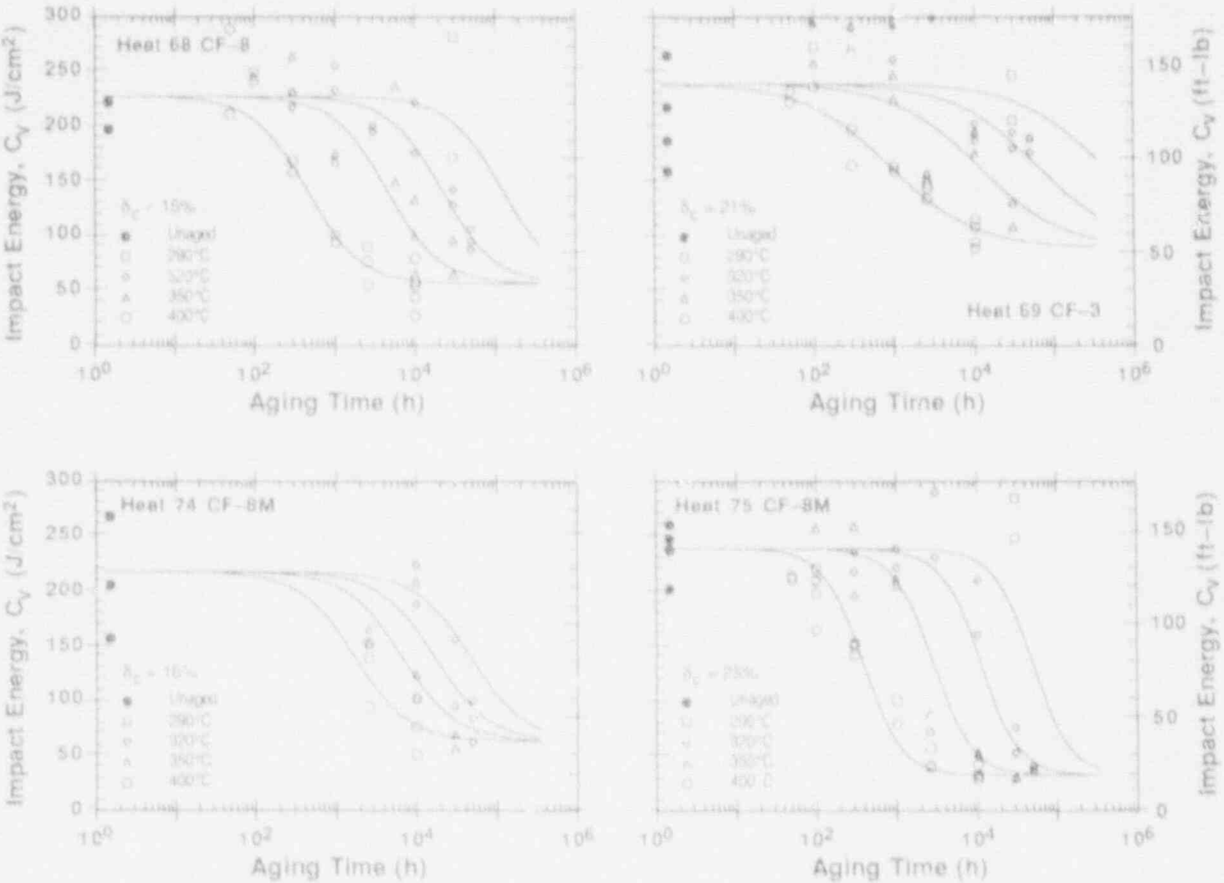
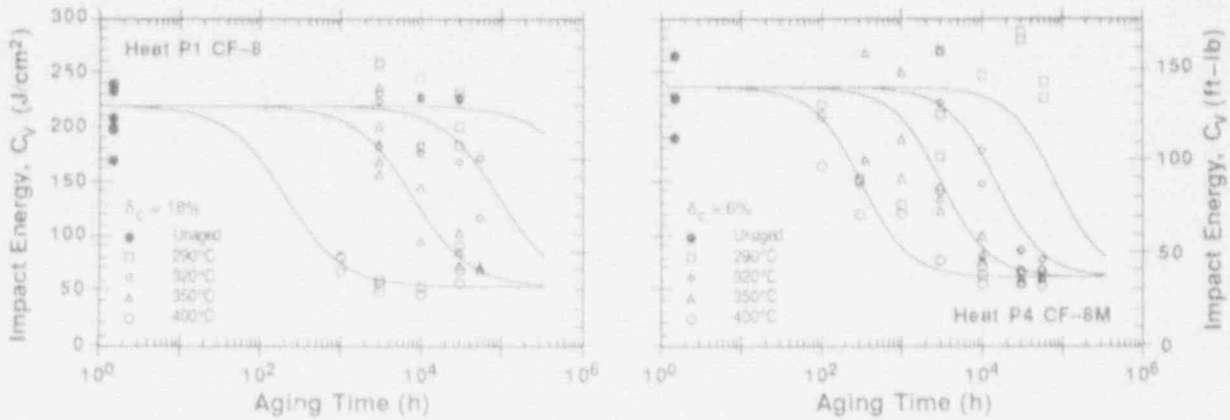


Figure 4. Effect of aging time and temperature on the room-temperature Charpy-impact energy of static-cast stainless steel slabs

pact energy during thermal aging at 400°C for some of the heats investigated at ANL,[5–7] FRA,[15] EPRI,[17] and GF[1] is shown in Fig. 7. The aging time to reach saturation varies by more than two orders of magnitude for these heats, e.g., <1,000 h for the EPRI heat, 1,000–10,000 h for the ANL and FRA heats, and 10,000–30,000 h for the GF heats. Longer aging times are needed to achieve saturation at lower temperatures; actual time depends on the kinetics of thermal embrittlement. For example, saturation impact energy is achieved after aging for 30,000 h at 350°C (662°F) for Heats 63, 64, 74, 75, and P4 (Figs. 3–5) and after 58,000 h at 320°C (608°F) for Heat P4 (Fig. 5). Other heats do not reach saturation even after 58,000 h at 350 or 320°C, because the aging behavior at 400°C is very slow and/or the activation energy for thermal embrittlement is high for these heats.

The constant θ, i.e., log of the aging time at 400°C (752°F) for a 50% reduction in Charpy-impact energy, has been shown to be a useful parameter for characterizing the kinetics of thermal embrittlement.[20,21] Activation energy for thermal embrittlement is high for steels that show fast embrittlement at 400°C and low for those that show slow embrittlement at 400°C. For example, the constant θ and activation energy for thermal embrittlement, respectively, are 3.0–4.0 and 60–105 kJ/mole for the GF heats, 2.3–3.5 and 95–250 kJ/mole for ANL heats, and 2.1 and 225 kJ/mole for EPRI heat. The results indicate that the constant θ, which basically defines the aging behavior at 400°C, is insensitive to the



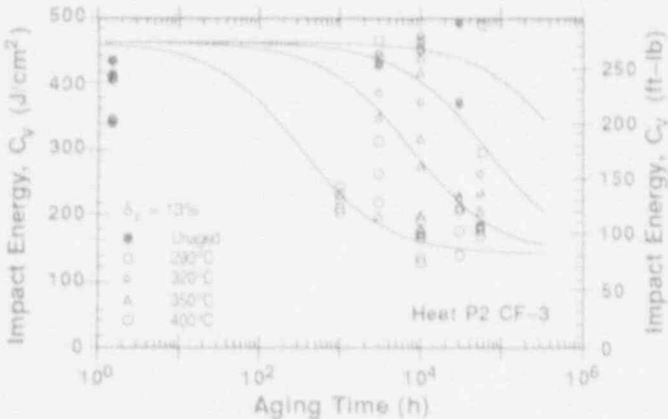


Figure 5.
Effect of aging time and temperature on the room-temperature Charpy-impact energy of centrifugally cast stainless steel pipes

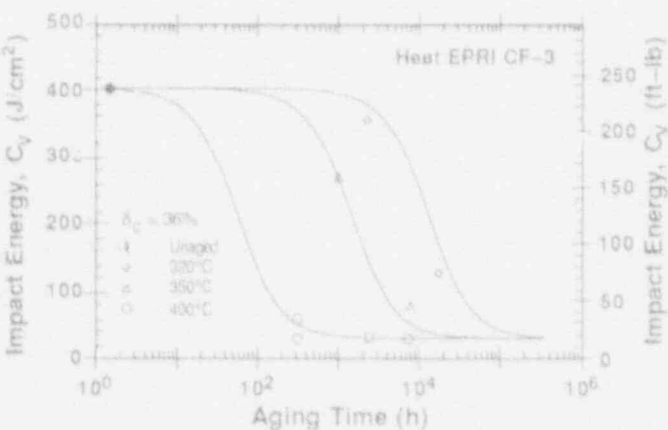


Figure 6.
Effect of aging time and temperature on the room-temperature Charpy-impact energy of static-cast stainless steel plate

Table 3. *Chemical composition and kinetics of thermal embrittlement of Georg Fischer, EPRI, and Framatome heats of cast stainless steels*

Heat	Chemical Composition (wt.%) Cr	Mo	Si	Ni	Mn	C	N	C_{Vsat} [J/cm²]	Constants β	θ	α	Q [kJ/mole (kcal/mole)]
277	20.5	0.06	1.81	8.13	0.54	0.052	0.019	33.5	0.488	3.65	0.55	88 (21.0)
278	20.2	0.13	1.00	8.27	0.28	0.038	0.030	68.3	0.381	4.05	0.47	63 (15.0)
279	22.0	0.22	1.36	7.85	0.37	0.040	0.032	23.8	0.586	3.21	0.60	92 (21.9)
280	21.6	0.25	1.37	8.00	0.50	0.028	0.038	24.4	0.591	3.30	0.73	87 (20.7)
281	23.1	0.17	0.45	8.60	0.41	0.036	0.053	26.6	0.560	3.76	0.42	93 (22.1)
282	22.5	0.15	0.35	8.53	0.43	0.035	0.040	30.0	0.525	3.73	0.43	98 (23.4)
283	22.6	0.23	0.53	7.88	0.48	0.036	0.032	23.8	0.580	3.65	0.43	83 (19.8)
284	23.0	0.17	0.52	8.23	0.28	0.025	0.037	23.8	0.560	3.71	0.41	87 (20.9)
291	19.6	0.66	1.59	10.60	0.28	0.065	0.054	121.9	0.235	3.89	0.79	77 (18.5)
292	21.6	0.13	1.57	7.52	0.34	0.090	0.039	22.2	0.392	3.08	0.46	99 (23.7)
285	18.8	2.35	0.86	9.49	0.48	0.047	0.039	64.3	0.347	3.76	0.34	82 (19.6)
286	20.2	2.44	1.33	9.13	0.40	0.072	0.062	20.5	0.571	3.11	0.62	106 (25.2)
287	20.5	2.58	0.51	8.46	0.50	0.047	0.033	23.8	0.563	3.52	0.42	92 (21.9)
288	19.6	2.53	1.70	8.40	0.47	0.052	0.022	19.4	0.643	3.02	0.64	106 (25.3)
289	19.7	2.30	1.44	8.25	0.48	0.091	0.032	21.1	0.571	3.32	0.39	90 (21.6)
290	20.0	2.40	1.51	8.30	0.41	0.054	0.050	21.1	0.602	3.49	0.11	81 (19.3)
EPRI	22.04	0.23	0.84	7.93	0.74	0.030	0.045	30.0	0.565	2.10	0.596	225 (54.8)
C	20.7	0.13	1.09	8.19	1.09	0.042	0.035	31.0	0.393	3.30	0.45	83 (19.9)
E	21.0	0.08	0.54	8.47	0.80	0.035	0.051	45.0	0.334	2.63	0.65	133 (31.8)
F	19.7	0.34	1.16	8.33	0.26	0.038	0.026	83.0	0.282	2.45	1.23	176 (41.1)
B	20.1	2.52	0.93	10.56	0.83	0.053	0.042	31.0	0.478	2.55	0.47	129 (30.7)
D	19.2	2.44	0.94	10.32	1.12	0.026	0.063	33.0	0.439	3.30	0.40	90 (21.4)

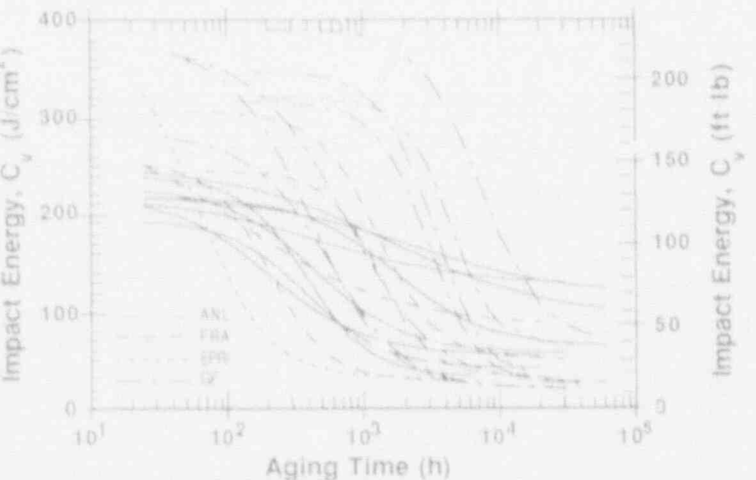


Figure 7. *Decrease in Charpy-impact energy for various heats of cast stainless steels aged at 400°C*

chemical composition of the steel. Production heat treatment, and possibly the casting process, influence θ and therefore the kinetics of thermal embrittlement.

The influence of heat treatment is observed in GF Heats 280 and 280N.[1] The two heats have the same composition and were given a production heat treatment of 12 h at 1010°C (1850°F) and water quenched. Heat 280 was given a second heat treatment of 4 h at 1050°C (1922°F) and water quenched. The aging behavior is significantly different for the two heats; θ is 3.3 and 2.3 for Heat 280 and 280N, respectively. Microstructural examination of aged cast stainless steels suggests that a large value of θ and a low value of activation energy are associated with the Ni-Si, Mo-Si, and Ni-Si-Mo clusters in the ferrite matrix.[9,10] These clusters are considered to be precursors of G phase nucleation and precipitation. Cast stainless steels with low activation energy and large θ value show G-phase precipitation after aging, and steels with high activation energy and low θ value do not contain G phase. The presence of Ni-Si-Mo clusters in the ferrite matrix of the unaged materials may be considered as an indicator for fast kinetics and a low activation energy for thermal embrittlement.

A procedure and correlations have been developed for estimating the saturation room-temperature impact energy and kinetics of thermal embrittlement of cast stainless steels from their chemical composition.[20,21] The room-temperature impact energy of a specific cast stainless steel is estimated as a function of time and temperature of reactor service. The correlations have been validated with Charpy-impact data on reactor-aged materials.[20]

2.2 Charpy Transition Curves

Charpy transition curves have been obtained for four experimental and two commercial heats aged up to 58,000 h at 290, 320, 350, and 400°C (554, 608, 662, and 752°F) and for nine experimental heats aged for 10,000 h at 400°C. The results are presented in Ref. 2 and Appendix A, Tables A-1 through A-3. The Charpy data were fitted with a hyperbolic tangent function of the form

$$C_V = K_o + B[1 + \tanh[(T - C)/D]], \quad (3)$$

where K_o is the lower-shelf energy, T is the test temperature (°C), B is half the distance between upper-shelf energy (USE) and lower-shelf energy, C is the mid-shelf Charpy transition temperature (CTT), and D is the half-width of the transition region. Values of the constants in Eq. 3 are given in Table 4. The effect of aging time and temperature on the Charpy transition curves for the various heats is shown in Figs. 8-10. The shift in Charpy transition curves for the EPRI heat aged up to 17,000 h at 320, 350, and 400°C is shown in Fig. 11. Thermal aging decreases the impact energy and shifts the transition curves to higher temperatures. Most una[illegible] partially aged cast stainless steels do not show a flat upper shelf as defined by Eq. 3. [illegible] maximum between -50 and 100°C and decreases at higher temperatures.

The results indicate a "saturation effect" for USE (defined as K_o+2B in Eq. 3) after aging. The USE decreases to a minimum saturation value in a relatively short time, i.e., <3,000 h at 400°C or <10,000 h at 350°C, and does not change further with longer aging times. After saturation of USE, the decrease in room-temperature impact energy is due to

Table 4. Values of constants in Eq. 3 for Charpy transition curve of cast stainless steels

Heat	Aging Condition		Constants			
	Temp. (°C)	Time (h)	K_0 (J/cm²)	B (J/cm²)	C (°C)	D (°C)
69	Unaged	–	40	130.3	-186.8	222.7
	290	30,000		86.4	-17[illegible].8	30.0
	320	10,000		78.2	-154.1	37.8
	320	30,000		90.5	-74.2	89.2
	320	50,000		80.5	-69.1	88.4
	350	2,570		69.1	-113.2	50.4
	350	10,000		73.5	-34.6	43.5
	350	30,000		59.2	-16.9	107.1
	400	2,570		55.6	-60.7	87.4
	400	10,000		54.7	-16.9	98.0
	450	2,570		50.6	-85.0	126.5
1	Unaged	–	50	62.8	-307.9	106.2
	320	30,000		81.8	-184.0	127.9
	350	9,980		49.8	-125.4	51.7
	400	9,980		46.7	-89.1	92.5
P2	Unaged		50	162.1	-189.0	44.1
	320	30,000		172.7	-42.2	71.9
	350	10,000		148.7	-43.1	87.8
	350	30,000		157.0	-5.8	97.6
68	Unaged	–	15	138.3	-59.8	99.9
	290	30,000		169.0	-12.1	98.4
	320	10,000		97.4	-40.9	46.0
	320	30,000		107.6	4.6	85.7
	320	50,000		111.1	35.1	48.0
	350	5,780		78.5	-12.6	60.7
	350	10,000		97.0	28.0	67.3
	350	30,000		86.3	53.[illegible]	85.7
	400	2,570		70.5	31.3	78.5
	400	10,000		68.6	64.0	64.3
	450	2,570		54.9	32.6	86.7
70	Unaged	–	15	119.7	-156.2	60.6
	350	2,570		105.6	-77.0	38.7
	350	10,000		89.2	23.6	121.7
	400	2,570		87.4	-1.7	116.2
	400	10,000		[illegible]	10.3	90.9
74	Unaged	–	15	89.5	-177.5	119.6
	290	30,000		140.9	-104.8	40.7
	320	10,000		91.1	-95.0	65.8
	320	30,000		87.1	-8.5	84.3
	320	[illegible]		67.6	-2.9	134.2
	350	[illegible]		89.0	-88.7	38.9
	350	10,000		71.5	-35.6	86.7
	350	30,000		81.2	79.[illegible]	168.5
	400	2,570		61.6	-37.2	49.6
	400	10,000		65.6	19.2	123.7
	450	2,570		3[illegible].2	-47.0	63.5
75	Unaged	–	15	92.0	-156.5	43.7
	290	30,000		121.6	-76.4	50.5
	320	10,000		90.4	-16.0	37.9
	320	30,000		78.4	83.0	140.1
	320	30,000		67.6	144.1	149.8
	350	2,570		70.9	-10.2	105.2
	350	10,000		71.3	80.5	74.4
	350	30,000		67.9	207.7	180.1
	400	2,570		52.7	45.5	83.1
	400	10,000		66.3	140.7	138.8
	450	2,570		34.0	20.8	99.4

Table 4. (Contd.)

Heat	Aging Condition		Constants			
	Temp (°C)	Time (h)	K_0 (J/cm^2)	B (J/cm^2)	C (°C)	D (°C)
47	Unaged		35	123.9	-200.9	100.5
	400	10,000	|	69.4	-129.8	30.1
51	Unaged		35	103.5	-201.6	73.5
	400	10,000	|	54.4	-131.3	20.0
52	Unaged		35	119.0	-193.7	66.3
	400	10,000	|	75.2	-156.8	21.1
59	Unaged		15	118.6	133.3	76.3
	400	10,000	|	85.0	1.8	119.2
60	Unaged		15	116.7	-129.3	77.0
	400	10,000	|	67.1	57.2	79.2
61	Unaged		15	137.1	-125.4	103.3
	400	10,000	|	80.6	-15.8	48.6
63	Unaged		20	118.3	-241.7	84.4
	400	10,000	|	69.3	-32.1	75.3
64	Unaged		15	99.5	-191.7	31.8
	400	10,000	|	47.0	59.3	127.7
65	Unaged		15	102.0	-184.3	67.4
	400	10,000	|	59.6	56.7	120.2

an increase in CTT, i.e., the value of constant B in Eq. 3 remains the same, and only the constants C and D increase with longer aging times. This behavior is observed at all aging temperatures and for all heats of material. Table 4 shows that the saturation value of USE for aged cast stainless steels decreases with increasing ferrite content and depends on the casting method and grade of the steel. For comparable ferrite content, CF-3 steels show the highest values of saturation USE and CF-8M steels the lowest. Also, centrifugally cast steels show higher USE than the static-cast steels. Saturation USE for the static-cast ANL heats is between 110 and 185 J/cm^2 (65 and 109 ft·lb); lowest values are ≈110 and 120 J/cm^2 (65 and 71 ft·lb) for Heats 64 and 75, respectively.

As discussed in Section 2.1, most cast stainless steels reach a saturation room-temperature impact energy after ≈3,000 h at 400°C or ≈30,000 h at 350°C, i.e., when the aging parameter P is ≈3.5. Because both room-temperature impact energy and USE appear to reach saturation values, Charpy transition curves may also show a "saturation effect." Transition curves for three grades of cast stainless steel aged to P values of 3.0–4.0 are shown in Fig. 12. A saturation effect on the transition curve is indicated for the materials that have a saturation room-temperature impact energy close to USE. The saturation room-temperature impact energy for Heat 69 is ≈89 (53 ft·lb) and the transition curves for P values of 3.4–4.0 are comparable. Saturation condition is not reached after 50,000 h at 320°C (P = 2.86). These results suggest a saturation effect on the transition curve, because an increase in CTT would mean a further decrease in room-temperature impact energy. For such materials, impact energy at reactor temperatures (280–320°C) would also saturate after aging and the value will be comparable to or slightly higher than the saturation room-temperature impact energy.

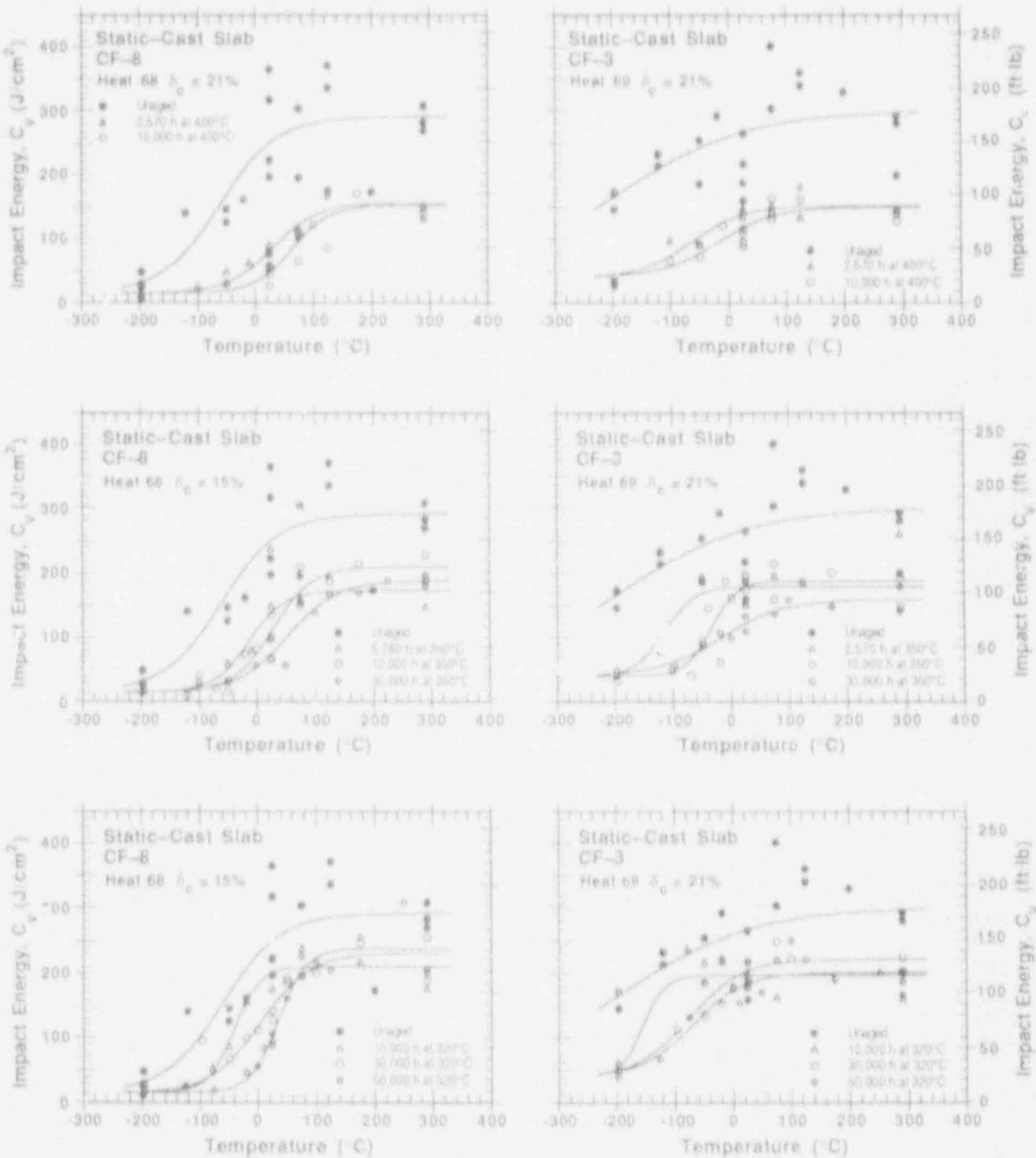
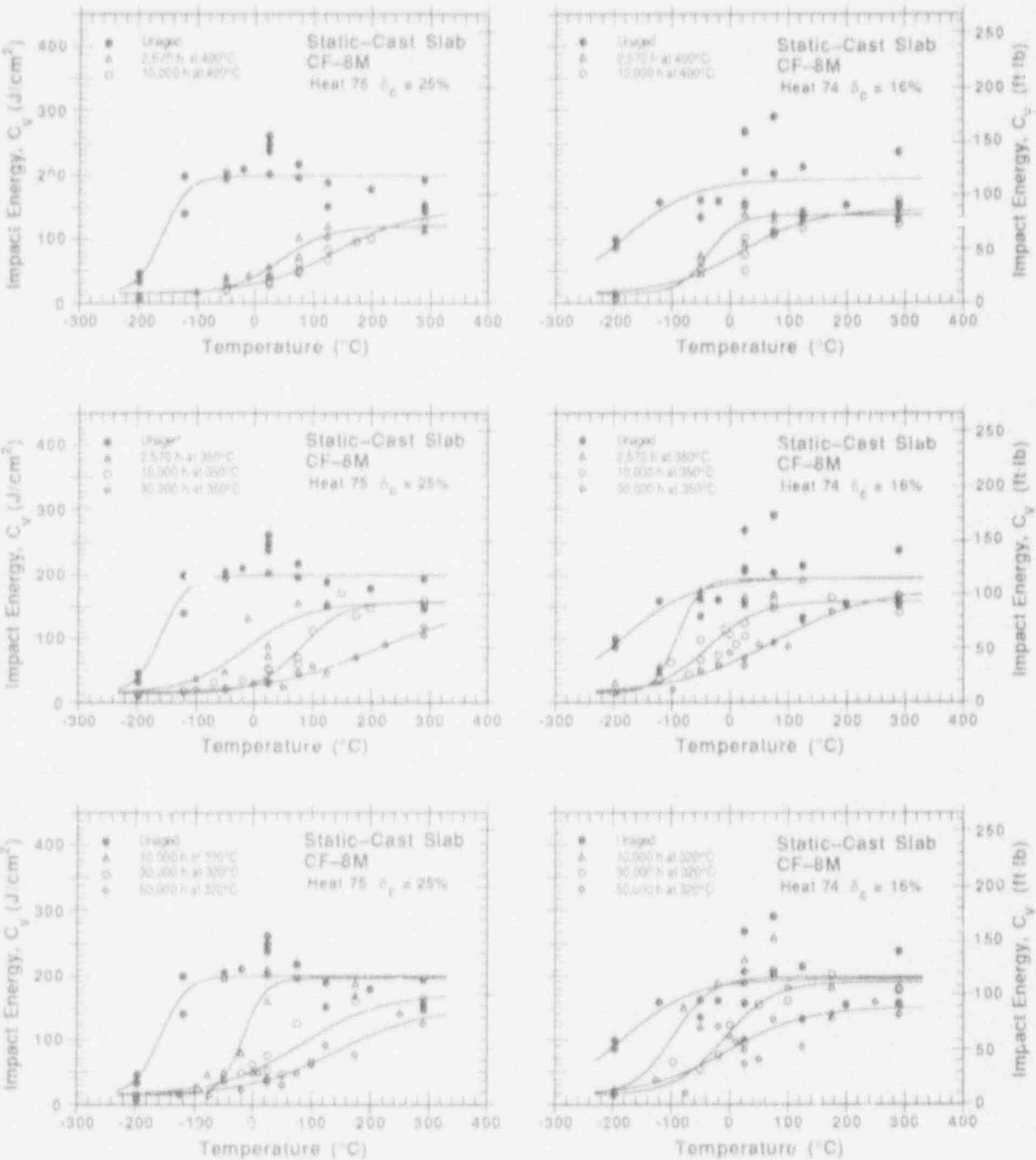


Figure 8. Effect of aging time and temperature on the Charpy-transition curves of experimental Heats 68 and 69



gure 9. *Effect of aging time and temperature on the Charpy-transition curves of experimental Heats 74 and 75*

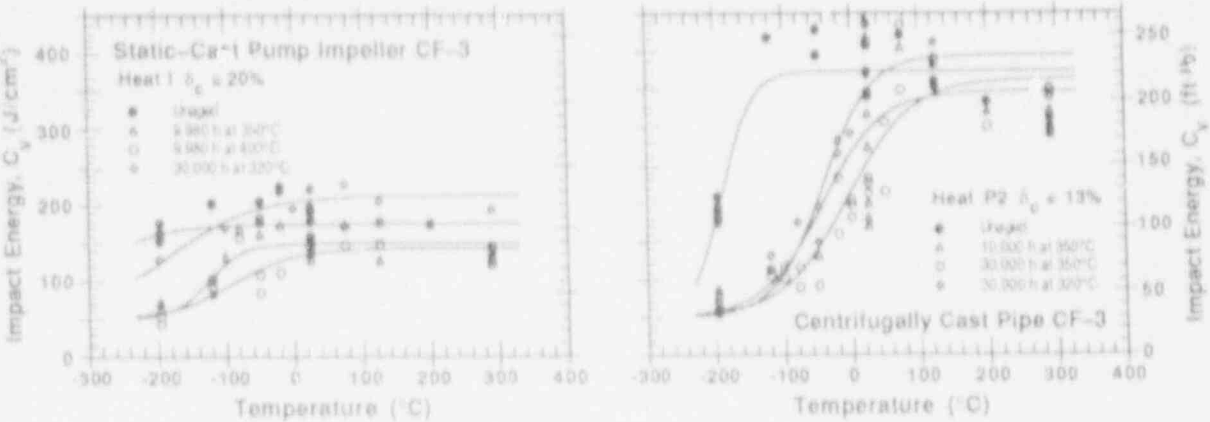


Figure 10. Effect of aging time and temperature on the Charpy-transition curves of commercial Heats I and P2

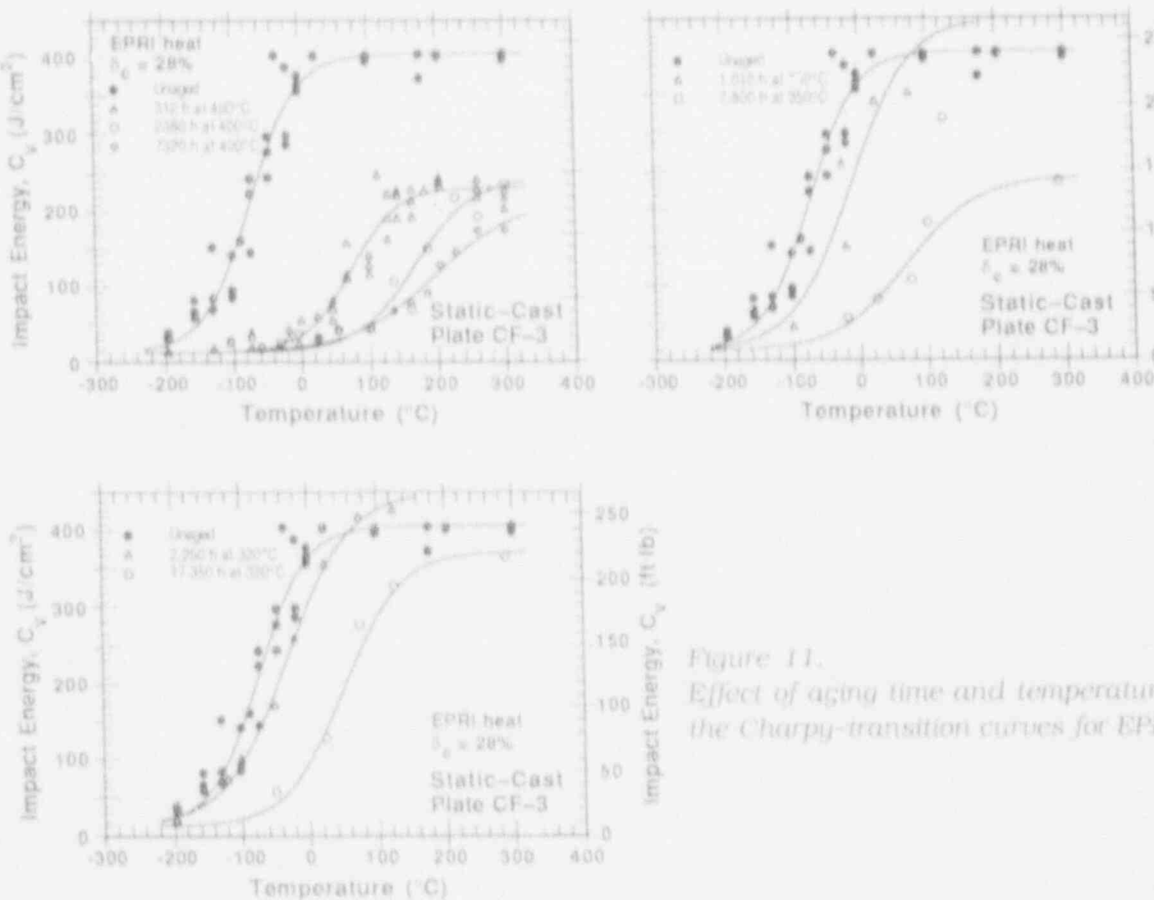


Figure 11. Effect of aging time and temperature on the Charpy-transition curves for EPRI heat

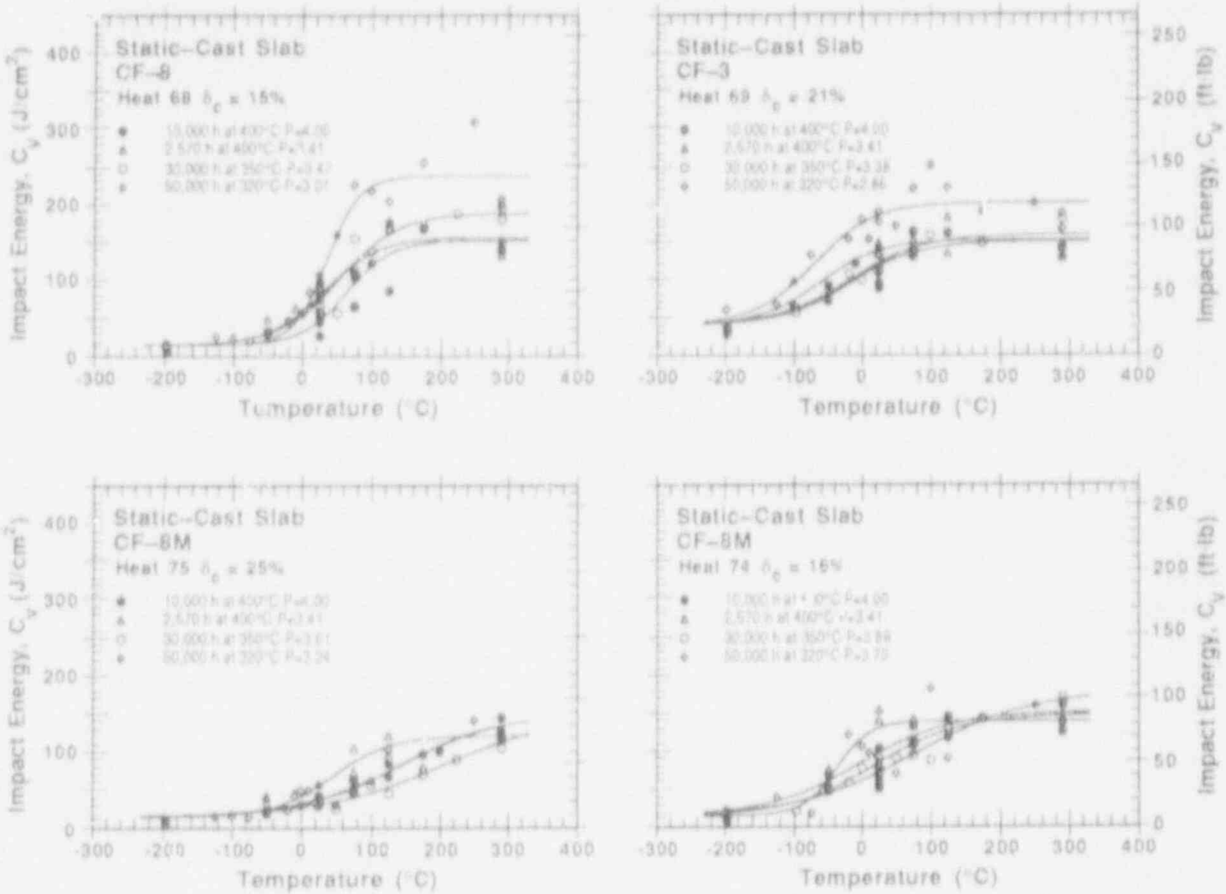


Figure 12. Charpy-transition curves for Heats 68, 69, 74, and 75 aged to P values between 3.0 and 4.0

The saturation room-temperature impact energy for Heat 75, e.g., 32 J/cm^2 (29 ft·lb) is close to the lower-shelf energy. Also, the transition curves for Heat 75 do not indicate a saturation effect. Although the room-temperature impact energy does not change for P values >3.5, the impact energy at reactor temperatures may continue to decrease with time. This behavior is also observed for the EPRI heat, as shown in Fig. 11. For such materials, impact energy at reactor temperatures will be anywhere between the saturation values of room-temperature impact energy and USE. The transition curves for heats that a saturation room-temperature impact energy in the transition region may or may not saturate depending on whether the value is close to USE or lower shelf. For example, the saturation room-temperature impact energy for Heats 68 and 74 is ≈57 and 63 (34 and 37 ft·lb), respectively. These values are greater than the mid-shelf impact energy for the materials, and the transition curves suggest a saturation (Fig. 12). Correlations have not been developed for estimating the Charpy-impact energy at reactor temperatures or the shift in CTT during thermal aging.

2.3 Recovery Annealing

Microstructural and annealing studies[2-4,8-10] on laboratory- and reactor-aged materials indicate that the mechanical properties of aged cast stainless steels can be restored by nealing the embrittled material for 1 h at 550°C and water-quenching. The α' phase, which is the primary cause for thermal embrittlement, is not stable at temperatures >550°C and therefore dissolves during the annealing treatment. The material is water-quenched to avoid formation of σ and other intermetallic phases that may also degrade mechanical properties. The influence of annealing on the Charpy transition curves for three laboratory-aged heats and for service-aged materials from the Shippingport and KRB reactors have been demonstrated.[20,22] The influence of annealing on an additional nine laboratory-aged heats of CF-3, CF-8, and CF-8M steels has also been investigated. The materials were aged for 10,000 h at 400°C prior to the annealing. The results are given in Appendix A, Tables A-3 and A-4. The effect of annealing on the transition curves of the various heats is shown in Fig. 13. The results indicate essentially complete recovery from embrittlement; the transition curves for the annealed materials agree very well with those for the unaged steel. Microstructural examination of the annealed material showed no α' phase, but the size and distribution of the G phase were the same as in the aged material.[8-10]

Charpy data for laboratory-aged materials indicate that the kinetics of embrittlement can also be obtained from the reembrittlement of recovery-annealed material. The Charpy-impact data for recovery-annealed CF-3, CF-8, and CF-8M steels aged up to 10,000 h at 400, 350, and 320°C are given in Appendix A, Table A-4, and the aging behaviors of unaged and recovery-annealed steels are shown in Fig. 14. The activation energies of the unaged materials are 168 ± 37, 167 ± 48, and 146 ± 21 kJ/mole for Heats 68, 69, and 75, respectively. The Charpy data for recovery-annealed and aged Heats 68, 69, and 75, respectively, yield activation energies of 122 ± 41, 176 ± 49, and 130 ± 28 kJ/mole, i.e., the kinetics of re-embrittlement are within the 95% confidence limits of the experimental values.

The results indicate that baseline mechanical properties, as well as the kinetics of embrittlement, of aged cast stainless steels can be determined from the recovery-annealed material. This may be very useful for evaluating degradation of mechanical properties of service-aged components, where the baseline mechanical properties of archive material are generally not available.

3 Tensile Properties

Tensile tests were conducted at room temperature and 290°C (554°F) on three commercial and five experimental heats aged up to 58,000 h at 290-450°C (554-842°F) and on the KRB pump cover plate material. The results from the tests, which were conducted at ANL and Materials Engineering Associates (MEA), are given in Appendix B. The engineering stress vs. strain curves for six of the heats of CF-3, CF-8, and CF-8M steel aged up to 50,000 h at 320, 350, and 400°C and tested at room temperature and 290°C (554°F) are shown in Figs. 15-20. At both test temperatures, thermal aging led to an increase in yield and ultimate stress and a slight decrease in ductility. For all heats, the increase in ultimate stress is substantially greater than the increase in yield stress. The Mo-bearing CF-8M steels are the most sensitive to thermal aging and Mo-free low-carbon CF-3 steels the least sensitive. Some heats show no change in yield stress. Furthermore, specimens aged for short times at high temperatures, e.g., ~3,000 h at 400 (752°F), often show a decrease in yield stress.

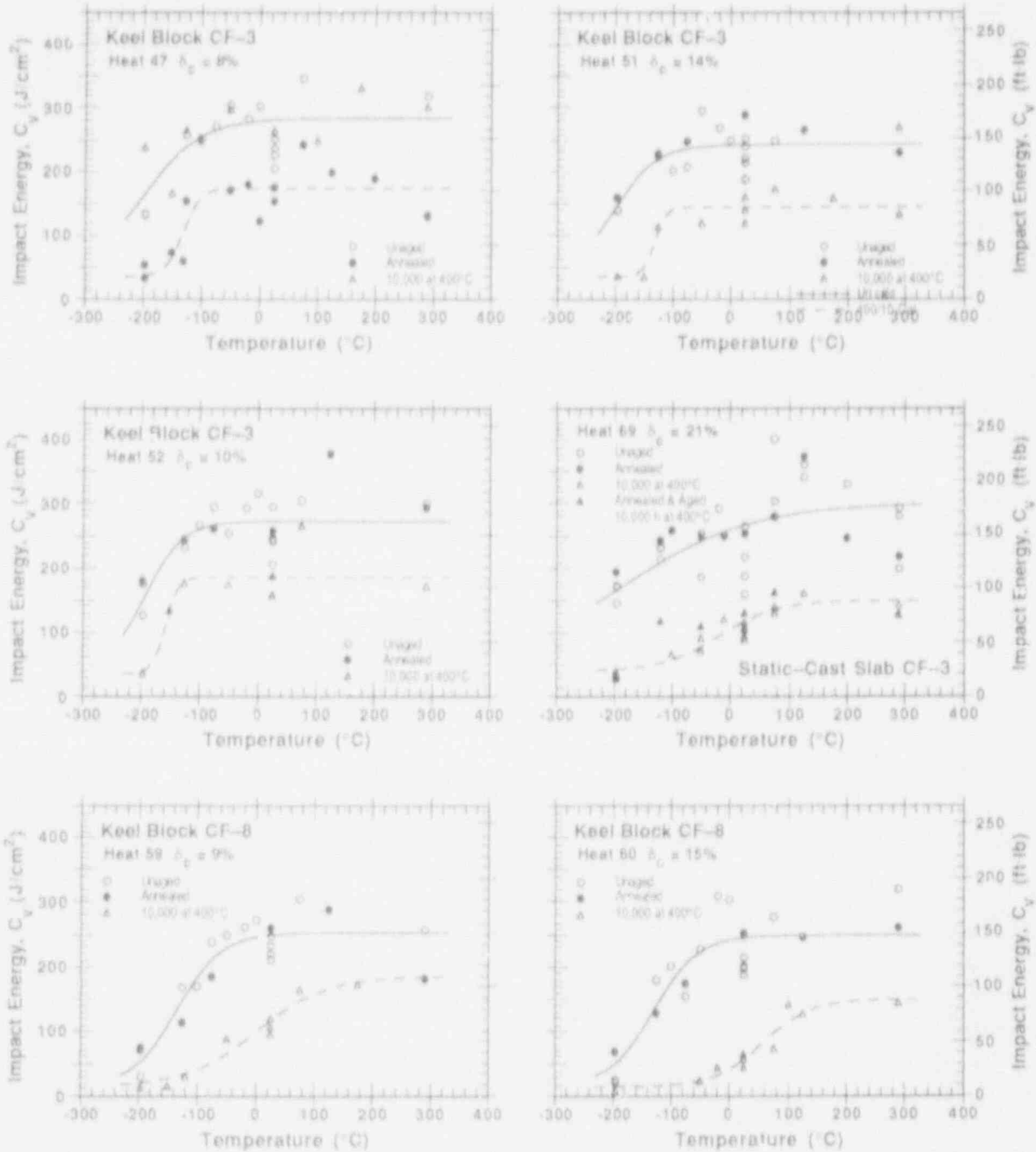


Figure 13. Effect of annealing on the Charpy transition curves for thermally aged CF-3, CF-8, and CF-8M steel

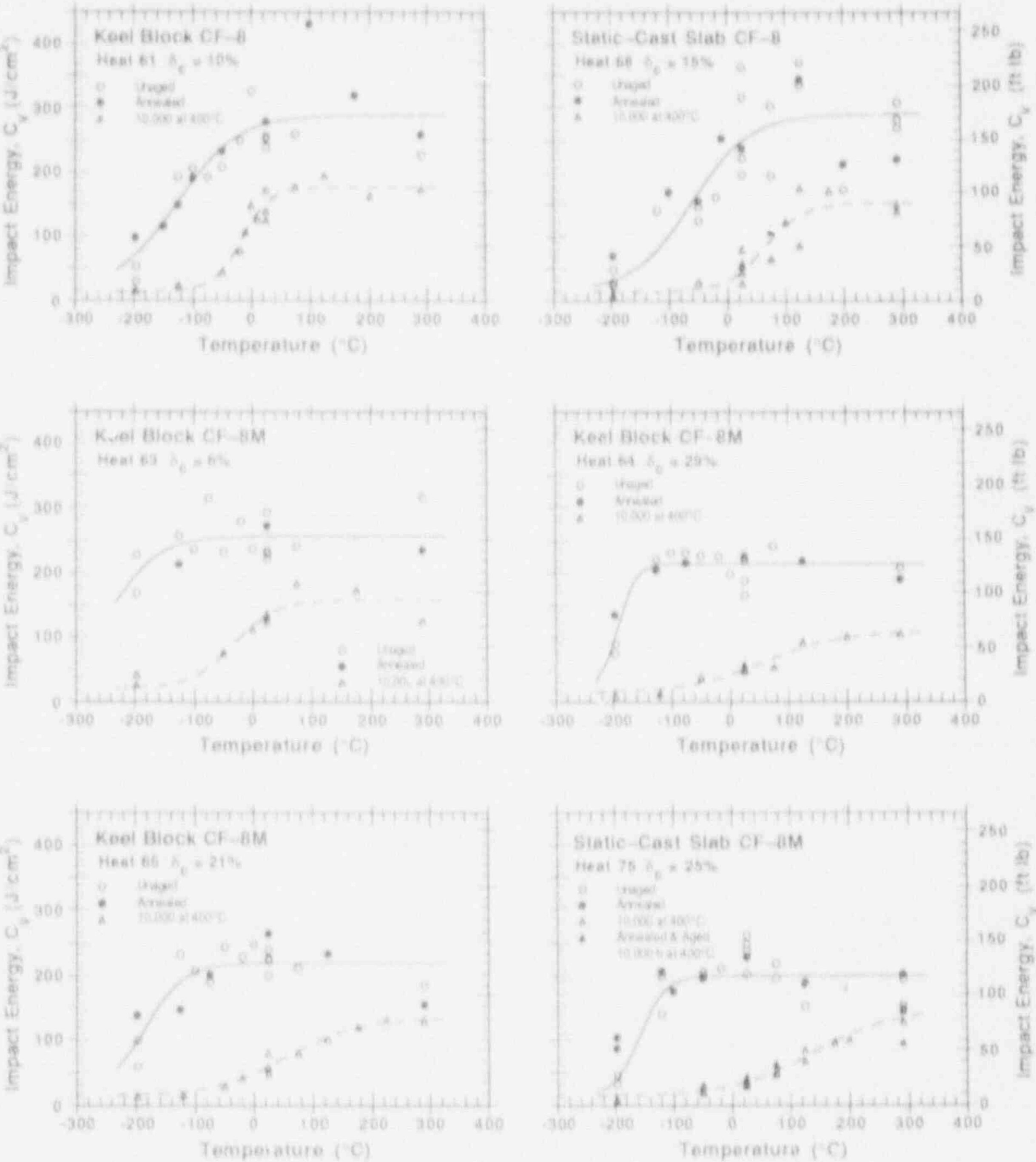
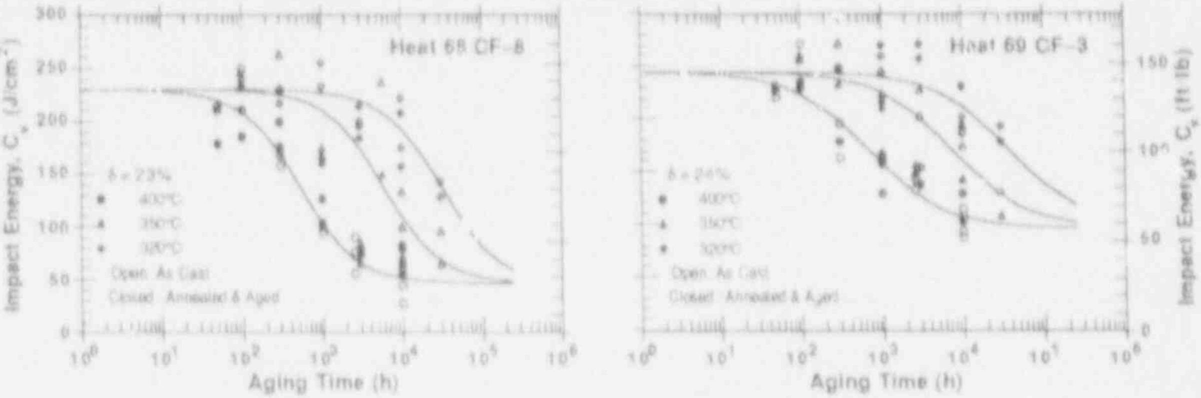


Figure 13. (Contd.)



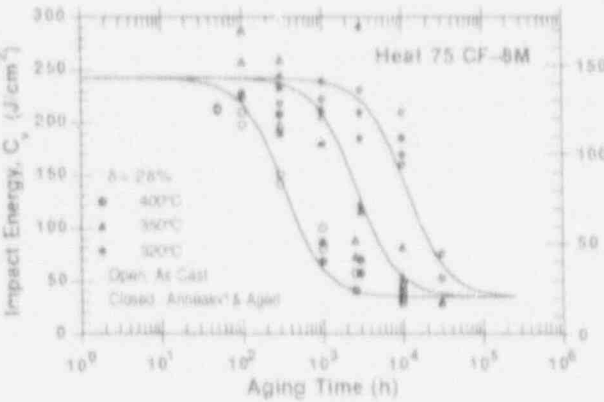


Figure 14.
Effect of thermal aging on RT impact energy of unaged and recovery-annealed CF-3, CF-8, and CF-8M steel. Solid lines represent the aging behavior of unaged material.

Thermal aging increases the strain-hardening rate of all grades of cast stainless steel. The increase is greater at room temperature than at 290°C, and CF-8M steels show a larger increase than do Mo-free grades of steel (Figs. 15-20). Tensile stress vs. strain data are being analyzed using the Ramberg-Osgood equation to evaluate the influence of thermal aging on the strain-hardening behavior of cast stainless steels.

The tensile data are in general agreement with the Charpy-impact data, i.e., for a specific heat, the increase in tensile stress corresponds to a decrease in impact energy. The results also indicate that the temperature dependence of the change in tensile strength is similar to that observed for the Charpy-impact data. Correlations have been developed for estimating the tensile flow stress of aged cast stainless steels from the kinetics of thermal embrittlement.[6] The ratio of the tensile flow stress of aged and unaged cast stainless steels at RT and 290°C (554°F) is expressed in terms of a normalized aging parameter. Flow stress is characterized as the mean of the 0.2% yield and ultimate stresses, and the aging parameter is normalized with respect to a θ value of 2.9. At both temperatures, the increase in flow stress of CF-3 steels is the lowest and that of CF-8M steels the largest.

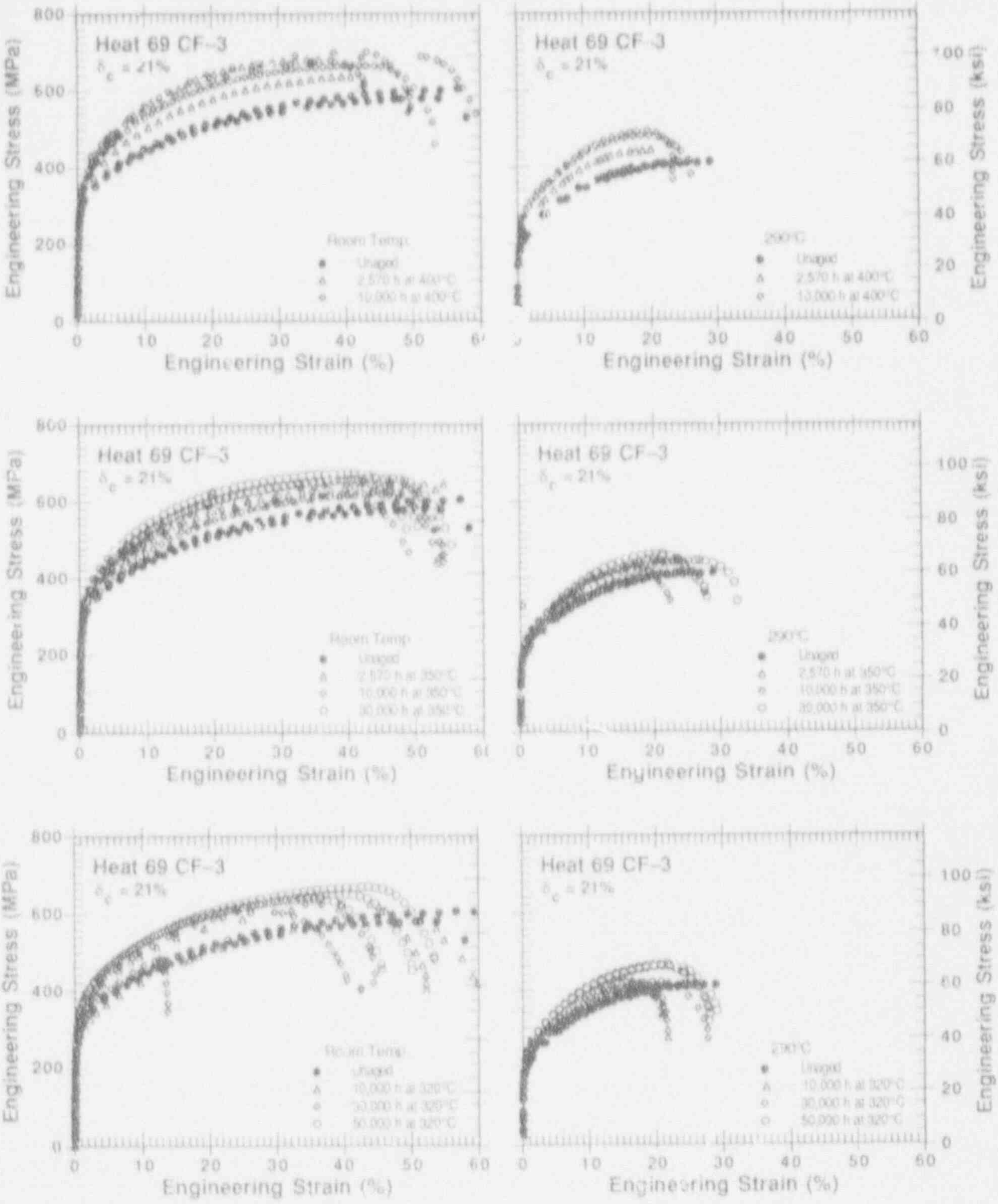


Figure 15. Effect of thermal aging on engineering stress vs. strain curves for Heat 69

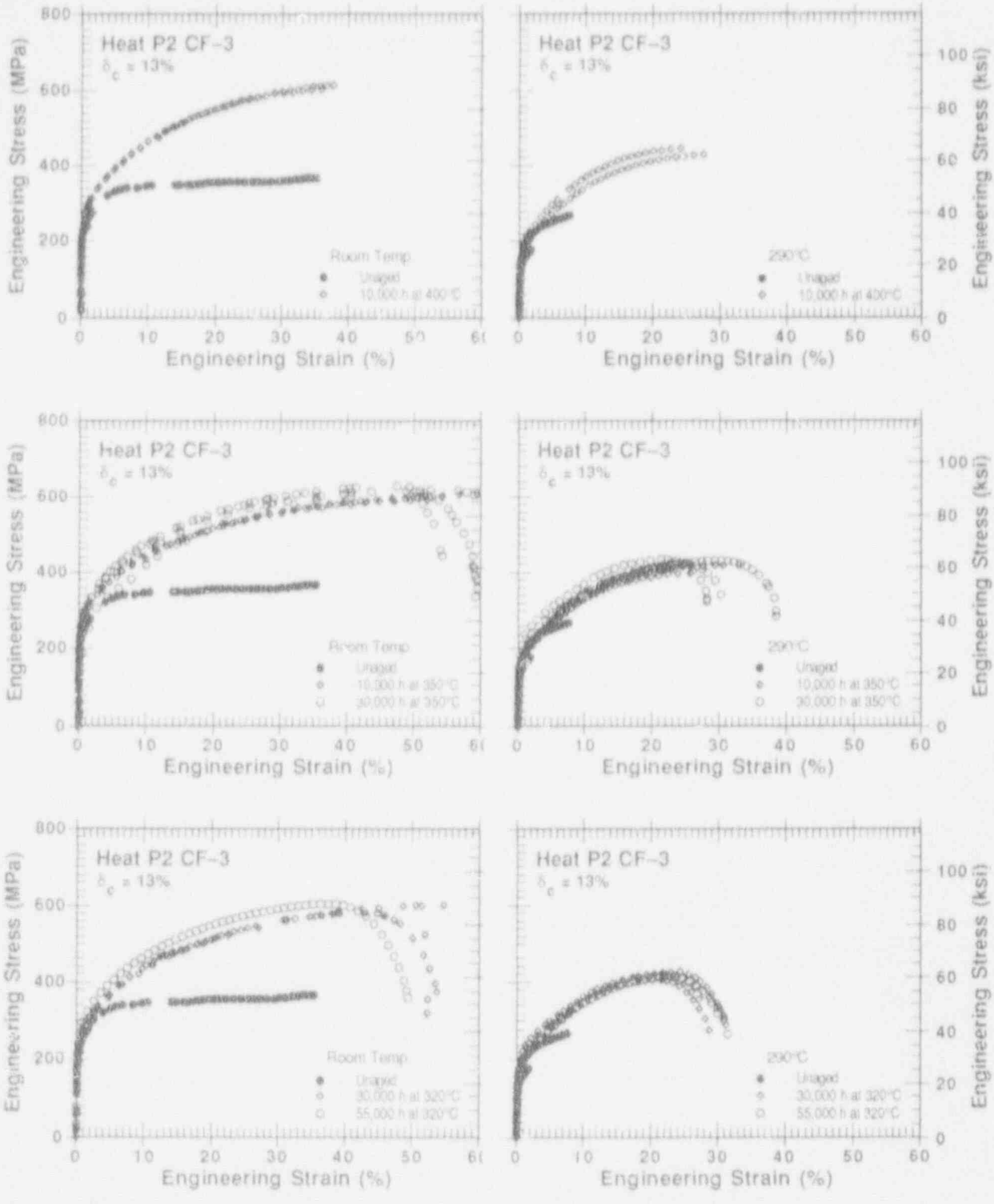


Figure 16. Effect of thermal aging on engineering stress vs. strain curves for Heat P2

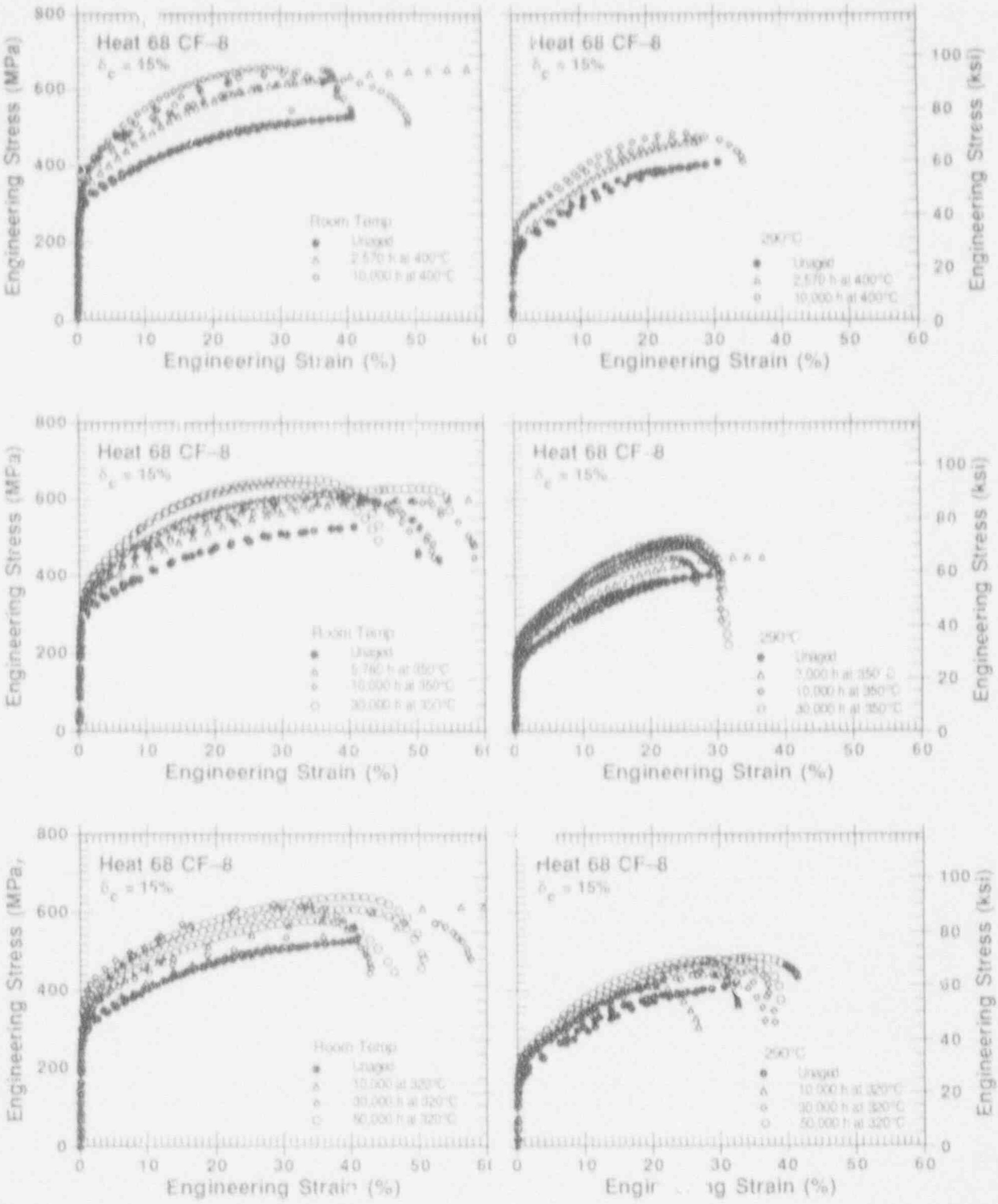


Figure 17. Effect of thermal aging on engineering stress vs. strain curves for Heat 68

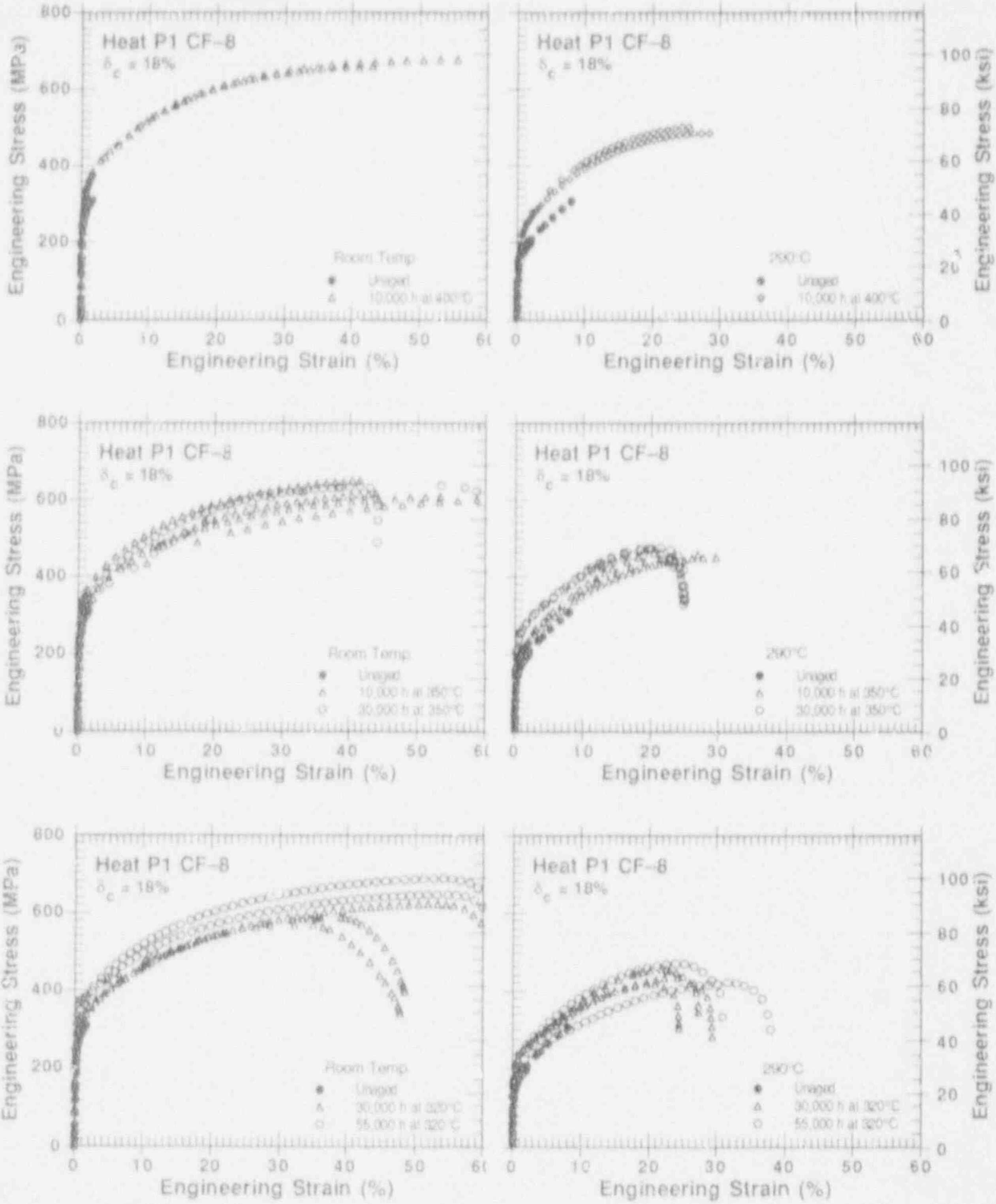


Figure 18. Effect of thermal aging on engineering stress vs. strain curves for Heat P1

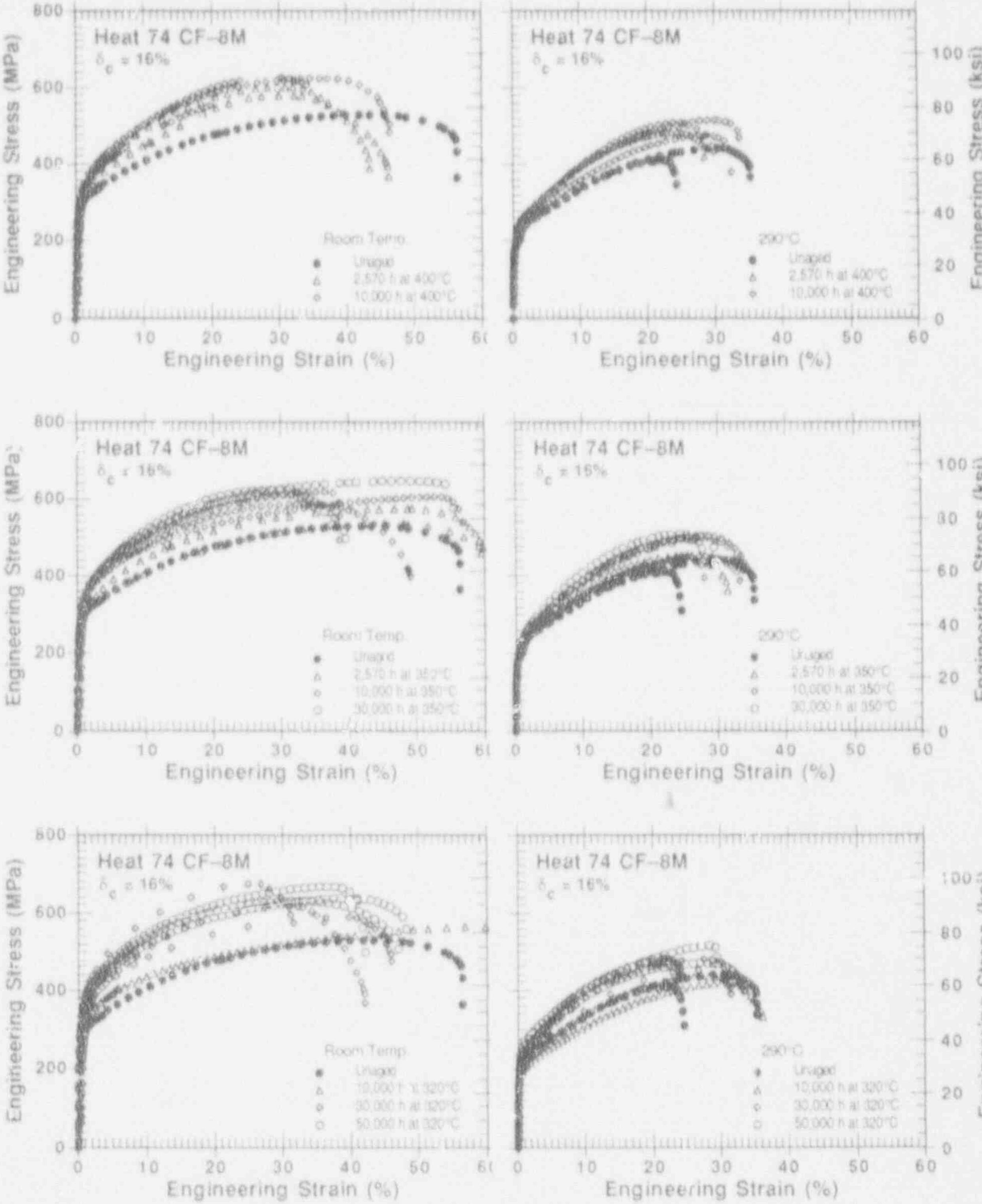


Figure 19. Effect of thermal aging on engineering stress vs. strain curves for Heat 74

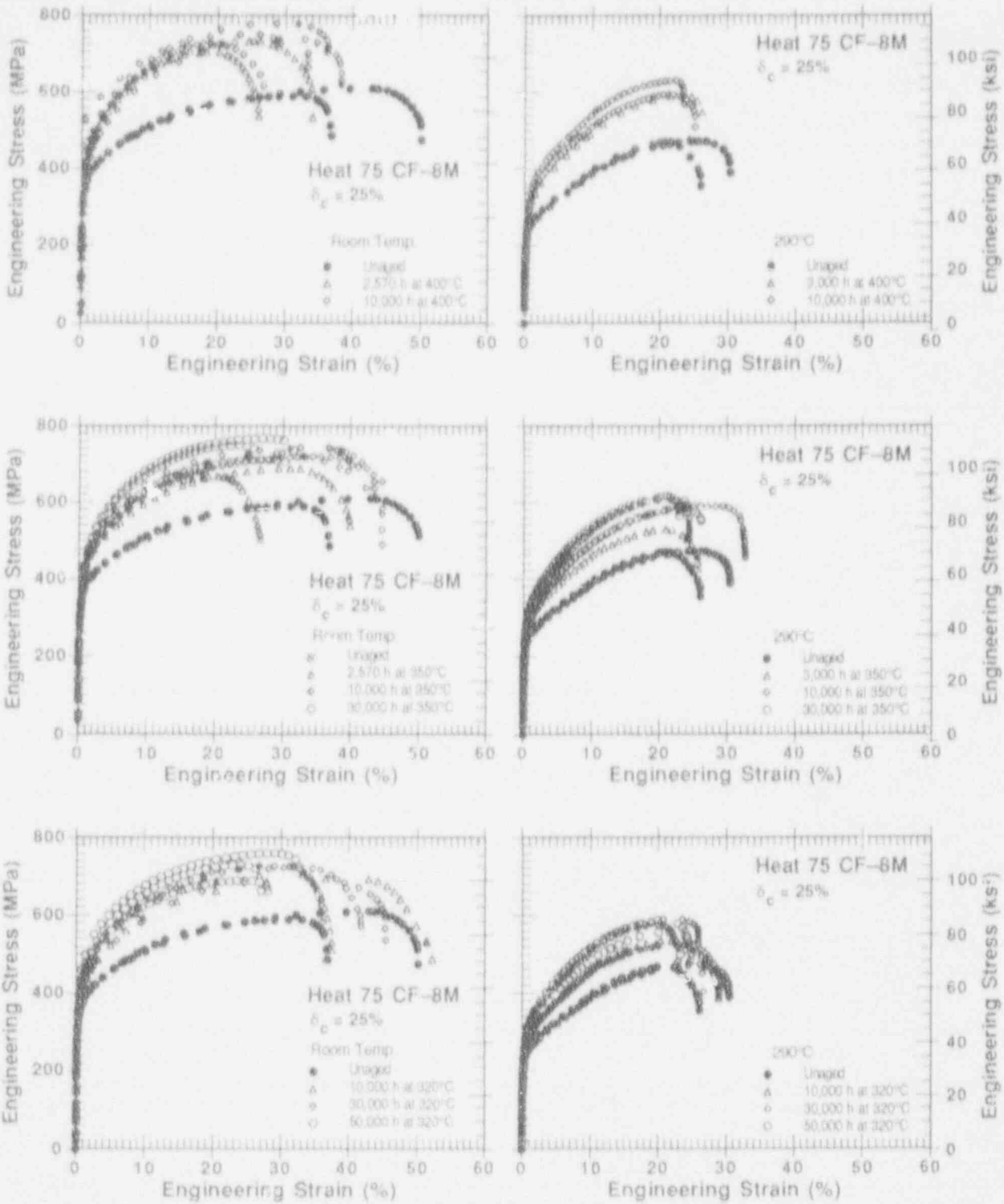


Figure 20. Effect of thermal aging on engineering stress vs. strain curves for Heat 75

4 Fracture Toughness

The J-R curve tests were conducted at room temperature and at 290°C (554°F) according to ASTM Specification E 813-85 and E 1152-87. Compact-tension specimens (CT), 25.4 mm thick (i.e., 1T size), were used for the tests. Table C-1, Appendix C contains the results from tests conducted at MEA and ANL on nine heats of cast stainless steel aged up to 30,000 h at temperatures between 290-450°C (554-842°F). The data and analyses of the tests conducted at ANL are compiled in Appendix C. The results indicate that the deformation J values predicted from the power-law relation are often higher than the observed values for crack extensions of >3 mm. For the room-temperature tests, the values calculated from power-law relation can be higher by a factor of 2. The discrepancy between the calculated and observed values of deformation J is small for the tests at 290°C. The modified J vs. Δa data show good agreement with the power-law relation.

4.1 Unaged Cast Stainless Steels

The fracture toughness J-R curves of unaged cast stainless steels vary significantly for the various heats. Figure 21 shows fracture toughness J-R curves for centrifugally and static-cast steels at room temperature and 290-320°C (554-608°F). Fracture toughness of centrifugally cast steels is significantly higher than than that of static-cast steels. The static-cast pump casing ring (Heat C1 with $\delta_c \approx 8\%$) shows the lowest fracture toughness and the centrifugally cast pipe (Heat P2 with $\delta_c \approx 12\%$) has the highest. The room-temperature J-R curves for unaged Heat C1 are marginally higher than those at 290°C. At temperatures up to 320°C, a lower-bound J-R curve for unaged static-cast stainless steels can be expressed as

$$J_d = 400[\Delta a]^{0.40} \quad (4)$$

and for centrifugally cast stainless steels as

$$J_d = 650[\Delta a]^{0.43}, \quad (5)$$

where Δa is in mm and J_d is in kJ/m².

Fracture toughness data for unaged cast stainless steels also indicate that J-R curves for structurally "weak" heats may be lower than those for wrought stainless steels. J-R curves for wrought stainless steels[23-28] at temperatures ≥290°C are compared with the lower-bound J-R curves for unaged cast stainless steels in Fig. 22. Fracture toughness of wrought stainless steels is higher than the lower-bound J-R curve for static-cast stainless steels.

4.2 Aged Cast Stainless Steels

The effects of aging time and temperature on the fracture toughness J-R curves of the various heats of cast stainless steel are shown in Figs. 23-28. Thermal aging of cast stainless steels decreases their fracture toughness at both room temperature and reactor temperature. The values of J_{Ic} and average tearing modulus for heats that are sensitive to

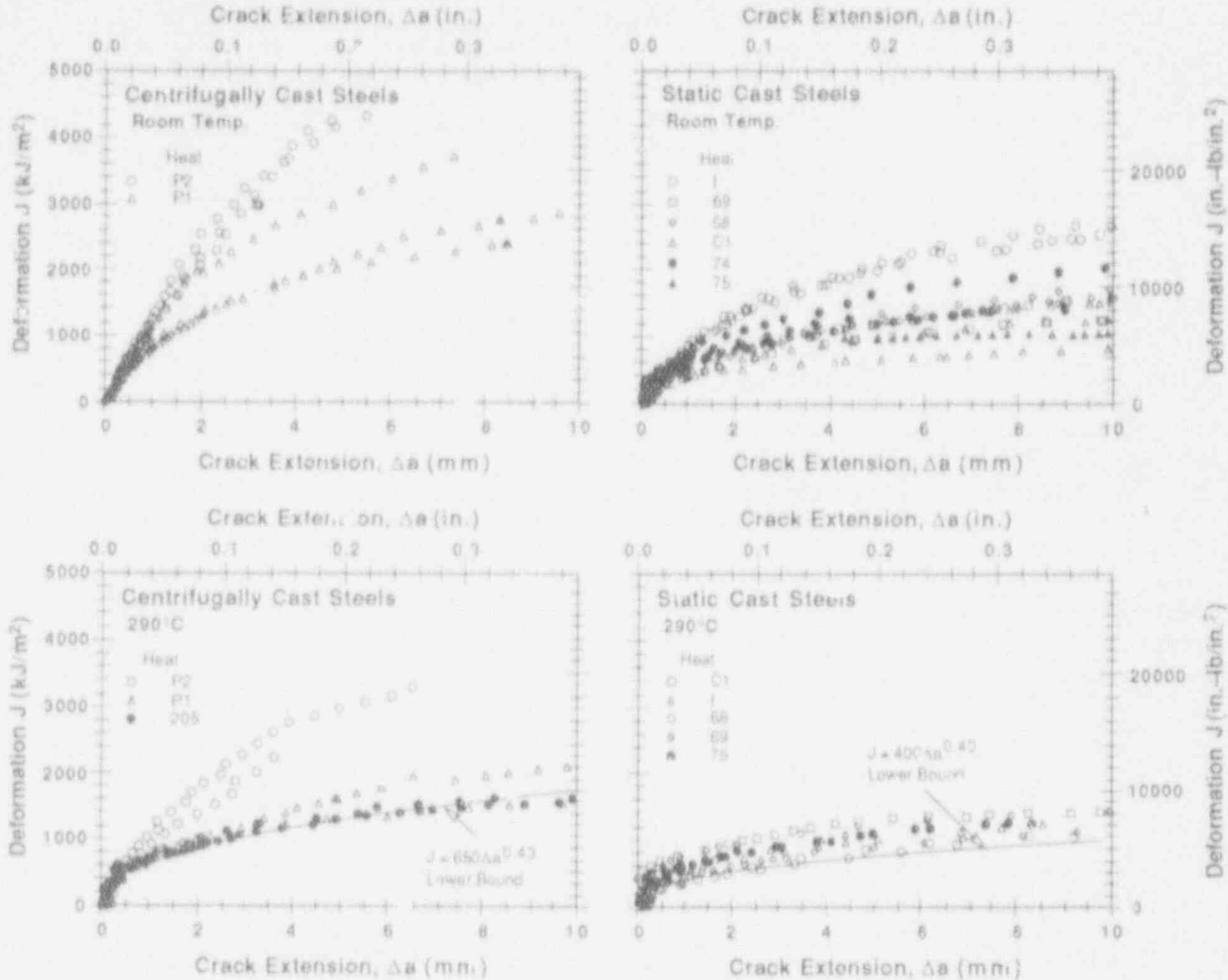


Figure 21. Fracture toughness J–R curves for centrifugally and static-cast stainless steels at room temperature and at 290°C

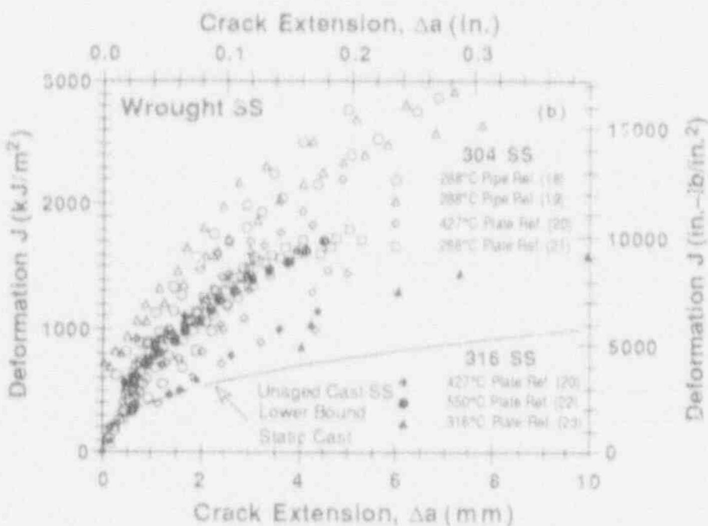


Figure 22. Fracture toughness J–R curves for wrought stainless steels at temperatures ≥290°C and lower-bound J–R curve for static-cast stainless steel

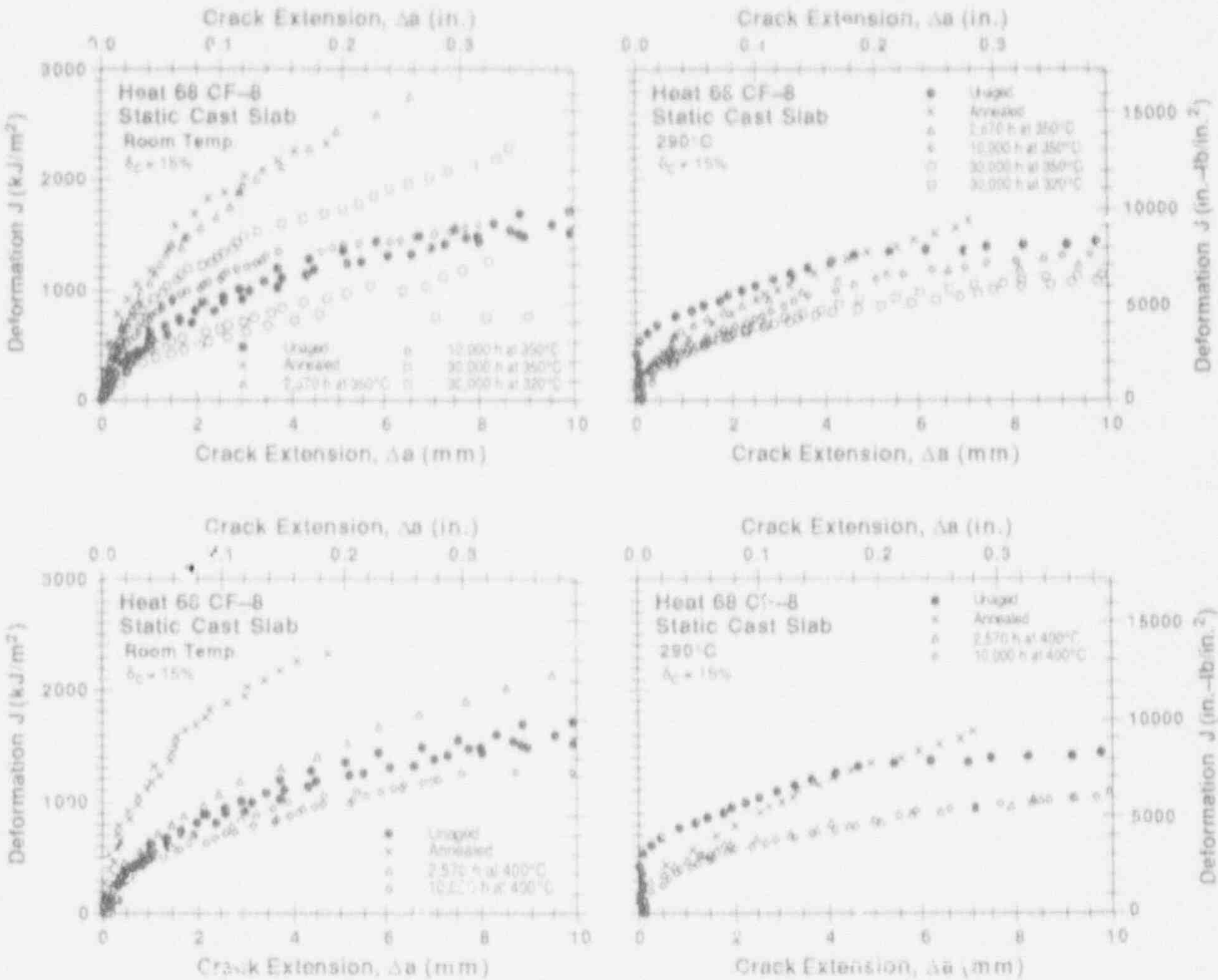


Figure 23. Effect of aging time and temperature on the fracture toughness J-R curves at room temperature and at 290°C for static-cast Heat 68

thermal aging are as low as ≈90 kJ/m² and ≈60, respectively. The J-R curve data are consistent with the Charpy-impact results, i.e., unaged and aged materials that show low impact energy also exhibit lower fracture toughness. All materials reach a minimum saturation fracture toughness after thermal aging, e.g., after 10,000 h at 400°C or 30,000 h at 350°C. The kinetics for the decrease in fracture toughness are identical to those observed for the change in Charpy-impact energy. In general, loss in toughness increases with an increase in ferrite content. The CF-3 steels show the smallest and CF-8M steels the largest toughness loss. Also, for a specific steel, the decrease in toughness is larger at room temperature than at 290°C (554°F).

The static-cast slabs (e.g., Heats 68, 69, and 75) exhibit an unusual aging behavior, viz. the room temperature fracture toughness increased initially after aging. For example the J-R curves for these heats aged for 2,570 h at 400°C (752°F), or up to 10,000 h at 350°C (662°F), or up to 30,000 h at 320°C (608°F) are often higher than those for the unaged ma-

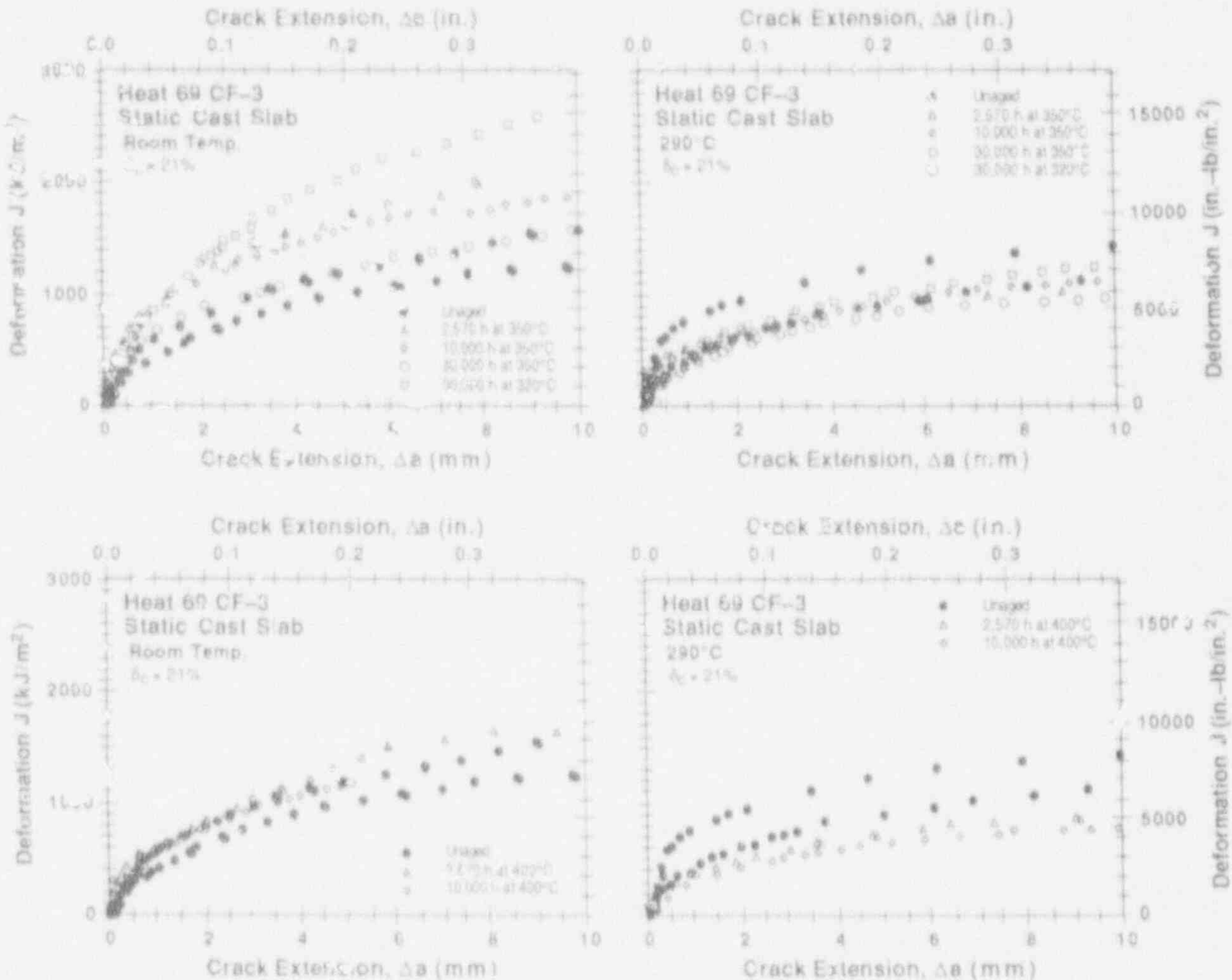


Figure 24. Effect of aging time and temperature on the fracture toughness J–R curves at room temperature and at 290°C for static-cast Heat 69

terials. An initial increase in fracture toughness was not observed at 290°C for static-cast stainless steel or for any other product form. The room-temperature J–R curves for the static-cast slabs in the unaged condition are exceptionally low, although their Charpy-impact energies are comparable with those for other heats. The poor fracture toughness of the cast slabs is most likely due to residual stresses introduced in the material either during casting or the production heat treatment. The initial increase in fracture toughness of the aged material is due to relaxation of the residual stresses during aging. Several observations support this argument:

- The yield stress of the cast slabs decreases initially after aging (Appendix B).
- Whereas the J_{IC} values of unaged cast stainless steels normally decrease with an increase in temperature, an opposite trend is observed for the thermally aged material (Table 5).

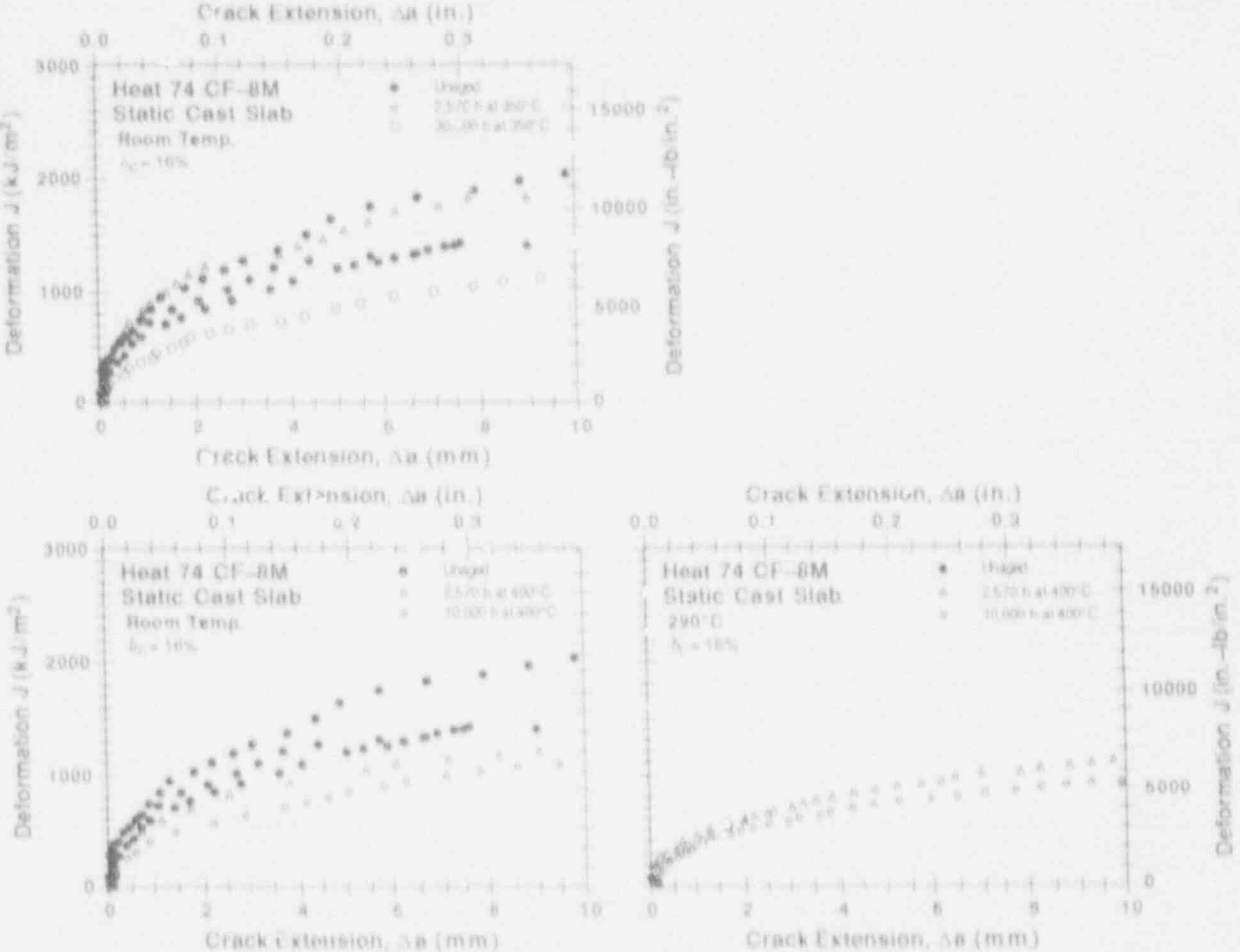


Figure 25. Effect of aging time and temperature on the fracture toughness J-R curves at room temperature and at 290°C for static-cast Heat 74

- Annealing studies indicate that thermal embrittlement of cast stainless steels can be reversed by annealing the embrittled material for 1 h at 550°C and then water quenching.[2-4,8-10] The Charpy-transition curves of recovery-annealed CF-3, CF-8, and CF-8M steels agree very well with those of unaged materials.[20,22] However, fracture toughness J-R curves of recovery-annealed Heats 68 and 75 are significantly higher than those of the unaged materials, Figs. 24 and 26. Fracture toughness of recovery-annealed materials is comparable to that of materials that were aged for relatively short times.

These results suggest that the mechanical test data obtained on unaged static-cast slabs do not represent baseline properties. For the static-cast slabs, fracture toughness should initially increase during reactor service before it decreases due to thermal embrittlement. J-R curves for the recovery-annealed material most likely represent the baseline properties without the effect of residual stresses.

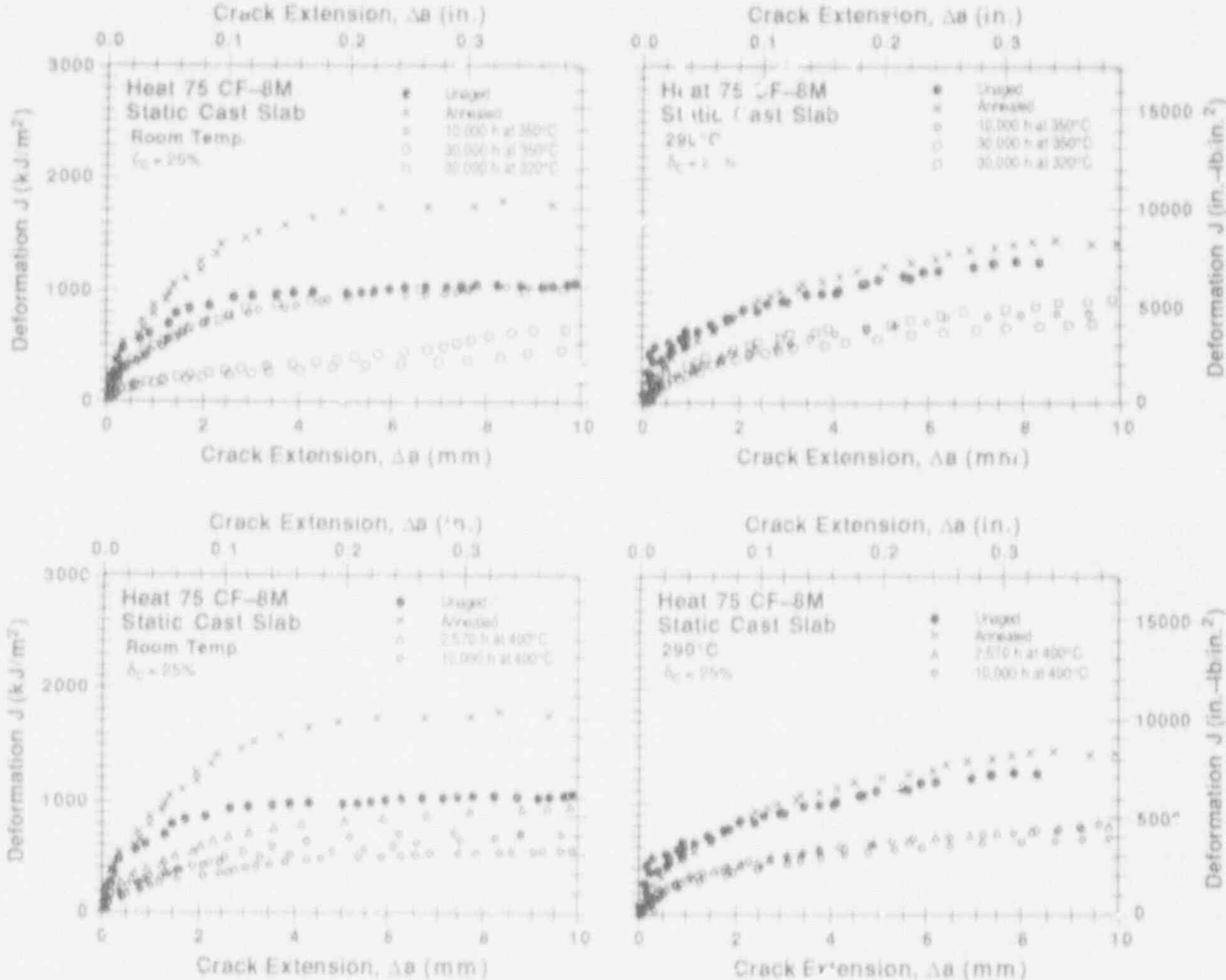


Figure 26. Effect of aging time and temperature on the fracture toughness J-R curves at room temperature and at 290°C for static-cast Heat 75

Thermally aged CF-8 steels (e.g., Heats 68 and P1) exhibit unstable crack growth. These events were generally observed beyond 5-mm crack growth. Crack growth was as high as 2.5 mm, accompanied with a load drop of >10 kN (see Appendix C for Heat 68 aged 30,000 h at 350°C). The ferrite/austenite phase boundaries in CF-8 steels contain large carbide particles and provide an easy path for crack propagation. Unstable crack growth occurs by cleavage of ferrite and separation of weak phase boundaries.

5 Conclusions

Charpy-impact, tensile, and fracture toughness J-R curve data are presented for several experimental and commercial heats of cast stainless steel that were aged up to 58,000 h at temperatures of 290–400°C. The results indicate that thermal aging increases the tensile stress and decreases the Charpy-impact and fracture toughness properties of cast stainless steels. In general, CF-3 steels are the least sensitive to thermal aging embrittle-

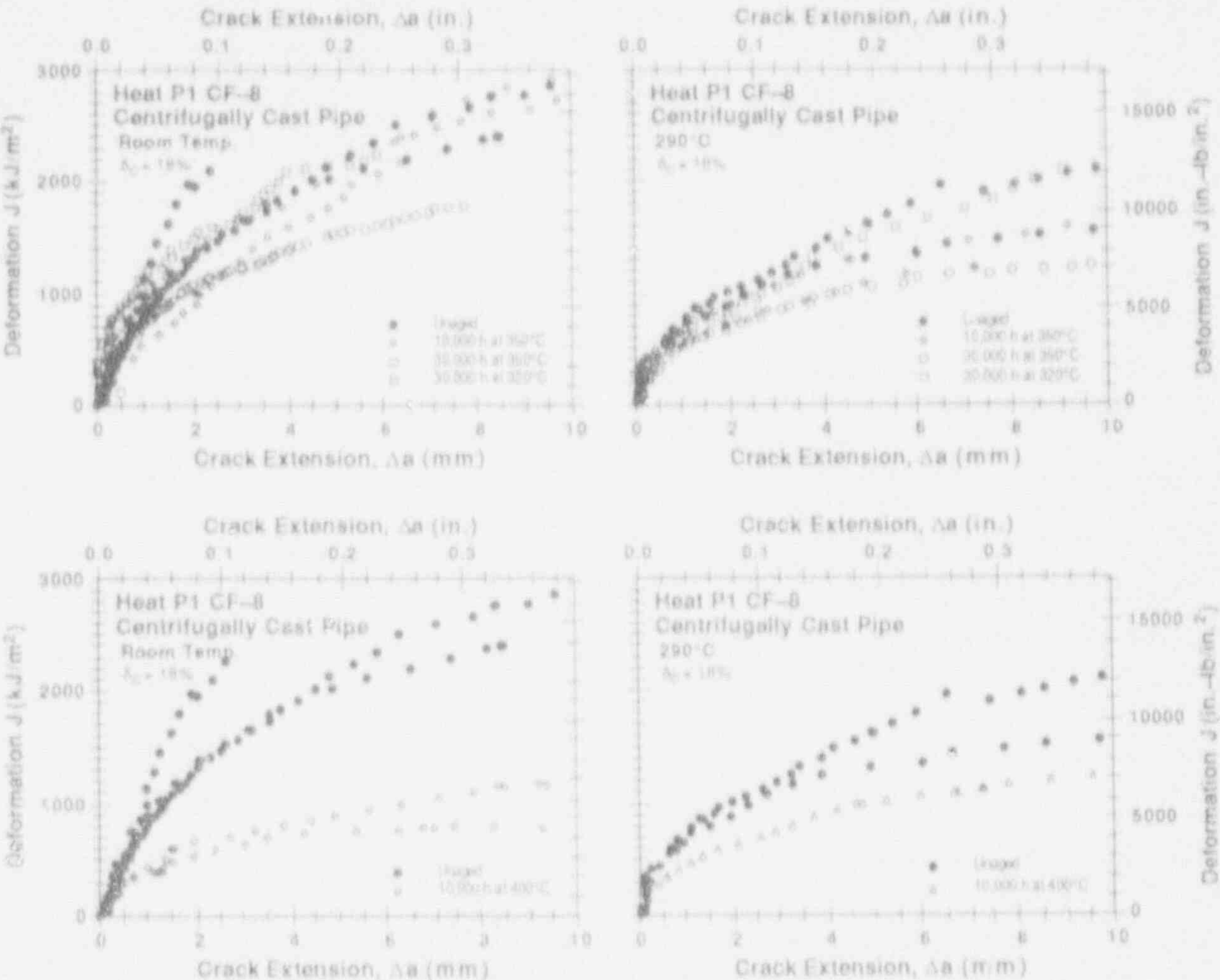


Figure 27. Effect of aging time and temperature on the fracture toughness J-R curves at room temperature and at 290°C for centrifugally cast Heat P1

ment and CF-8M steels the most sensitive. At room and reactor temperatures, the increase in flow stress of fully aged cast stainless steels is ≈10% for CF-3 steels, and ≈20% for CF-8 and CF-8M steels. The values of fracture toughness J_{IC} and average tearing modulus for heats that are sensitive to thermal aging (e.g., CF-8M steels) are as low as ≈90 kJ/m^2 and ≈60, respectively.

Acknowledgments

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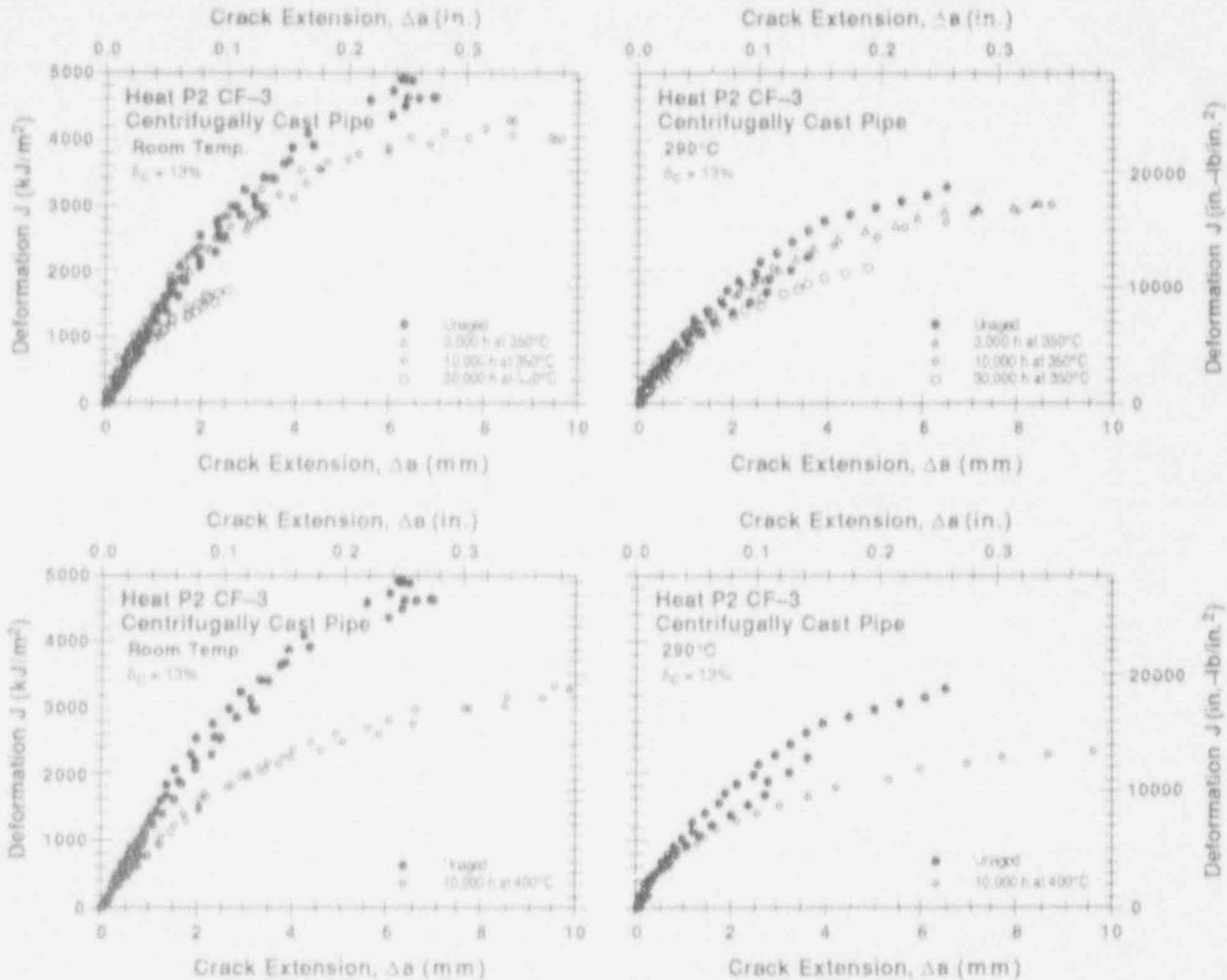

Figure 28. Effect of aging time and temperature on the fracture toughness J-R curves at room temperature and at 290°C for centrifugally cast Heat P2

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Appendix A

Charpy–Impact Energy

The specimen blanks for mechanical tests were obtained from the various experimental and commercial heats of cast stainless steel. The orientation and location of the mechanical-test specimens from pipe sections, slabs, and keel blocks are shown in Fig. A-1. The specimen blanks were aged up to 58,000 h at temperatures between 290 and 400°C (554 and 752°F).

Charpy-impact tests were conducted on Charpy-impact V-notch specimens according to American Society for Testing and Materials (ASTM) Specification E 23. Test specimens, shown in Fig. A-2, were machined from the blanks after thermal aging. A Dynatup Model 8000A drop-weight impact machine with an instrumented tup and data readout system was used for the Charpy-impact tests. The available energy and impact velocity of the machine can be varied by altering the weight of the crosshead and the drop height; maximum energy and velocity obtainable with the machine were 1.5 kJ and 4 m/s, respectively. Load- and energy-time data were obtained from an instrumented tup and recorded on a dual-beam storage oscilloscope. The instrumented tup consists of a striking head and a strain gauge with a four-arm semiconductor bridge circuit. The strain gauge, which measures the compressive load on the tup during the test, was calibrated by a dynamic loading technique. Initial and final velocities of the tup were measured optically. The load-time traces from each test were digitized and stored on a floppy disk for analysis. Total energy was computed from the load-time trace; the value was corrected for the effects of tup velocity.

The instrumented tup and data readout instrumentation were periodically calibrated by fracturing standard V-notch specimens fabricated from 6061-T6 aluminum and 4340 steel with a hardness of Rockwell R_C 54. Amplifier gain was adjusted from the load- and energy-time traces for the aluminum specimen so that the recorded load limit coincided with the load limit for the material (i.e., 7.74 kN). The linearity of the calibration was established from the results for the 4340 steel specimen, which has a higher limit load. Accuracy of the impact-test machine was also checked periodically with Standard Reference Materials 2092 and 2096 (having Charpy-impact energies of 16.41 and 16 .12 J, respectively) obtained from the National Institute of Standards and Technology. Tests on the reference materials were performed at -40°C (-40°F) in accordance with the testing procedures of Section 11 of ASTM E 23.

The specimens for high-temperature tests were heated by resistance heating. Pneumatic clamps were used to make electrical connection and hold the specimens in position on the anvils. The anvils were electrically insulated from the base plate. Power to the specimen was interrupted immediately before impact to release the clamps and remove any constraint on the specimen. The temperature was monitored and controlled by a thermocouple attached to the specimen. Specimens for the low-temperature tests were cooled in either a refrigerated bath or liquid nitrogen.

Charpy-impact data for the various experimental and commercial heats aged up to 10,000 h at various temperatures have been presented earlier.[A-1] The data for materials that were aged longer than 10,000 h are given in Table A-1. The impact energies are normalized with respect to the cross-sectional area of the specimens (impact energy in ft·lb can be obtained from J/cm^2 by multiplying by 0.59). Charpy-impact results for recovery-annealed materials (from three experimental heats as well as the KRB pump cover plate) that were aged up to 10,000 h at 320, 350, and 400°C are given in Table A-2. Material from the experimental heats was originally aged for 10,000 h at 400°C whereas the KRB pump cover plate was aged during reactor service. All materials were annealed for 1 h at 550°C and then water quenched.

Table A-3 gives the Charpy-impact data for the EPRI heat aged at 320 and 350°C for times up to ≈17,000 h. Specimen blanks were obtained from broken compact-tension specimens of the unaged material. The materials were used by the Electric Power Research Institute to study thermal embrittlement of cast stainless steels; the results for 400°C aging have been presented earlier.[A-2]

The values of 0.2% yield and maximum load for each test are also listed in Tables A-1 to A-3, and may be used for estimating tensile properties of the cast materials. For a Charpy specimen, the yield stress is estimated from the expression

$$\sigma_y = CPy\,B/Wb^2\,, \qquad \text{(A-1)}$$

taken from Ref. A-3, where Py is the yield load, W is the specimen width, B is the specimen thickness, b is the uncracked ligament, and C is a constant. The yield load was obtained from the load-time traces of the Charpy tests. Deviation from linearity in the load-time trace occurred at 125 to 150 μs for the various heats. The load at 200 μs was estimated to represent 0.2% yield stress. The actual time for 0.2% yield varies with the strain hardening rate of the material; the load at 0.2% yield can be obtained from a power law fit of the data. The error in the estimated values was <5% for the various tests. The ultimate stress was also obtained from the impact data by means of Eq. A-1 and the maximum load Pm. The constant C was determined by comparing the tensile and Charpy-impact data. The best value of the constant for yield stress was 1.50 for steels of all grades. The constant for ultimate stress was 2.28 for CF-3 and CF-8 steels and 2.54 for CF-8M steel. The estimated values of tensile stress are based on the assumption that strain rate effects are insignificant for the various heats and aging conditions. Equation A-1 should not be used for estimating ultimate stress at temperatures corresponding to the lower-shelf and transition regions.

References

A-1. O. K. Chopra and A. Sather, "*Initial Assessment of the Mechanisms and Significance of Low-Temperature Embrittlement of Cast Stainless Steels in LWR Systems*," NUREG/CR-5385, ANL-89/17 (August 1990).

A-2. P. McConnell and J. W. Sheckherd, *Fracture Toughness Characterization of Thermally Embrittled Cast Duplex Stainless Steel*, Report NP-5439, Electric Power Research Institute, Palo Alto, CA (September 1987).

A-3. W. L. Server, "Impact Three-Point Bend Testing for Notched and Precracked Specimens," *J. Test. Eval.*, **6**, 29 (1978).

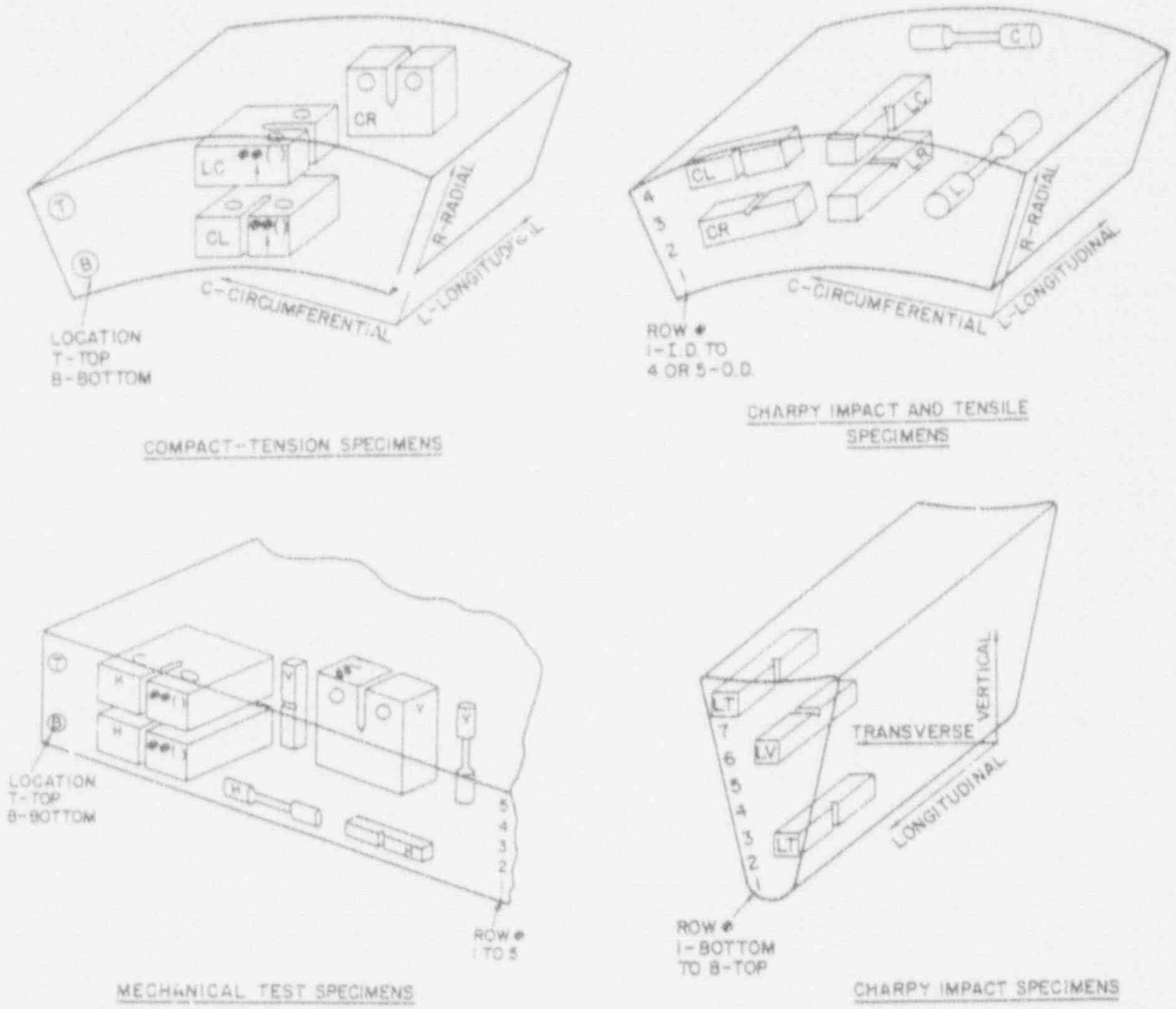


Figure A-1. Orientation and location of the mechanical-test specimens taken from (a) and (b) pipe sections, (c) slabs, and (d) keel blocks.

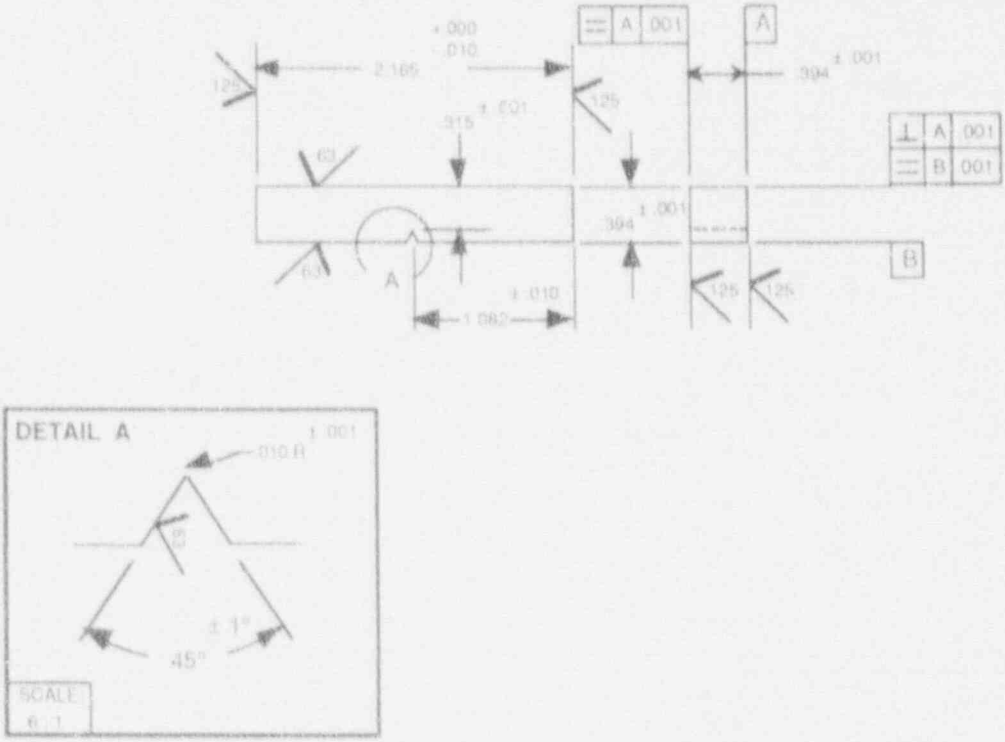


Figure A-2.   Configuration of Charpy-impact test specimen

Table A-1. Charpy-impact test results for aged commercial and experimental heats of cast stainless steel

Specimen ID	Heat	Aging Temp. (°C)	Aging Time (h)	Test Temp. (°C)	Impact Energy (J/cm²)	Yield Load (kN)	Max. Load (kN)
			Keel Blocks (CF-3 Grade)				
472-S08	47	290	30000	25	263.5	9.276	15.682
472-S09	47	290	30000	25	268.0	9.227	15.672
472-S13	47	290	58000	25	212.2	9.462	15.975
472-S14	47	290	58000	25	236.2	9.042	15.516
474-S16	47	320	30000	25	202.4	9.618	16.316
474-S17	47	320	30000	25	186.9	9.598	16.209
474-S18	47	320	30000	25	190.5	10.155	16.219
473-S07	47	320	55000	25	223.4	9.413	16.024
473-S08	47	320	55000	25	138.7	9.442	16.082
475-S13	47	350	30000	25	165.9	9.647	16.492
475-S14	47	350	30000	25	154.2	9.950	15.496
475-S15	47	350	30000	25	161.3	10.173	16.512
475-S16	47	350	55000	25	143.5	9.872	14.920
475-S18	47	350	55000	25	127.8	9.569	15.164
476-S10	47	400	30000	25	177.1	9.555	15.792
476-S11	47	400	30000	25	173.8	9.575	16.338
478-S01	47	400	54800	25	197.2	9.579	16.180
478-S03	47	400	54800	25	188.8	9.686	16.043
512-S07	51	290	30000	25	236.4	10.331	16.805
512-S08	51	290	30000	25	263.0	10.477	17.234
512-S09	51	290	30000	25	259.0	10.634	16.893
512-S14	51	290	58000	25	264.2	10.546	17.547
512-S15	51	290	58000	25	230.1	10.565	17.742
514-S16	51	320	30000	25	195.1	11.171	17.889
514-S17	51	320	30000	25	237.4	11.424	18.562
514-S18	51	320	30000	25	251.1	11.454	19.099
513-S08	51	320	55000	25	162.8	11.376	17.039
513-S09	51	320	55000	25	196.0	11.256	17.593
515-S13	51	350	30000	25	194.7	11.620	18.338
515-S14	51	350	30000	25	197.5	11.249	17.947
515-S15	51	350	30000	25	180.1	11.415	18.084
515-S16	51	350	55000	25	160.6	10.917	16.951
515-S18	51	350	55000	25	161.6	11.200	17.117
516-S10	51	400	30000	25	171.2	11.653	18.720
516-S11	51	400	30000	25	158.9	11.507	18.437
518-S01	51	400	54800	25	116.8	11.561	16.248
518-S03	51	400	54800	25	111.7	11.551	16.141
522-S07	52	290	30000	25	237.1	9.618	16.258
522-S08	52	290	30000	25	291.5	9.696	16.258
522-S09	52	290	30000	25	248.8	9.882	16.482
522-S13	52	290	58000	25	275.0	10.077	16.395
522-S14	52	290	58000	25	275.6	9.794	16.365
524-S16	52	320	30000	25	242.5	10.428	16.980
524-S17	52	320	30000	25	283.5	10.321	17.439
524-S18	52	320	30000	25	262.2	10.389	17.303
523-S07	52	320	55000	25	245.7	10.223	16.961
523-S08	52	320	55000	25	231.8	10.223	16.883
525-S13	52	350	30000	25	259.2	9.999	17.156
525-S14	52	350	30000	25	270.9	9.813	17.225
525-S15	52	350	30000	25	254.5	10.067	17.166
525-S16	52	350	55000	25	250.9	10.116	16.736
525-S18	52	350	55000	25	240.5	9.979	17.049

Table A-1. (Contd.)

Specimen ID	Heat	Aging Temp (°C)	Aging Time (h)	Test Temp. (°C)	Impact Energy (J/cm^2)	Yield Load (kN)	Max. Load (kN)
526-S11	52	400	30000	25	337.5	12.794	22.887
528-S01	52	400	54800	25	185.6	10.624	16.824
528-S03	52	400	54800	25	170.2	10.585	17.107
562-S07	56	290	30000	25	223.0	9.852	15.633
562-S08	56	290	30000	25	260.2	9.911	15.936
562-S09	56	290	30000	25	249.6	10.057	16.248
562-S14	56	290	58000	25	196.0	9.393	15.164
562-S15	56	290	58000	25	228.9	9.413	16.609
564-S16	56	320	30000	25	240.0	10.116	16.502
564-S17	56	320	30000	25	208.7	10.380	16.395
564-S18	56	320	30000	25	219.0	10.350	16.951
563-S08	56	320	55000	25	233.8	9.589	16.873
563-S09	56	320	55000	25	206.7	9.716	16.316
565-S13	56	350	30000	25	203.6	10.302	16.590
565-S14	56	350	30000	25	232.1	10.067	17.[illegible]60
565-S15	56	350	30000	25	247.7	9.989	17.088
565-S16	56	350	55000	25	193.2	10.292	15.975
565-S18	56	350	55000	25	185.1	10.087	16.258
566-S10	56	400	30000	25	140.3	10.404	16.572
566-S11	56	400	30000	25	161.7	9.838	16.436
568-S01	56	400	54800	25	118.7	10.477	14.295
568-S03	56	400	54800	25	120.4	10.565	1[illegible].643
			Keel Blocks (CF-8 Grade)				
592-S07	59	290	30000	25	258.6	10.477	1[illegible]54
592-S08	59	290	30000	25	254.5	10.389	16.512
592-S09	59	290	30000	25	298.6	10.116	17.010
592-S13	59	290	58000	25	230.3	10.428	16.580
592-S14	59	290	58000	25	280.0	10.253	16.688
594-S16	59	320	30000	25	217.6	10.868	17.449
594-S17	59	320	30000	25	190.9	11.239	18.201
594-S18	59	320	30000	25	219.1	11.366	17.820
594-S16	59	320	30000	25	217.6	10.868	17.449
593-S07	59	320	55000	25	176.2	10.907	16.619
593-S08	59	320	55000	25	180.6	10.468	17.068
595-S13	59	350	30000	25	146.4	11.551	17.303
595-S14	59	350	30000	25	173.6	11.239	16.756
595-S15	59	350	30000	25	175.2	11.473	17.498
595-S16	59	350	55000	25	127.5	10.809	16.551
595-S18	59	350	55000	25	139.3	10.751	16.746
596-S10	59	400	30000	25	87.4	10.882	15.577
596-S11	59	400	30000	25	175.4	12.843	21.896
598-S01	59	400	54800	25	92.9	11.239	14.657
598-S03	59	400	54800	25	64.8	11.258	12.694
602-S07	60	290	30000	25	229.2	11.376	17.488
602-S08	60	290	30000	25	258.8	11.053	17.937
602-S09	60	290	30000	25	240.7	11.317	17.752
602-S14	60	290	58000	25	217.5	11.190	17.625
602-S15	60	290	58000	25	215.4	11.542	17.791
60[illegible]-S16	60	320	30000	25	149.2	12.001	18.133
604-S17	60	320	30000	25	219.9	12.030	18.865
604-S18	60	320	30000	25	200.6	12.333	18.963
603-S08	60	320	55000	25	90.5	12.313	17.469
603-S09	60	320	55000	25	136.8	12.518	17.683

Table A-1. (Contd.)

Specimen ID	Heat	Aging Temp (°C)	Aging Time (h)	Test Temp. (°C)	Impact Energy (J/cm²)	Yield Load (kN)	Max. Load (kN)
605-S13	60	350	30000	25	117.4	11.786	18.240
605-S14	60	350	30000	25	96.0	12.274	17.605
605-S15	60	350	30000	25	56.8	12.362	13.104
605-S16	60	350	55000	25	73.1	12.479	15.369
605-S18	60	350	55000	25	75.9	12.108	15.789
606-S10	60	400	30000	25	55.7	12.766	16.250
606-S11	60	400	30000	25	75.8	12.795	17.031
608-S01	60	400	54800	25	46.9	12.489	13.221
608-S03	60	400	54800	25	28.2	12.538	13.026
612-S07	61	290	30000	25	259.1	11.073	17.195
612-S08	61	290	30000	25	292.0	11.717	16.717
612-S09	61	290	30000	25	266.4	10.819	17.703
612-S13	61	290	58000	25	235.3	11.161	17.293
612-S14	61	290	58000	25	287.7	11.034	17.332
614-S16	61	320	30000	25	225.0	11.464	17.683
614-S17	61	320	30000	25	262.9	11.971	18.533
614-S18	61	320	30000	25	236.8	12.108	18.631
613-S07	61	320	55000	25	303.3	11.366	17.547
613-S08	61	320	55000	25	225.2	11.327	17.713
615-S13	61	350	30000	25	202.8	11.620	18.055
615-S14	61	350	30000	25	189.2	11.727	18.035
615-S15	61	350	30000	25	197.9	11.473	18.055
615-S16	61	350	55000	25	147.7	11.805	17.166
615-S18	61	350	55000	25	149.0	11.745	16.713
616-S10	61	400	30000	25	137.2	11.761	17.724
616-S11	61	400	30000	25	159.9	11.341	18.115
618-S01	61	400	54800	25	110.0	11.600	15.721
618-S03	61	400	54800	25	62.2	12.362	14.129
			Keel Blocks (CF-8M Grade)				
632-S07	63	290	30000	25	195.7	9.696	15.701
632-S08	63	290	30000	25	215.0	9.755	15.506
632-S09	63	290	30000	25	235.4	9.979	16.531
632-S14	63	290	58000	25	210.1	9.667	15.955
632-S15	63	290	58000	25	213.1	9.559	16.111
634-S16	63	320	30000	25	152.6	10.829	15.975
634-S17	63	320	30000	25	171.0	10.262	16.365
634-S18	63	320	30000	25	187.2	10.282	16.482
633-S08	63	320	55000	25	177.6	10.262	16.434
633-S09	63	320	55000	25	155.1	10.603	15.617
635-S13	63	350	30000	25	137.6	10.389	15.594
635-S14	63	350	30000	25	100.6	10.341	14.237
635-S15	63	350	30000	25	178.1	10.360	16.502
635-S16	63	350	55000	25	160.8	10.253	17.010
635-S18	63	350	55000	25	122.9	9.608	15.701
636-S10	63	400	30000	25	191.9	10.343	17.187
636-S11	63	400	30000	25	152.1	10.258	15.694
638-S01	63	400	54800	25	121.1	10.575	15.174
638-S03	63	400	54800	25	130.0	10.848	15.770
642-S07	64	290	30000	25	198.1	12.010	18.748
642-S08	64	290	30000	25	214.8	12.518	19.138
642-S09	64	290	30000	25	213.6	12.674	19.236
642-S13	64	290	58000	25	138.7	12.684	18.723
642-S14	64	290	58000	25	150.4	12.967	18.621
644-S16	64	320	30000	25	66.4	14.041	17.879
644-S17	64	320	30000	25	67.9	13.817	16.941
644-S18	64	320	30000	25	67.8	13.963	18.240

Table A-1. (Contd.)

Specimen ID	Heat	Aging Temp. (°C)	Aging Time (h)	Test Temp. (°C)	Impact Energy (J/cm²)	Yield Load (kN)	Max. Load (kN)
643-S07	64	320	55000	25	43.3	13.700	16.199
643-S08	64	320	55000	25	50.9	13.553	15.877
645-S13	64	350	30000	25	59.3	13.827	18.191
645-S14	64	350	30000	25	51.3	13.866	17.654
645-S15	64	350	30000	25	54.0	13.914	16.951
645-S16	64	350	55000	25	40.1	13.807	15.291
645-S18	64	350	55000	25	38.0	13.856	15.926
646-S10	64	400	30000	25	34.9	13.479	15.675
646-S11	64	400	30000	25	44.0	13.566	16.846
648-S01	64	400	54800	25	30.3	13.670	14.988
648-S03	64	400	54800	25	31.7	13.748	15.057
652-S07	65	290	30000	25	190.4	12.459	18.181
652-S08	65	290	30000	25	217.1	12.274	18.748
652-S09	65	290	30000	25	217.6	12.918	18.904
652-S14	65	290	58000	25	187.3	12.489	18.933
652-S15	65	290	58000	25	202.4	12.850	19.617
654-S16	65	320	30000	25	115.1	13.700	20.066
654-S17	65	320	30000	25	100.2	13.231	18.797
654-S18	65	320	30000	25	94.6	13.729	18.963
653-S08	65	320	55000	25	64.8	13.084	16.277
653-S09	65	320	55000	25	66.0	12.957	15.936
655-S13	65	350	30000	25	97.1	13.856	19.734
655-S14	65	350	30000	25	126.0	13.895	20.037
655-S15	65	350	30000	25	79.7	13.202	17.449
655-S16	65	350	55000	25	57.0	13.202	16.131
655-S18	65	350	55000	25	62.9	13.250	15.906
656-S10	65	400	30000	25	92.9	13.440	19.979
656-S11	65	400	30000	25	61.3	13.361	17.129
658-S01	65	400	54800	25	48.7	12.531	14.687
658-S03	65	400	54800	25	54.1	13.680	16.639
662-S07	66	290	30000	25	222.3	10.995	17.889
662-S08	66	290	30000	25	248.2	9.823	17.752
662-S09	66	290	30000	25	228.6	10.966	17.810
662-S13	66	290	58000	25	187.3	10.917	17.400
662-S14	66	290	58000	25	235.7	10.907	17.937
664-S16	66	320	30000	25	145.9	11.483	17.840
664-S17	66	320	30000	25	208.5	11.854	18.787
664-S18	66	320	30000	25	188.3	12.225	19.607
663-S07	66	320	55000	25	99.3	11.590	16.238
663-S08	66	320	55000	25	117.7	11.659	17.410
665-S13	66	350	30000	25	144.2	11.405	18.553
665-S14	66	350	30000	25	156.1	11.747	18.035
665-S15	66	350	30000	25	147.9	11.630	18.357
665-S16	66	350	55000	25	118.9	11.649	17.010
665-S18	66	350	55000	25	85.1	11.542	15.330
666-S10	66	400	30000	25	135.5	11.556	18.934
666-S11	66	400	30000	25	129.8	11.312	18.300
668-S01	66	400	54800	25	81.3	11.444	15.301
668-S03	66	400	54800	25	86.5	11.825	16.482
			Commercial Heats (CF-3 Grade)				
I3C-022	1	290	30000	25	301.4	9.686	17.098
I3V-049	1	290	30000	25	240.5	9.960	16.883
I3V-050	1	290	30000	25	195.5	10.116	15.565
I1V-038	1	320	30000	-197	128.0	12.293	23.864
I1V-039	1	320	30000	-100	169.7	12.098	22.224
I1V-041	1	320	30000	-50	184.9	12.186	21.677

Table A-1. (Contd.)

Specimen ID	Heat	Aging Temp. (°C)	Aging Time (h)	Test Temp. (°C)	Impact Energy (J/cm²)	Yield Load (kN)	Max. Load (kN)
I1V-042	I	320	30000	-20	217.9	11.229	20.525
I1V-043	I	320	30000	0	195.9	10.858	18.260
I1V-040	I	320	30000	20	319.8	15.073	25.731
I1V-047	I	320	30000	25	220.9	10.214	17.244
I2V-025	I	320	30000	25	222.7	10.018	17.420
I2V-026	I	320	30000	25	199.7	10.223	16.863
I1V-044	I	320	30000	75	227.4	9.306	15.379
I1V-045	I	320	30000	125	204.8	8.603	14.061
I1V-046	I	320	30000	290	194.1	6.503	11.366
I3V-042	I	320	55000	25	186.9	10.253	17.400
I3V-043	I	320	55000	25	199.4	10.594	17.537
I3V-044	I	320	55000	25	201.3	10.360	17.615
I3V-045	I	320	55000	25	186.4	10.087	17.000
I3C-016	I	320	55000	25	152.1	9.511	16.434
I3C-017	I	320	55000	25	181.5	9.901	16.736
I3V-025	I	350	30000	25	170.8	10.692	17.644
I3V-026	I	350	30000	25	177.1	10.428	17.791
I3V-027	I	350	30000	25	180.8	11.835	19.256
I3V-016	I	400	30000	25	122.9	10.931	16.114
I3V-017	I	400	30000	25	153.1	10.941	18.232
P21-A39	P2	290	58000	25	488.2	9.657	16.697
P21-A40	P2	290	58000	25	295.5	9.452	16.746
P21-T19	P2	290	58000	25	489.9	9.569	16.756
P21-A11	P2	320	30000	-197	69.2	12.430	16.512
P21-A13	P2	320	30000	-120	130.6	13.475	22.439
P22-A22	P2	320	30000	-80	174.7	12.176	21.931
P22-A23	P2	320	30000	-50	148.5	12.196	18.640
P22-A24	P2	320	30000	-20	266.2	11.532	19.812
P22-A25	P2	320	30000	0	292.8	11.132	18.972
P21-T12	P2	320	30000	25	369.8	9.901	16.980
P22-A21	P2	320	30000	25	491.3	10.009	17.771
P22-A27	P2	320	30000	25	374.6	9.862	17.010
P22-A28	P2	320	30000	25	493.9	9.813	17.186
P22-A26	P2	320	30000	75	458.1	9.413	15.897
P21-T11	P2	320	30000	125	412.1	8.192	14.549
P21-A12	P2	320	30000	290	351.3	6.562	12.479
P25-T11	P2	320	30000	290	339.7	6.679	11.932
P21-A24	P2	320	55000	25	234.3	10.096	16.648
P21-T14	P2	320	55000	25	263.0	9.960	17.010
P23-A28	P2	350	30000	-196	58.4	12.997	18.318
P23-A29	P2	350	30000	-196	55.7	12.674	16.609
P23-T11	P2	350	30000	-196	61.5	12.333	17.732
P23-A30	P2	350	30000	-120	104.6	11.385	20.505
P23-T12	P2	350	30000	-120	112.6	11.415	21.121
P23-A31	P2	350	30000	-100	115.9	12.538	20.847
P23-T13	P2	350	30000	-100	101.5	12.342	19.480
P23-A32	P2	350	30000	-78	89.4	12.479	19.207
P23-T14	P2	350	30000	-78	115.3	12.313	19.871
P23-A33	P2	350	30000	-50	91.8	11.669	17.186
P23-T15	P2	350	30000	-50	182.3	11.561	20.847
P23-A34	P2	350	30000	-20	159.6	11.200	19.275
P23-T16	P2	350	30000	-20	234.2	10.868	20.183
P23-A34	P2	350	30000	0	204.4	10.878	18.406
P23-T17	P2	350	30000	0	198.7	10.809	18.250
P23-T22	P2	350	30000	25	233.2	10.165	17.186
P24-A27	P2	350	30000	25	227.1	10.126	17.283
P25-A21	P2	350	30000	25	212.6	10.155	16.531
P23-T23	P2	350	30000	50	307.2	9.706	16.736
P25-A22	P2	350	30000	50	215.7	9.491	16.043
P23-A36	P2	350	30000	75	349.1	9.286	15.281

Table A-1. (Cont'd.)

Specimen ID	Heat	Aging Temp. (°C)	Aging Time (h)	Test Temp. (°C)	Impact Energy (J/cm^2)	Yield Load (kN)	Max. Load (kN)
P23-T18	P2	350	30000	75	434.5	8.700	15.174
P23-A37	P2	350	30000	125	387.5	7.880	13.621
P23-T19	P2	350	30000	125	391.0	7.343	13.729
P23-T20	P2	350	30000	200	376.4	6.962	13.280
P23-A38	P2	350	30000	290	342.6	6.034	11.776
P23-A39	P2	350	30000	290	340.8	6.279	11.825
P23-T21	P2	350	30000	290	350.1	6.269	12.010
P22-A12	P2	350	55000	25	236.7	9.735	17.156
P22-A16	P2	350	55000	25	206.6	9.833	16.717
P22-T14	P2	350	55000	25	184.4	10.106	16.482
P25-A18	P2	400	30000	25	175.9	10.277	16.856
P25-A19	P2	400	30000	25	139.5	9.994	16.192
P24-T09	P2	400	30000	25	209.1	10.043	17.265
P24-A11	P2	400	54800	25	177.6	9.813	16.795
P24-A13	P2	400	54800	25	183.6	9.872	16.482
P24-T11	P2	400	54800	25	168.8	9.999	15.672
			<u>Commercial Heats (CF-8 Grade)</u>				
C1-A097	C1	290	58000	25	78.8	8.788	12.528
C1-A098	C1	290	58000	25	104.5	9.061	14.071
C1-A082	C1	320	30000	25	52.5	9.579	12.557
C1-A083	C1	320	30000	25	48.5	9.901	11.825
C1-A085	C1	320	55000	25	70.2	9.686	11.747
C1-A086	C1	320	55000	25	58.5	9.315	11.219
C1-A056	C1	350	10000	25	68.0	9.335	13.094
C1-A057	C1	350	10000	25	59.5	9.823	13.534
C1-A066	C1	350	30000	25	63.7	9.393	12.762
C1-A067	C1	350	30000	25	25.4	9.257	9.725
P11-A20	P1	290	30000	25	183.6	10.448	16.443
P11-A21	P1	290	30000	25	200.2	11.327	16.121
P11-T09	P1	290	30000	25	232.8	11.532	16.395
P11-A31	P1	290	58000	25	382.3	11.503	17.557
P14-A28	P1	290	58000	25	330.5	11.376	18.123
P11-T03	P1	320	30000	25	168.4	11.376	17.254
P12-A20	P1	320	30000	25	225.5	11.835	18.640
P12-A21	P1	320	30000	25	228.1	11.620	18.943
P12-A24	P1	320	55000	25	117.1	11.796	17.078
P13-T12	P1	320	55000	25	172.2	11.464	18.435
P12-T09	P1	350	30000	25	73.4	11.835	15.272
P13-A23	P1	350	30000	25	103.4	11.844	16.795
P13-A24	P1	350	30000	25	86.2	11.962	15.565
P12-A16	P1	350	55000	25	69.6	11.844	15.701
P13-A29	P1	350	55000	25	72.8	11.639	14.657
P13-A11	P1	400	30000	25	57.9	12.063	15.284
P14-A20	P1	400	30000	25	91.1	16.765	20.267
P13-T10	P1	400	30000	25	69.7	11.939	18.293
			<u>Commercial Heats (CF-8M Grade)</u>				
P41-A41	P4	290	30000	25	288.4	11.971	17.986
P41-A42	P4	290	30000	25	280.7	12.098	17.283
P41-A42	P4	290	58000	25	242.8	11.727	17.127
P41-A43	P4	290	58000	25	227.2	11.649	17.410
P41-A26	P4	320	30000	25	86.7	12.567	15.643
P41-A27	P4	320	30000	25	88.1	12.528	15.106
P41-A30	P4	320	55000	25	69.4	11.942	13.641
P41-A31	P4	320	55000	25	78.4	11.678	14.178
P42-A49	P4	350	30000	25	57.7	12.459	14.803
P42-A50	P4	350	30000	25	68.5	9.130	18.297

Table A-1. (Contd.)

Specimen ID	Heat	Aging Temp. (°C)	Aging Time (h)	Test Temp. (°C)	Impact Energy (J/cm²)	Yield Load (kN)	Max. Load (kN)
P41-A14	P4	350	55000	25	61.2	12.508	13.641
P41-A16	P4	350	55000	25	63.4	12.254	14.315
P42-A40	P4	400	30000	25	57.3	12.424	13.303
P42-A41	P4	400	30000	25	68.4	15.021	0.000
P42-A43	P4	400	54800	25	68.0	12.147	13.787
P42-A45	P4	400	54800	25	55.0	12.342	13.621
			<u>76-mm Slabs (CF-3 Grade)</u>				
693-28	69	290	30000	-196	71.0	11.454	17.869
694-28	69	290	30000	-196	81.3	11.268	19.656
693-29	69	290	30000	-120	213.4	10.731	24.372
69-131	69	290	30000	-120	226.2	11.991	23.357
694-29	69	290	30000	-100	202.4	11.034	21.912
693-30	69	290	30000	-80	240.7	11.922	22.273
694-34	69	290	30000	-50	248.1	10.243	20.310
69-132	69	290	30000	-20	295.9	11.483	20.027
693-31	69	290	30000	10	205.0	11.313	18.375
693-32	69	290	30000	25	205.4	10.292	17.791
69-133	69	290	30000	25	246.9	10.594	17.810
694-35	69	290	30000	75	192.6	8.769	14.940
693-33	69	290	30000	175	168.1	7.314	12.733
693-34	69	290	30000	290	200.4	5.478	10.936
69-134	69	290	30000	290	196.2	5.263	10.653
691-37	69	320	30000	-197	50.1	12.420	18.221
691-38	69	320	30000	-96	113.2	12.811	20.710
691-39	69	320	30000	-50	135.9	12.098	20.310
69-237	69	320	30000	-20	220.5	11.971	20.720
692-27	69	320	30000	0	175.5	11.210	18.748
692-38	69	320	30000	25	194.1	10.897	17.449
69-238	69	320	30000	25	179.8	10.204	17.332
692-39	69	320	30000	75	248.9	9.296	15.877
69-239	69	320	30000	100	222.6	8.241	14.705
693-37	69	320	30000	290	223.8	7.128	12.391
69-240	69	320	30000	290	202.2	6.982	12.254
69-258	69	320	50000	-197	38.6	11.981	15.115
691-31	69	320	50000	-197	59.9	12.030	19.021
692-31	69	320	50000	-125	66.9	12.225	17.498
691-32	69	320	50000	-75	131.4	12.088	21.248
692-32	69	320	50000	-20	153.1	11.473	19.617
691-33	69	320	50000	0	178.6	10.741	18.709
69-259	69	320	50000	10	152.4	10.057	16.121
692-33	69	320	50000	25	176.0	10.565	17.664
691-34	69	320	50000	25	188.0	10.380	17.928
69-260	69	320	50000	25	189.2	10.487	17.635
692-34	69	320	50000	50	169.7	10.067	15.662
691-35	69	320	50000	75	219.7	8.815	15.401
69-261	69	320	50000	100	250.4	8.300	14.920
692-35	69	320	50000	125	220.4	8.300	14.461
691-36	69	320	50000	175	189.7	7.460	13.690
69-262	69	320	50000	250	200.2	6.620	12.157
692-36	69	320	50000	290	165.7	5.937	11.512
69-263	69	320	50000	290	186.4	6.269	11.346
693-10	69	350	30000	-196	39.3	12.762	16.570
693-11	69	350	30000	-97	56.6	12.987	18.172
693-16	69	350	30000	-50	87.6	12.567	19.841
693-17	69	350	30000	-20	106.5	12.001	18.845
694-10	69	350	30000	0	98.8	10.604	17.010
693-18	69	350	30000	25	131.4	10.214	17.137
69-125	69	350	30000	25	108.7	10.194	16.316
694-11	69	350	30000	75	135.7	9.628	15.428
694-12	69	350	30000	100	157.5	9.335	15.106

Table A-1. (Contd.)

Specimen ID	Heat	Aging Temp. (°C)	Aging Time (h)	Test Temp. (°C)	Impact Energy (J/cm²)	Yield Load (kN)	Max. Load (kN)
694-13	69	350	30000	175	147.7	8.700	14.315
694-14	69	[illegible]	30000	290	141.0	7.724	12.948
69-126	69	350	30000	290	178.6	7.372	12.870
			76-mm Slab (CF-8 Grade)				
683-28	68	290	30000	-196	44.5	16.473	18.084
683-29	68	290	30000	-120	39.7	14.901	16.395
684-28	68	290	30000	-100	109.9	[illegible]	19.461
683-30	68	290	30000	-80	62.4	13.934	17.234
684-29	68	290	30000	-50	91.5	12.704	19.246
68-141	68	290	30000	-20	192.6	12.254	19.041
683-31	68	290	30000	0	222.5	11.776	18.640
684-30	68	290	30000	10	209.2	11.913	18.113
683-32	68	290	30000	25	171.8	11.005	16.199
68-142	68	290	30000	25	281.6	11.317	17.557
683-34	68	290	30000	50	309.1	10.760	17.157
68-143	68	290	30000	75	299.7	9.921	16.072
684-34	68	290	30000	125	411.9	8.388	14.217
683-36	68	290	30000	175	373.5	7.362	13.211
684-35	68	290	30000	200	346.9	7.636	12.782
683-35	68	290	30000	290	341.4	6.601	11.864
68-144	68	290	30000	290	335.9	6.591	[illegible]
681-37	68	320	30000	-197	25.5	14.969	[illegible]
681-38	68	320	30000	-96	95.5	15.145	21.414
68-247	68	320	30000	-50	67.5	13.895	17.908
681-39	68	320	30000	-20	99.1	12.420	18.191
68-248	68	320	30000	0	111.5	12.098	17.088
682-37	68	320	30000	25	128.1	11.630	16.648
68-249	68	320	30000	25	142.1	11.561	17.820
682-38	68	320	30000	50	191.4	10.653	16.922
68-258	68	320	30000	50	185.6	10.682	16.209
682-39	68	320	[illegible]	100	200.4	9.804	15.711
68-259	68	320	30000	175	246.0	8.046	14.217
683-37	68	320	30000	290	187.9	7.411	12.723
68-260	68	320	30000	290	254.4	6.728	11.747
68-268	68	320	50000	-197	12.9	12.128	12.128
681-31	68	320	50000	-197	9.4	12.577	12.577
682-31	68	320	50000	-125	25.4	14.080	14.393
681-32	68	320	50000	-75	19.5	12.196	12.196
682-32	68	320	50000	-20	46.1	12.899	14.344
681-33	68	320	50000	0	56.6	11.922	13.641
68-269	68	320	50000	10	83.6	11.473	14.412
682-33	68	320	50000	25	94.2	11.551	15.233
681-34	68	320	50000	25	105.9	11.258	15.447
68-270	68	320	50000	25	87.9	11.317	16.346
682-34	68	320	50000	50	159.5	10.692	16.951
681-35	68	320	50000	75	225.5	9.745	15.662
68-271	68	320	50000	100	216.9	9.061	15.262
682-35	68	320	50000	125	203.7	9.384	14.910
681-36	68	320	50000	175	254.5	7.472	13.590
68-272	68	320	50000	250	308.0	6.611	11.913
682-36	68	320	50000	290	205.5	6.923	12.459
68-273	68	320	50000	290	199.2	6.552	12.069
683-10	68	350	30000	-196	15.6	12.791	12.791
683-11	68	350	30000	-50	33.0	13.924	15.272
683-12	68	350	30000	0	56.1	12.713	15.037
683-13	68	350	30000	25	65.1	12.098	15.789
68-135	68	350	30000	25	96.0	12.088	16.326
683-14	68	350	30000	50	56.6	11.229	13.787
683-15	68	350	30000	75	154.4	10.214	16.492
683-16	68	350	30000	100	137.9	10.087	15.809
68-136	68	350	30000	125	165.9	9.345	15.252
683-17	68	350	30000	175	168.0	9.677	14.295

Table A-1. (Contd.)

Specimen ID	Heat	Aging Temp. (°C)	Aging Time (h)	Test Temp. (°C)	Impact Energy (J/cm²)	Yield Load (kN)	Max. Load (kN)
684-13	68	350	30000	225	187.1	8.620	13.829
683-18	68	350	30000	290	179.8	7.851	13.329
68-137	68	350	30000	290	195.5	7.636	12.674
			76-mm Slabs (CF-8M Grade)				
743-28	74	290	30000	-196	35.5	16.883	16.883
74[illegible]-28	74	290	30000	-196	34.1	16.658	18.416
743-29	74	290	30000	-120	139.6	15.223	21.511
744-29	74	290	30000	-100	116.2	13.651	18.299
743-30	74	290	30000	-80	256.5	12.977	22.224
744-30	74	290	30000	-50	308.5	13.973	21.072
74-131	74	290	30000	-20	286.4	11.717	18.308
743-31	74	290	30000	0	273.9	11.835	18.738
744-31	74	290	30000	10	335.5	10.516	17.273
743-32	74	290	30000	[illegible]5	344.9	10.594	17.078
74-132	74	290	30000	25	326.6	10.702	18.133
744-32	74	290	30000	75	261.1	8.605	13.174
743-33	74	290	30000	175	235.6	7.773	13.133
743-34	74	290	30000	290	289.0	6.386	11.678
74-133	74	290	30000	290	283.3	6.698	11.971
741-37	74	320	30000	-197	15.4	14.285	14.285
741-38	74	320	30000	-96	65.1	15.692	20.418
74-237	74	320	30000	-50	53.8	14.451	15.604
741-39	74	320	30000	-20	75.8	12.606	15.018
74-238	74	320	30000	0	122.5	12.264	17.508
742-37	74	320	30000	25	95.4	10.800	15.692
74-239	74	320	30000	25	156.1	11.649	17.537
742-38	74	320	30000	50	154.3	11.200	16.356
742-40	74	320	30000	75	207.2	10.712	16.395
742-39	74	320	30000	100	160.5	9.3[illegible]3	15.701
74-241	74	320	30000	175	201.4	8.017	14.051
743-37	74	320	30000	290	176.0	7.773	12.997
74-292	74	320	30000	290	179.8	7.812	12.909
74-258	74	320	50000	-197	22.2	15.311	15.643
741-31	74	320	50000	-197	13.5	13.866	13.866
742-31	74	320	50000	-125	38.5	14.041	16.54[illegible]
741-32	74	320	50000	-75	17.5	13.123	12.123
742-32	74	320	50000	-20	120.4	12.010	16.600
741-33	74	320	50000	0	105.6	11.590	16.551
74-259	74	320	50000	10	96.4	11.239	14.266
742-33	74	320	50000	25	100.5	11.200	[illegible]160
741-34	74	320	50000	25	62.1	11.756	14.[illegible]0
74-260	74	320	50000	25	84.5	11.200	14.85[illegible]
742-34	74	320	50000	50	69.5	10.438	[illegible]2.655
741-35	74	320	50000	75	131.7	9.813	14.686
74-261	74	320	50000	100	180.7	8.983	15.692
742-35	74	320	50000	125	89.4	8.778	13.436
741-36	74	320	50000	175	139.9	8.466	13.377
74-262	74	320	50000	250	158.0	7.294	13.3[illegible]7
742-36	74	320	50000	290	156.0	6.669	12.606
74-263	74	320	50000	290	138.7	6.513	12.225
743-10	74	350	30000	-196	15.1	14.735	14.735
743-11	74	350	30000	-97	20.6	14.149	14.149
743-12	74	350	30000	-50	49.6	13.592	15.281
743-16	74	350	30000	-20	58.6	12.157	15.574
743-17	74	350	30000	0	76.6	11.913	15.965
743-18	74	350	30000	25	69.1	11.727	14.578
74-125	74	350	30000	25	56.9	11.590	13.953
744-10	74	350	30000	50	89.8	10.878	15.233
744-11	74	350	30000	75	93.3	10.155	14.910
744-12	74	350	30000	100	87.0	10.321	14.686
74-126	74	350	30000	125	127.7	9.481	15.311
744-13	74	350	30000	17[illegible]	141.6	8.788	14.207

Table A-1. (Contd.)

Specimen ID	Heat	Aging Temp. (°C)	Aging Time (h)	Test Temp. (°C)	Impact Energy (J/cm²)	Yield Load (kN)	Max. Load (kN)
744-14	74	350	30000	290	160.4	8.446	13.895
74-127	74	350	30000	290	168.7	6.200	10.985
753-28	75	290	30000	-196	25.7	18.308	18.308
754-31	75	290	30000	-120	56.7	15.945	19.500
75-131	75	290	30000	-100	89.7	11.268	21.677
753-29	75	290	30000	-80	117.5	15.535	19.002
754-32	75	290	30000	-50	196.6	14.627	21.960
75-132	75	290	30000	-20	229.2	13.680	20.623
753-31	75	290	30000	-20	234.7	13.358	20.867
754-33	75	290	30000	0	249.0	13.582	20.378
753-32	75	290	30000	10	262.5	12.538	19.529
754-34	75	290	30000	25	247.4	12.362	19.441
75-133	75	290	30000	25	284.6	12.850	19.656
753-33	75	290	30000	50	250.1	11.815	17.898
754-35	75	290	30000	125	275.7	9.608	16.297
753-34	75	290	30000	200	258.1	8.153	14.207
753-35	75	290	30000	290	239.5	7.558	12.782
75-134	75	290	30000	290	235.5	7.665	13.231
751-37	75	320	30000	-197	9.3	12.811	12.811
751-38	75	320	30000	-96	25.5	17.225	18.181
75-237	75	320	30000	-50	37.6	15.496	17.332
751-39	75	320	30000	20	49.6	14.696	17.234
75-238	75	320	30000	0	62.2	13.993	16.522
752-37	75	320	30000	25	52.7	13.358	15.916
75-239	75	320	30000	25	75.9	13.485	16.883
752-38	75	320	30000	50	46.5	12.665	14.657
75-240	75	320	30000	75	125.9	12.420	17.683
752-39	75	320	30000	100	65.6	11.385	14.471
75-241	75	320	30000	175	160.8	10.038	16.190
753-37	75	320	30000	290	155.8	8.212	14.988
75-242	75	320	30000	290	164.2	9.237	14.393
75-258	75	320	50000	-197	10.3	13.748	13.748
751-31	75	320	50000	-197	7.4	11.454	11.454
752-31	75	320	50000	-125	15.9	14.334	14.334
751-32	75	320	50000	-75	14.5	14.696	14.696
752-32	75	320	50000	-20	22.6	13.368	13.368
751-33	75	320	50000	0	49.3	13.465	15.389
75-259	75	320	50000	10	49.1	13.387	15.486
752-33	75	320	50000	25	40.5	11.560	13.780
751-34	75	320	50000	25	36.9	13.084	14.139
75-260	75	320	50000	25	34.5	13.299	14.022
752-34	75	320	50000	50	30.4	11.796	13.133
751-35	75	320	50000	75	48.1	10.285	13.066
75-261	75	320	50000	100	61.3	11.229	13.348
752-35	75	320	50000	125	92.4	10.575	14.647
751-36	75	320	50000	175	77.5	10.448	14.061
75-262	75	320	50000	250	140.6	8.661	14.149
75-263	75	320	50000	290	124.7	8.192	13.709
754-10	75	350	30000	-196	10.5	15.291	15.291
754-11	75	350	30000	-50	23.9	14.774	14.988
754-13	75	350	30000	0	30.2	13.924	15.272
753-13	75	350	30000	25	29.7	12.518	13.436
75-125	75	350	30000	25	31.2	13.338	14.783
753-14	75	350	30000	50	24.7	12.733	13.221
753-15	75	350	30000	75	46.6	11.932	13.924
753-16	75	350	30000	100	56.8	12.362	15.418
75-126	75	350	30000	125	45.2	11.786	13.983
753-17	75	350	30000	175	70.2	11.620	14.998
754-14	75	350	30000	225	90.1	10.604	14.871
753-18	75	350	30000	290	104.8	9.598	14.188
75-127	75	350	30000	290	118.9	9.872	15.662

Table A-2. Charpy-impact test results for the EPRI heat of cast stainless steel

Specimen ID	Heat	Aging Temp. (°C)	Aging Time (h)	Test Temp. (°C)	Impact Energy (J/cm²)	Yield Load (kN)	Max. Load (kN)
2B1-06	EPRI	320	2250	-197	22.2	15.594	15.594
2B1-07	EPRI	320	2250	-120	74.7	14.871	16.522
2B1-01	EPRI	320	2250	-100	101.8	15.506	20.847
2B1-08	EPRI	320	2250	-50	171.1	14.168	21.482
2B1-02	EPRI	320	2250	-20	259.9	13.680	20.867
2B1-03	EPRI	320	2250	25	356.9	12.040	18.719
2B1-04	EPRI	320	2250	75	418.2	11.092	17.078
2B1-05	EPRI	320	2250	125	427.8	10.282	15.516
2B2-01	EPRI	320	17350	-197	17.7	14.451	14.451
2B2-02	EPRI	320	17350	-50	57.6	16.131	19.666
2B2-03	EPRI	320	17350	25	128.5	13.719	19.304
2B2-06	EPRI	320	17350	75	277.4	11.835	18.025
2B2-04	EPRI	320	17350	125	328.1	10.770	16.912
2B2-05	EPRI	320	17350	290	367.3	8.886	13.817
2A2-01	EPRI	350	1010	-100	45.1	15.662	18.084
2A2-02	EPRI	350	1010	-20	150.7	14.207	20.505
2A2-03	EPRI	350	1010	25	260.6	14.305	21.990
2A2-06	EPRI	350	1010	25	342.1	12.606	19.343
2A2-04	EPRI	350	1010	75	352.4	11.503	17.244
2A2-05	EPRI	350	1010	125	452.8	10.917	16.522
2B1-01	EPRI	350	7800	-20	55.9	12.889	18.445
2B1-02	EPRI	350	7800	25	80.5	13.104	17.010
2B1-03	EPRI	350	7800	75	105.9	11.815	16.658
2B1-05	EPRI	350	7800	100	181.4	11.268	17.410
2B1-04	EPRI	350	7800	125	318.7	11.776	18.172
2B1-06	EPRI	350	7800	290	236.0	9.784	14.657

Table A-3. *Charpy-impact test results for the experimental heats of cast stainless steel in the unaged, fully aged, and annealed conditions. The annealed samples were originally aged for 10,000 h at 400°C.*

Specimen ID	Heat	Aging Temp. (°C)	Aging Time (h)	Test Temp. (°C)	Impact Energy (J/cm²)	Yield Load (kN)	Max. Load (kN)
473-S15	47	–	–	-196	133.3	12.400	23.000
476-S15	47	–	–	-196	131.9	12.320	22.961
478-S09	47	–	–	-125	256.5	11.122	21.248
478-S08	47	–	–	-100	251.7	11.659	21.257
478-S07	47	–	–	-75	270.5	11.258	20.349
478-S06	47	–	–	-50	304.2	11.126	19.076
478-S05	47	–	–	-20	282.0	10.0[illegible]7	17.566
478-S04	47	–	–	0	301.5	9.657	16.258
473-S13	47	–	–	25	235.3	9.681	15.552
473-S14	47	–	–	25	203.9	10.202	15.035
476-S13	47	–	–	25	224.9	9.337	14.563
476-S14	47	–	–	25	250.3	8.984	14.805
478-S16	47	–	–	75	346.4	8.124	13.211
478-S17	47	–		290	317.7	5.478	11.024
477-C04	47	400	10000	-197	33.9	12.932	15.175
478-S10	47	400	10000	-197	54.0	12.059	15.447
477-C08	47	400	10000	-150	73.4	12.840	18.709
477-C09	47	400	10000	-130	59.8	11.590	14.920
478-S11	47	400	10000	-125	153.7	11.708	21.912
477-C05	47	400	10000	-50	170.5	11.952	19.744
478-S12	47	400	10000	-20	180.2	11.024	1[illegible].513
477-C06	47	400	10000	0	122.9	10.389	15.594
476-S07	47	400	9980	25	153.0	10.166	16.343
476-S08	47	400	9980	25	174.9	10.273	16.170
476-S09	47	400	9980	25	174.7	9.440	16.145
478-S13	47	400	10000	75	242.0	8.505	14.256
477-C07	47	400	10000	125	198.0	7.284	13.280
478-S15	47	400	10000	200	189.1	6.454	11.825
478-S14	47	400	10000	290	130.2	5.888	10.355
476-C01	47	–	Annealed	-197	238.4	11.581	24.802
476-C02	47	–	Annealed	-150	165.6	11.132	20.876
476-C03	47	–	Annealed	-125	264.4	10.790	21.150
476-C04	47	–	Annealed	-100	248.9	10.868	20.789
476-C05	47	–	Annealed	-50	297.1	11.219	19.285
476-C06	47	–	Annealed	25	262.9	9.013	15.506
477-C01	47	–	Annealed	100	248.2	7.372	12.508
477-C02	47	–	Annealed	175	330.9	6.432	11.584
477-C03	47	–	Annealed	290	300.6	5.136	9.901
513-C15	51	–	–	-196	138.3	13.797	23.330
516-S15	51	–	–	-196	139.9	14.369	24.454
518-S15	51	–	–	-125	223.3	12.831	2[illegible].068
518-S14	51	–	–	-100	202.0	13.270	21.658
518-S13	51	–	–	-75	206.8	12.411	21.208
518-S09	51	–	–	-50	295.6	12.430	20.945
518-S08	51	–	–	-20	268.1	11.903	19.334
518-S07	51	–	–	0	248.3	11.307	17.976
515-C08	51	–	–	25	239.3	10.951	17.519
516-S13	51	–	–	25	213.5	10.177	16.480
513-S14	51	–	–	25	220.5	10.463	16.565
515-C07	51	–	–	25	251.2	11.000	17.451
516-S14	51	–	–	25	187.3	10.546	16.865
513-S13	51	–	–	25	188.8	10.670	16.645
518-S16	51	–	–	75	247.7	8.671	14.325
518-S17	51	–	–	290	269.0	5.859	10.341
516-C04	51	400	9980	-196	35.9	14.804	16.647
517-C08	51	400	10000	-150	35.4	14.998	17.029
511-S07	51	400	10000	-125	113.1	13.436	22.341
511-S08	51	400	10000	-50	1[illegible]9.9	13.309	20.759

Table A-3. (Contd.)

Specimen ID	Heat	Aging Temp. (°C)	Aging Time (h)	Test Temp. (°C)	Impact Energy (J/cm²)	Yield Load (kN)	Max Load (kN)
516-S07	51	400	9980	25	120.0	11.600	18.073
516-S08	51	400	9980	25	159.8	11.647	18.736
516-S09	51	400	9980	25	140.4	11.082	17.522
511-S09	51	400	10000	75	172.2	9.520	15.906
517-C09	51	400	10000	175	158.6	7.138	12.879
517-C07	51	400	10000	290	133.0	6.611	12.069
518-S04	51	550	1	-197	159.1	12.704	24.226
518-S05	51	550	1	-125	227.9	12.586	23.532
518-S06	51	550	1	-75	246.9	12.76[illegible]	22.107
518-S10	51	550	1	25	288.9	10.58[illegible]	17.400
518-S11	51	550	1	125	264.3	7.694	13.446
518-S12	51	550	1	290	229.5	6.132	11.092
523-S15	52	–	–	-196	175.1	12.273	24.344
526-S15	52	–	–	-196	126.6	14.640	22.020
528-S12	52	–	–	-125	231.7	11.522	22.087
528-S11	52	–	–	-100	266.9	11.[illegible]	22.741
528-S10	52	–	–	-75	294.7	11.532	21.716
521-S06	52	–	–	-50	253.8	11.102	20.300
521-S05	52	–	–	-20	292.8	10.422	18.806
521-S04	52	–	–	0	316.4	10.302	17.635
525-C09	52	–	–	25	245.2	10.141	16.729
526-S13	52	–	–	25	244.9	8.565	14.593
526-S14	52	–	–	25	295.2	9.135	15.739
523-S14	52	–	–	25	241.3	10.136	16.150
523-S13	52	–	–	25	206.2	10.288	15.533
528-S16	52	–	–	75	305.7	8.261	13.231
528-S17	52	–	–	290	300.0	5.400	10.096
526-C04	52	400	9980	-196	36.7	13.376	17.377
526-S17	52	400	10000	-150	134.2	12.010	22.146
521-S07	52	400	10000	-125	176.5	11.942	22.292
521-S08	52	400	10000	-50	173.5	11.659	20.193
526-S08	52	400	9980	25	156.7	10.880	16.295
526-S07	52	400	9980	25	187.4	10.379	[illegible]44
526-S09	52	400	9980	25	158.5	10.911	17.[illegible]64
521-S09	52	400	10000	75	266.1	8.612	15.252
526-S16	52	400	10000	290	171.0	5.781	11.278
528-S04	52	–	Annealed	-197	179.7	10.917	23.611
528-S05	52	–	Annealed	-125	243.9	11.024	22.917
528-S06	52	–	Annealed	-75	261.1	11.464	21.619
528-S07	52	–	Annealed	25	257.2	9.618	16.600
526-S08	52	–	Annealed	125	378.2	7.294	12.928
528-S09	52	–	Annealed	290	293.8	5.253	9.960
593-S15	59	–	–	-196	75.3	16.459	21.763
596-S15	59	–	–	-196	30.0	16.352	16.160
598-S15	59	–	–	-125	168.7	13.455	22.986
598-S14	59	–	–	-100	169.3	14.041	22.097
598-S13	59	–	–	-75	237.5	13.651	21.492
598-S12	59	–	–	-50	248.4	12.440	20.017
598-S11	59	–	–	-20	260.6	11.649	18.201
598-S10	59	–	–	0	271.5	11.024	17.781
593-S13	59	–	–	25	247.1	10.549	15.948
596-S14	59	–	–	25	231.7	10.324	15.885
596-S13	59	–	–	25	210.5	10.998	15.826
593-S14	59	–	–	25	21[illegible].1	10.452	16.114
598-S16	59	–	–	75	303.8	9.569	14.979
598-S17	59	–	–	290	255.6	5.732	10.526

Table A-3. (Contd.)

Specimen ID	Heat	Aging Temp (°C)	Aging Time (h)	Test Temp (°C)	Impact Energy (J/cm²)	Yield Load (kN)	Max. Load (kN)
596-C04	59	400	9980	-196	13.5	14.768	14.768
598-S04	59	400	10000	-150	16.1	14.168	14.168
598-S05	59	400	10000	-120	31.2	13.758	14.481
597-C07	59	400	10000	-50	88.9	12.821	18.347
596-S07	59	400	9980	25	106.3	11.240	16.531
596-S09	59	400	9980	25	95.8	10.880	15.742
596-S08	59	400	9980	25	119.7	10.560	16.582
597-C08	59	400	10000	75	164.2	8.954	15.203
598-S06	59	400	10000	175	173.1	7.441	13.026
597-C09	59	400	10000	290	183.4	6.650	12.254
591-S04	59	-	Annealed	-197	71.3	14.559	19.383
591-S05	59	-	Annealed	-125	113.6	12.586	19.529
591-S06	59	-	Annealed	-75	184.3	12.577	20.281
598-S07	59	-	Annealed	25	259.4	10.428	16.248
598-S08	59	-	Annealed	125	287.5	7.491	13.049
598-S09	59	-	Annealed	290	181.0	6.005	11.112
606-S15	60	-	-	-196	21.7	15.569	15.569
603-S15	60	-	-	-196	25.4	14.771	14.771
608-S09	60	-	-	-125	179.8	14.500	22.087
608-S08	60	-	-	-100	200.7	14.979	22.585
608-S07	60	-	-	-75	154.1	14.491	21.404
608-S06	60	-	-	-50	226.8	13.680	20.544
608-S05	60	-	-	-20	308.1	12.645	19.568
608-S04	60	-	-	0	303.1	12.001	18.094
606-S13	60	-	-	25	200.7	10.728	16.532
603-S14	60	-	-	25	200.3	10.509	16.180
605-C09	60	-	-	25	213.6	11.702	18.076
606-S14	60	-	-	25	196.5	11.194	17.397
603-S13	60	-	-	25	187.6	11.455	16.452
608-S13	60	-	-	75	276.3	9.667	14.871
608-S14	60	-	-	290	319.2	6.279	10.770
606-C04	60	400	9980	-190	8.0	14.910	14.910
608-S10	60	400	10000	-50	23.9	13.959	15.221
608-S17	60	400	10000	-20	44.5	13.397	15.145
606-S07	60	400	9980	25	57.1	12.320	14.901
606-S08	60	400	9980	25	64.5	12.560	16.140
606-S09	60	400	9980	25	45.1	12.400	14.173
608-S11	60	400	10000	75	73.0	10.516	14.451
608-S18	60	400	10000	100	141.6	10.194	16.004
608-S12	60	400	10000	125	126.8	9.559	14.539
608-S16	60	400	10000	290	144.4	7.284	12.616
601-S07	60	-	Annealed	-197	68.8	16.414	21.033
601-S08	60	-	Annealed	-125	128.6	14.959	22.224
602-S09	60	-	Annealed	-75	174.4	13.993	22.458
607-C07	60	-	Annealed	25	251.7	11.005	17.898
607-C08	60	-	Annealed	125	245.4	8.651	13.787
607-C09	60	-	Annealed	290	260.0	5.047	11.150
613-S15	61	-	-	-196	29.8	17.680	18.351
616-S15	61	-	-	-196	53.8	18.160	19.571
618-S09	61	-	-	-125	192.6	14.207	22.449
618-S08	61	-	-	-100	255.3	15.252	22.068
618-S07	61	-	-	-75	192.4	14.871	21.374
617-C06	61	-	-	-50	207.5	13.299	20.378
618-S15	61	-	-	-20	249.1	12.536	18.758
617-C04	61	-	-	0	326.3	11.571	17.430
616-S14	61	-	-	25	255.7	10.945	16.943
616-S13	61	-	-	25	252.4	10.709	16.700
613-S13	61	-	-	25	253.4	0.580	16.424
613-S14	61	-	-	25	238.7	0.456	16.652
618-S13	61	-	-	75	259.6	9.960	15.399
618-S14	61	-	-	290	227.6	5.585	10.067

Table A-3. (Contd.)

Specimen ID	Heat	Aging Temp. (°C)	Aging Time (h)	Test Temp. (°C)	Impact Energy (J/cm²)	Yield Load (kN)	Max. Load (kN)
615-C04	61	400	10000	-197	17.3	14.930	14.930
618-S04	61	400	10000	-197	15.2	14.359	14.359
618-S05	61	400	10000	-125	23.9	14.725	15.652
615-C05	61	400	10000	-50	44.6	14.051	15.135
618-S06	61	400	10000	-20	77.8	14.119	16.307
617-C03	61	400	10000	-10	107.0	12.137	18.006
615-C06	61	400	10000	0	147.8	12.665	17.879
618-S12	61	400	10000	10	127.1	11.981	16.854
616-S09	61	400	9980	25	139.0	12.128	17.658
616-S08	61	400	9980	25	171.4	11.807	19.295
616-S07	61	400	9980	25	125.2	12.134	17.495
618-S10	61	400	10000	75	177.5	10.145	16.199
617-C01	61	400	10000	125	193.8	8.798	14.988
617-C02	61	400	10000	200	162.9	7.304	13.182
618-S11	61	400	10000	290	173.4	6.601	12.293
611-S01	61	-	Annealed	-197	97.8	16.844	22.859
611-S02	61	-	Annealed	-150	115.8	15.701	23.239
611-S03	61	-	Annealed	-125	148.6	14.832	22.195
612-S10	61	-	Annealed	-100	190.7	14.491	23.562
612-S11	61	-	Annealed	-50	233.2	12.694	19.754
612-S12	61	-	Annealed	25	279.0	11.327	16.971
615-C01	61	-	Annealed	100	431.5	8.837	14.862
615-C02	61	-	Annealed	175	319.8	7.353	12.987
615-C03	61	-	Annealed	290	259.2	6.240	11.464
633-S15	63	-	-	-196	167.4	15.560	24.060
636-S15	63	-	-	-196	227.8	16.880	25.206
638-S15	63	-	-	-125	257.3	13.299	21.208
638-S14	63	-	-	-100	236.1	12.557	19.480
638-S13	63	-	-	-75	314.8	13.006	19.490
631-S06	63	-	-	-50	232.0	11.141	17.840
631-S05	63	-	-	-20	278.9	10.585	16.316
631-S04	63	-	-	0	236.4	9.901	15.555
633-S14	63	-	-	25	293.2	9.585	15.493
633-S13	63	-	-	25	233.9	9.793	15.088
635-C07	63	-	-	25	229.6	9.565	15.460
636-S13	63	-	-	25	221.9	10.112	15.519
638-S16	63	-	-	75	240.6	9.071	14.188
638-S17	63	-	-	290	316.5	5.595	10.721
638-S07	63	400	10000	-197	26.0	15.975	16.492
636-C04	63	400	9980	-196	42.0	16.179	19.694
638-S08	63	400	10000	-50	75.8	12.645	15.565
638-S11	63	400	10000	0	112.7	11.014	16.365
636-S09	63	400	9980	25	135.2	9.915	15.835
636-S08	63	400	9980	25	130.7	9.897	16.760
636-S07	63	400	9980	25	123.5	10.480	15.770
638-S09	63	400	10000	75	183.1	8.524	15.154
638-S12	63	400	10000	175	173.1	6.816	12.625
638-S10	63	400	10000	290	124.6	6.601	11.581
631-S07	63	-	Annealed	-125	213.1	12.860	20.886
631-S08	63	-	Annealed	25	271.9	9.298	14.920
631-S09	63	-	Annealed	290	234.9	5.331	10.663
643-S15	64	-	-	-196	74.2	19.572	21.541
646-S15	64	-	-	-196	90.6	18.880	25.636
648-S09	64	-	-	-125	220.1	15.740	24.587
648-S08	64	-	-	-100	230.0	15.916	23.474
648-S07	64	-	-	-75	230.8	15.711	22.976
648-S06	64	-	-	-50	226.4	14.012	20.906
648-S05	64	-	-	-20	225.4	13.299	19.763
648-S04	64	-	-	0	198.4	12.645	18.465
646-S14	64	-	-	25	187.7	11.620	17.441

Table A-3. (Contd.)

Specimen ID	Heat	Aging Temp (°C)	Aging Time (h)	Test Temp (°C)	Impact Energy (J/cm²)	Yield Load (kN)	Max. Load (kN)
643-S13	64	–	–	25	165.5	11.326	17.238
646-S13	64	–	–	25	220.5	0.000	0.000
643-S14	64	–	–	25	225.4	11.644	18.345
645-C09	64	–	–	25	62.6	10.391	15.753
648-S10	64	–	–	75	241.0	10.409	16.180
648-S11	64	–	–	290	206.9	6.835	11.766
646-C04	64	400	9980	-196	9.6	16.364	16.378
648-S14	64	400	[illegible]00	-120	12.5	15.340	15.340
647-C07	64	400	10000	-50	37.6	15.330	17.77[illegible]
646-S07	64	400	9980	25	47.5	14.271	17.474
646-S09	64	400	9980	25	57.0	14.640	17.557
646-S08	64	400	9980	25	50.1	14.240	17.140
647-C08	64	400	10000	75	54.0	11.835	14.305
647-C09	64	400	10000	125	92.3	10.468	16.180
648-S15	64	400	10000	200	101.0	9.618	14.969
648-S13	64	400	10000	290	104.6	9.003	14.266
641-S07	64	–	Annealed	-197	135.2	17.898	25.856
641-S08	64	–	Annealed	-125	204.0	14.852	23.952
641-S09	64	–	Annealed	-75	215.4	15.242	23.249
648-S16	64	–	Annealed	25	226.2	12.040	18.650
648-S17	64	–	Annealed	125	217.7	9.530	15.496
648-S18	64	–	Annealed	290	189.3	6.708	11.971
656-S15	65	–	–	-196	99.6	20.464	26.942
653-S15	65	–	–	-196	69.3	20.340	22.247
656-C04	65	–	–	-125	231.8	15.887	25.095
657-C09	65	–	–	-100	206.5	15.301	23.132
657-C07	65	–	–	-75	188.7	14.793	21.677
658-S06	65	–	–	-50	243.4	14.276	20.750
658-S05	65	–	–	-20	227.7	13.390	18.784
658-S04	65	–	–	0	246.3	12.787	18.787
653-S14	65	–	–	25	238.5	11.245	18.247
656-S13	65	–	–	25	226.1	11.829	17.632
656-S14	65	–	–	25	222.5	11.554	18.139
653-S13	65	–	–	25	199.1	12.247	18.151
656-C06	65	–	–	75	211.4	10.497	16.326
657-C03	65	–	–	290	183.8	6.845	12.010
658-S10	65	400	10000	-197	13.6	17.801	17.801
658-S15	65	400	10000	-120	15.4	13.983	13.983
658-S11	65	400	10000	-50	28.9	14.920	15.047
658-S16	65	400	10000	-20	42.1	14.080	15.604
656-S08	65	400	9980	25	79.7	13.631	18.184
656-S07	65	400	9980	25	49.4	13.616	16.580
656-S09	65	400	9980	25	56.4	14.[illegible]80	17.682
658-S11	65	400	10000	75	80.2	11.141	15.799
658-S13	65	400	10000	125	101.4	10.487	15.955
658-S17	65	400	10000	175	119.9	9.079	15.916
658-S18	65	400	10000	225	131.1	9.061	14.998
658-S14	65	400	10000	290	130.2	8.310	14.383
656-C01	65	–	Annealed	-197	138.2	19.119	26.589
656-C02	65	–	Annealed	-125	146.4	16.043	23.689
656-C03	65	–	Annealed	-75	200.7	14.598	22.204
658-S07	65	–	Annealed	25	263.6	11.942	18.328
658-S08	65	–	Annealed	125	232.6	8.281	14.989
658-S09	65	–	Annealed	290	154.7	6.982	12.245

Table A-4. Charpy-impact test results on the reembrittlement of recovery-annealed cast stainless steels. All samples were originally aged for 10,000 h at 400°C and then annealed for 1 h at 550°C and water quenched.

Specimen ID	Heat	Aging Temp. (°C)	Aging Time (h)	Test Temp. (°C)	Impact Energy (J/cm²)	Yield Load (kN)	Max. Load (kN)
683-55A	68		Annealed	-197	70.0	15.838	19.607
684-52A	68		Annealed	-100	169.6	14.276	21.472
683-54A	68		Annealed	-50	155.3	12.977	20.994
684-53A	68		Annealed	-10	253.3	11.893	18.572
683-53A	68		Annealed	25	237.4	10.946	16.785
683-52A	68		Annealed	125	345.0	9.267	14.451
684-54A	68		Annealed	200	212.7	8.144	12.85
683-51A	68		Annealed	290	220.5	7.382	11.883
68-317A	68	320	3000	25	214.5	10.770	16.024
68-318A	68	320	3000	25	184.3	10.926	17.322
68-319A	68	320	10000	25	157.3	12.010	18.455
68-320A	68	320	10000	25	208.0	11.893	18.211
68-308A	68	350	100	25	236.1	11.327	17.683
68-309A	68	350	300	25	230.9	11.112	17.020
68-310A	68	350	300	25	280.8	11.883	17.615
68-311A	68	350	1000	25	160.8	10.946	17.273
68-312A	68	350	1000	25	166.4	10.800	17.527
68-313A	68	350	3000	25	84.1	11.063	14.578
68-314A	68	350	3000	25	65.6	11.239	14.061
68-315A	68	350	10000	25	55.2	12.782	15.008
68-316A	68	350	10000	25	71.1	12.352	16.063
684-58A	68	400	50	25	213.7	11.278	16.941
684-59A	68	400	50	25	179.0	11.249	16.600
68-301A	68	400	100	25	211.5	12.059	17.683
684-60A	68	400	100	25	186.0	11.756	17.635
68-302A	68	400	300	25	175.9	12.352	18.611
68-303A	68	400	300	25	199.7	11.835	18.347
68-304A	68	400	1000	25	126.5	11.903	17.254
68-305A	68	400	1000	25	103.9	12.791	16.287
68-306A	68	400	3000	25	73.7	11.678	14.803
68-307A	68	400	3000	25	78.5	11.962	14.783
683-56A	68	400	10000	-197	12.1	13.358	13.358
684-55A	68	400	10000	-120	28.0	16.277	16.277
683-57A	68	400	10000	-50	32.3	14.051	14.325
681-59A	68	400	10000	25	82.6	13.368	16.063
682-59A	68	400	10000	25	66.7	12.811	15.164
683-58A	68	400	10000	75	82.2	10.800	15.076
683-59A	68	400	10000	290	129.8	7.597	12.284
693-55A	69		Annealed	-197	194.1	11.249	25.251
694-51A	69		Annealed	-120	242.7	10.966	23.474
694-52A	69		Annealed	-100	258.5	11.219	22.800
693-54A	69		Annealed	-50	248.4	11.200	20.789
694-53A	69		Annealed	-10	249.9	10.780	18.865
693-53A	69		Annealed	25	253.5	9.833	17.283
694-54A	69		Annealed	75	230.3	8.886	14.588
693-52A	69		Annealed	125	373.5	7.636	13.612
694-55A	69		Annealed	200	246.6	7.187	12.323
693-51A	69		Annealed	290	218.1	6.308	11.239
69-305A	69	320	1000	25	244.7	9.939	17.088
69-206A	69	320	1000	25	270.7	10.223	17.391
69-307A	69	320	3000	25	271.8	10.175	17.469
69-308A	69	320	3000	25	258.2	10.487	17.723
69-309A	69	320	10000	75	289.4	11.132	18.699
69-310A	69	320	10000	25	231.5	10.741	18.015
69-318A	69	350	100	25	261.8	10.516	17.498
692-56A	69	350	100	25	235.3	10.145	16.688

Table A-4. (Cont'd.).

Specimen ID	Heat	Aging Temp. [°C]	Aging Time [h]	Test Temp. [°C]	Impact Energy [J/cm²]	Yield Load [kN]	Max. Load [kN]
69-319A	69	350	300	25	248.2	10.175	17.186
692-57A	69	350	300	25	234.3	10.194	17.879
69-301A	69	330	1000	25	212.2	10.487	17.996
692-59A	69	350	1000	25	219.2	10.380	17.332
69-320A	69	350	3000	25	229.0	10.477	18.230
692-58A	69	350	3000	25	203.8	10.272	17.225
69-303A	69	350	10000	25	143.4	10.780	17.723
69-304A	69	350	10000	25	168.3	11.053	18.004
69-311A	69	400	50	25	232.2	10.136	17.459
691-56A	69	400	50	25	228.2	10.526	17.361
69-314A	69	400	100	25	236.5	10.438	18.133
691-59A	69	400	100	25	230.6	10.946	18.035
69-312A	69	400	300	25	248.9	10.682	18.523
691-57A	69	400	300	25	180.2	10.751	17.625
69-313A	69	400	1000	25	167.8	10.946	18.338
691-58A	69	400	1000	25	129.9	10.839	17.273
69-316A	69	400	3000	25	138.5	10.555	17.410
691-60A	69	400	3000	25	155.3	11.464	17.459
691-54A	69	400	10000	-197	39.3	12.831	17.498
692-51A	69	400	10000	-120	118.5	11.171	19.343
691-55A	69	400	10000	-50	109.9	13.690	19.900
693-60A	69	400	10000	25	103.7	11.571	17.635
694-60A	69	400	10000	25	130.2	11.874	17.508
692-52A	69	400	10000	75	161.9	8.095	14.364
692-53A	69	400	10000	290	129.6	7.528	12.635
754-57A	75		Annealed	-197	86.6	18.142	24.128
754-60A	75		Annealed	-197	103.8	18.601	25.300
754-58A	75		Annealed	-120	205.2	16.717	25.192
754-59A	75		Annealed	-100	174.8	16.453	24.987
753-60A	75		Annealed	-50	198.0	13.631	21.003
753-59A	75		Annealed	25	228.3	12.264	18.865
753-58A	75		Annealed	125	186.7	10.116	15.770
753-57A	75		Annealed	290	201.5	8.134	13.524
754-52A	75	320	3000	25	184.8	12.821	18.953
754-53A	75	320	3000	25	209.2	12.411	18.709
754-54A	75	320	10000	25	185.4	13.153	19.832
754-55A	75	320	10000	25	170.1	14.041	18.738
752-59A	75	350	300	25	234.1	13.133	19.822
752-60A	75	350	300	25	244.8	13.084	20.007
753-51A	75	350	1000	25	182.8	13.182	19.675
753-52A	75	350	1000	25	180.6	13.17[illegible]	19.226
753-53A	75	350	3000	25	115.9	13.426	18.416
753-54A	75	350	3000	25	122.8	13.270	19.343
753-55A	75	350	10000	25	82.4	14.705	19.500
754-51A	75	350	10000	25	33.7	15.467	15.789
751-56A	75	400	100	25	227.0	13.250	20.525
751-57A	75	400	100	25	223.9	12.80[illegible]	19.666
751-58A	75	400	300	25	208.0	13.573	20.955
751-59A	75	400	300	25	189.8	13.553	20.369
751-60A	75	400	1000	25	86.2	13.553	17.683
752-56A	75	400	1000	25	68.3	13.700	16.502
752-57A	75	400	3000	25	57.3	13.827	16.756
752-58A	75	400	3000	25	70.0	13.963	17.098
75-301A	75	400	10000	-197	9.1	15.330	15.330
75-302A	75	400	10000	-50	30.7	16.277	16.277
75-365A	75	400	10000	25	43.4	14.871	16.531
75-366A	75	400	10000	25	37.7	15.330	16.980
75-303A	75	400	10000	75	62.4	13.211	16.404
75-304A	75	400	10000	290	95.4	9.970	14.334

Appendix B

Tensile Properties

Tensile tests were conducted at Materials Engineering Associates (MEA) and at Argonne National Laboratory (ANL). Details of the test procedure and results for the tests at MEA have been presented earlier.[B-1,B-2] Tests at ANL were performed according to ASTM Specification E 8 and E 21 in an Instron tensile test machine with a maxin ,n loading capacity of 90 kN (20 kips). Cylindrical specimens with a diameter of 5.08 mm (0.2 in.) and a gauge length of 20.3 mm (0.8 in.) were used for all the tests. An axial extensometer, with an initial gauge length of 20.3 mm (0.8 in.), was used for continuous measurem of strain during room temperatur tests. An IBM computer was used to digitize load, crosshead movement, and axial displacement data and store it on floppy disks. Analog traces of load-vs.-crosshead displacement and load-vs.-extensometer displacement were also obtained for each test.

The true stress-strain data were calculated up to the maximum load using the constant-volume criterion, which assumes a homogeneous distribution of strain along the gauge length. However, most specimens showed inhomogeneous deformation because of the relatively large grain structure. The specimen surfaces along the gauge length were irregular, and the fracture cross sections were often elliptical. These factors create some uncertainty in the true stress-strain data. The true fracture stress was obtained from the fracture load and cross sectional area at fracture. The strain at fracture, i.e., total elongation, was determined from extensometer displacements. Total elongation was also measured from crosshead displacements; the values obtained from extensometer were ≈64% of the values determined from crosshead displacement. Correlations between crosshead displacement and total strain in the specimen gauge length were also developed from the room temperature tests. These correlations were used to correct the data for the elevated temperature tests.

The tests at 290°C (~550°F) were conducted in a forced-air recirculating furnace. Thermocouples were mounted above and below the specimen gauge length to monitor and control the temperature within ±2°C. For the tests on samples aged for <10,000 h, an axial extensometer was not used for the elevated temperature tests. Total strain in the specimen gauge length was determined from correlations developed from the room temperature tests. The total elongation was determined from the crosshead displacement multiplied by 0.64.

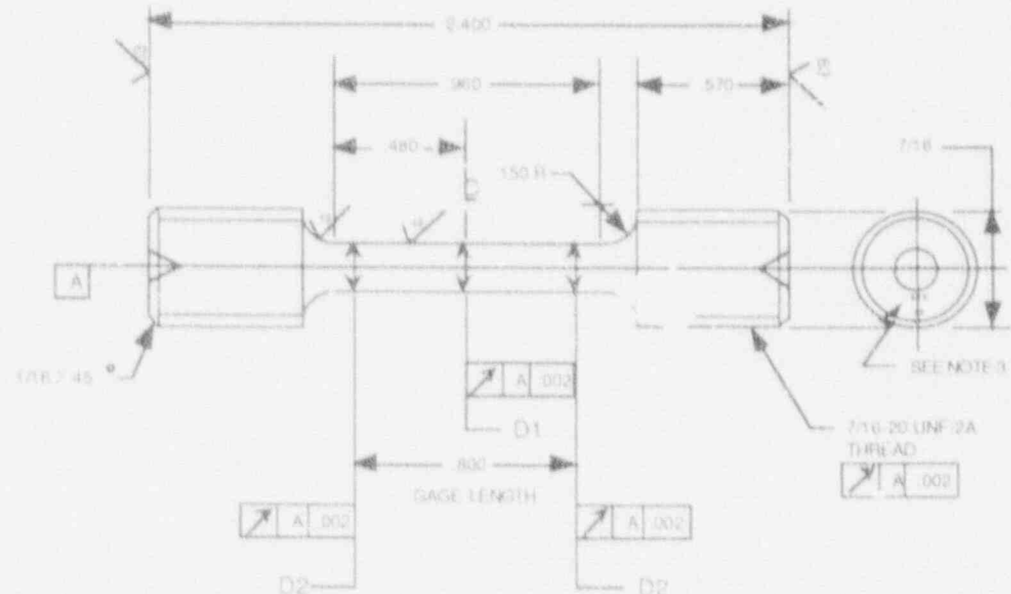
Elevated temperature tests on the long-term aged samples were conducted with a clip gauge mounted on the specimen grips. Total strain in the specimen gauge length was determined from correlations developed from room-temperature tests conducted with both clip gauge attached to the specimen grips and extensometer mounted on the specimen gauge length.

The results for 10 commercial and xperimental heats ag 1 up to 58,000 h at temperatures between 290 and 450°C are given in Table B-1; re from the tests at MEA are also included in the table.

References

B-1. A. L. Hiser, *Compilation of Tensile and J-R Curve Data from Thermally-Aged Stainless Steel*, MEA-2239, Vols. I-III, Materials Engineering Associates, Inc. (October 1987).

B-2. A. L. Hiser, *Tensile and J-R Curve Characterization of Thermally Aged Cast Stainless Steels*, NUREG/CR-502-, MEA-2229, Materials Engineering Associates, Inc. (September 1988).



D1 = .200 ±.001
D2 = FROM .001 TO .002 + D1
TOLERANCES = ± .005 UNLESS NOTED

1. THE .800 INCH GAGE LENGTH TO HAVE UNIFORM SLOPE FROM MAX. DIA. D2 TO MIN. DIA. D1. UNIFORM SLOPE MUST NOT EXCEED .004 CHANGE IN DIA. PER 1 INCH CHANGE IN LENGTH.
2. ALL RADII MUST BLEND WITHOUT UNDERCUTS OR STEPS.
3. DIMENSIONS AND SPECIFICATIONS TYPICAL BOTH ENDS.
4. ALL SURFACES TO BE FREE OF BURRS.

Figure B-1. Configuration of tensile test specimen

Table B-1. Tensile test results for cast stainless steels

Specimen Number	Orientation[a]	Heat	Test Temp. (°C)	Engineering 0.2% Yield Stress (MPa)	Engineering Ultimate Stress (MPa)	Fracture Stress (MPa)	Elongation (%)	Red. in Area (%)	Aging Condition Temp. (°C)	Aging Condition Time (h)	Ref.[b]
					CF-3 Grade						
11V-01	L	1	25	264.8	508.8	1636.6	84.6	79.3	Unaged		2
11V-02	L	1	25	242.1	583.4	1698.5	78.4	79.5	Unaged		2
12V-01	L	1	25	251.0	579.9	1274.6	77.4	74.3	Unaged		2
12V-02	L	1	25	257.7	578.1	1671.8	75.0	80.2	Unaged		2
13C-01	L	1	25	239.7	517.6	1274.8	66.2	69.5	Unaged		2
12V-23	L	1	25	235.8	637.3	1387.7	72.5	66.7	320	30000	1
13C-14	L	1	25	278.2	633.9	1411.7	56.9	68.2	320	30000	1
13V-38	L	1	25	255.0	609.6	1432.6	56.6	68.5	320	30000	1
13V-39	L	1	25	282.5	452.7	858.8	12.7	50.5	320	30000	1
11V-26	L	1	25	281.3	61[illegible]	1897.6	60.6	77.4	350	10000	2
11V-27	L	1	25	303.4	644.7	1445.0	–	62.2	350	10000	2
12V-19	L	1	25	314.7	642.0	1296.9	72.0	68.4	350	10000	2
12V-03	L	1	290	169.2	409.2	756.1	–	58.9	Unaged		2
12V-06	L	1	290	178.5	402.4	837.8	39.4	64.6	Unaged		2
13C-02	L	1	290	158.6	387.3	819.5	33.0	66.2	Unaged		2
12V-24	L	1	290	178.6	445.9	710.7	28.9	57.2	320	30000	1
13C-15	L	1	290	163.6	427.2	810.4	27.9	67.2	320	30000	1
13V-40	L	1	290	–	470.5	828.9	18.5	54.7	320	30000	1
11V-28	L	1	290	192.4	381.1	503.0	–	36.0	350	10000	2
11V-29	L	1	290	189.0	442.8	780.5	34.2	59.7	350	10000	2
12V-20	L	1	290	179.1	437.8	756.0	39.0	51.6	350	10000	2
P21T-01	C	P2	25	216.3	538.3	1000.4	72.6	59.9	Unaged		2
P23T-01	C	P2	25	238.1	556.8	1568.6	106.0	84.4	Unaged		2
P22A-01	L	P2	25	206.4	561.7	1094.5	73.7	75.7	Unaged		2
P23A-01	L	P2	25	216.7	536.9	887.4	62.4	75.1	Unaged		2
P22T-16	C	P2	25	247.0	580.1	1547.8	65.4	79.9	290	30000	1
P21A-31	L	P2	25	242.6	571.1	2017.1	65.9	84.7	290	30000	1
P25A-28	L	P2	25	223.9	548.3	1797.3	57.2	87.0	290	30000	1
P21A-36	L	P2	25	263.6	583.8	1564.4	58.3	79.3	290	58000	1
P24T-14	C	P2	25	229.4	600.0	1944.4	73.1	82.3	320	30000	1
P25T-10	C	P2	25	258.1	581.8	1535.3	55.4	75.5	320	30000	1
P22A-36	L	P2	25	237.4	603.0	1487.0	77.8	80.5	320	30000	1
P21A-19	L	P2	25	249.7	605.2	1673.6	49.4	78.3	320	55000	1
P22T-04	C	P2	25	252.3	601.8	2162.5	–	85.3	350	10000	2
P23A-14	L	P2	25	249.2	594.3	2783.2	73.6	88.5	350	10000	2
P23A-26	L	P2	25	265.2	608.5	1830.3	76.6	78.8	350	10000	2
P22T-11	C	P2	25	249.3	628.4	1235.0	68.6	64.4	350	30000	1
P22A-13	L	P2	25	245.5	615.4	1598.5	65.5	76.2	350	30000	1
P24A-32	L	P2	25	225.4	617.2	1799.8	68.9	79.0	350	30000	1
P24T-05	C	P2	25	233.5	603.1	1268.2	–	68.8	400	10000	2
P24A-04	L	P2	25	236.2	616.8	2384.5	–	78.0	400	10000	2
P21T-02	C	P2	290	161.3	387.1	819.1	44.6	72.2	Unaged		2
P23T-02	C	P2	290	154.2	405.0	688.2	42.4	65.9	Unaged		2
P22A-02	L	P2	290	137.9	406.9	755.7	47.2	65.9	Unaged		2
P23A-02	L	P2	290	144.0	385.1	538.7	39.9	59.6	Unaged		2
P21A-32	L	P2	290	162.3	403.4	830.6	36.8	74.5	290	30000	1
P21A-33	L	P2	290	155.2	405.9	740.8	35.0	73.7	290	30000	1
P24T-16	C	P2	290	148.2	407.0	389.5	39.9	78.7	290	30000	1
P21A-37	L	P2	290	164.2	410.7	1152.1	33.1	72.2	290	58000	1
P22T-17	C	P2	290	177.5	422.7	1094.7	37.9	72.3	290	58000	1
P21A-14	L	P2	290	153.2	428.9	968.4	31.4	73.0	320	30000	1
P21A-15	L	P2	290	163.9	422.7	815.5	30.9	62.9	320	30000	1
P21A-16	L	P2	290	152.6	407.7	870.6	28.8	71.9	320	30000	1
P25T-12	C	P2	290	171.4	418.4	790.5	31.5	62.5	320	55000	1
P21A-18	L	P2	290	168.6	416.4	980.1	31.2	67.9	320	55000	1

Table B-1. (Contd.)

Specimen Number	Orientation[a]	Heat	Test Temp. (°C)	Engineering 0.2% Yield Stress (MPa)	Engineering Ultimate Stress (MPa)	Fracture Stress (MPa)	Elongation (%)	Red. in Area (%)	Aging Condition Temp. (°C)	Aging Condition Time (h)	Ref.[b]
P21T-08	C	P2	290	155.6	423.5	876.3	49.8	70.7	350	10000	2
P22T-05	C	P2	290	153.8	399.0	696.5	43.0	66.9	350	10000	2
P23A-15	L	P2	290	161.0	415.4	900.5	–	69.7	350	10000	2
P23A-27	L	P2	290	154.1	419.4	970.7	39.6	72.9	350	10000	2
P22T-12	C	P2	290	167.0	436.2	740.2	28.2	56.0	350	30000	1
P24A-30	L	P2	290	142.4	432.1	828.0	38.5	60.9	350	30000	1
P24A-33	L	P2	290	149.1	425.7	463.7	41.5	62.6	350	30000	1
P24T-06	C	P2	290	160.4	447.1	818.5	40.2	56.4	400	10000	2
P24A-05	L	P2	290	146.6	430.6	655.0	40.2	53.8	400	10000	2
693-40	H	69	25	278.8	606.0	1070.1	57.1	48.9	Unaged		2
693-41	H	69	25	273.4	585.6	1093.4	54.1	54.4	Unaged		2
694-30	H	69	25	253.6	592.7	1430.6	50.1	71.8	290	30000	1
694-31	H	69	25	264.1	588.9	1714.0	51.1	76.4	290	30000	1
69-135	V	69	25	244.7	600.6	1617.5	62.8	74.5	290	30000	1
694-21	H	69	25	286.7	624.6	1757.0	52.2	76.1	320	10000	1
694-25	H	69	25	232.1	585.4	1428.3	70.5	75.2	320	10000	1
692-40	H	69	25	289.6	622.0	1516.1	43.6	72.3	320	30000	1
692-41	H	69	25	269.4	604.4	1623.8	38.0	75.2	320	30000	1
69-245	V	69	25	272.5	485.8	–	12.9	25.4	320	30000	1
691-28	H	69	25	291.6	637.9	1484.8	45.7	69.2	320	50000	1
691-29	H	69	25	287.7	650.5	1604.0	50.3	71.7	320	50000	1
69-230	V	69	25	298.8	669.4	1713.1	53.5	71.8	320	50000	1
692-25	H	69	25	285.4	633.4	1483.2	67.7	76.2	350	2570	2
692-26	H	69	25	302.6	648.2	1364.3	62.5	72.4	350	2570	2
694-06	H	69	25	292.1	652.0	1902.3	54.2	76.0	350	10000	1
694-07	H	69	25	266.2	635.5	1480.4	53.5	71.6	350	10000	1
694-08	H	69	25	246.8	619.9	1564.4	54.7	72.7	350	10000	1
69-119	V	69	25	249.6	617.3	1811.6	51.6	78.4	350	10000	1
693-12	H	69	25	270.9	674.0	1795.8	50.6	71.4	350	30000	1
693-13	H	69	25	259.2	655.1	1665.4	49.0	68.9	350	30000	1
69-130	V	69	25	258.4	661.2	1936.1	55.3	74.8	350	30000	1
692-16	H	69	25	253.6	638.8	1358.9	52.4	72.4	400	2570	2
692-17	H	69	25	300.9	683.2	1309.9	44.3	60.6	400	2570	2
692-15	H	69	25	287.8	673.9	1409.6	43.6	56.8	400	10000	1
692-22	H	69	25	278.6	699.1	1727.1	51.2	68.3	400	10000	1
692-23	H	69	25	260.5	664.7	1653.4	53.3	72.0	400	10000	1
69-109	V	69	25	276.7	688.0	1796.6	65.7	73.5	400	10000	1
691-04	H	69	25	271.3	691.9	1476.9	36.5	71.4	450	2570	2
691-05	H	69	25	263.1	664.6	1528.2	56.6	73.2	450	2570	2
693-42	H	69	290	190.8	420.9	908.2	35.9	63.4	Unaged		2
694-40	H	69	290	177.0	417.0	809.0	33.6	59.7	Unaged		2
694-32	H	69	290	176.8	401.9	422.9	29.4	67.0	290	30000	1
694-33	H	69	290	173.0	386.7	543.7	21.5	51.3	290	30000	1
69-236	V	69	290	194.1	440.5	818.0	30.8	61.9	290	30000	1
694-26	H	69	290	174.4	408.7	697.5	21.8	60.5	320	10000	1
694-27	H	69	290	183.5	422.8	973.7	20.9	65.3	320	10000	1
692-42	H	69	290	178.5	423.2	709.8	21.6	55.0	320	30000	1
694-39	H	69	290	168.2	413.8	692.4	21.3	51.7	320	30000	1
69-246	V	69	290	165.5	423.0	921.8	27.8	70.6	320	30000	1
692-28	H	69	290	209.1	462.5	895.8	28.1	59.8	320	55000	1
692-29	H	69	290	212.3	464.4	911.6	27.9	58.5	320	55000	1
69-130	V	69	290	204.7	468.0	733.1	29.1	52.8	320	55000	1
692-27	H	69	290	173.1	451.3	752.6	32.3	53.8	350	2570	2
694-09	H	69	290	156.4	413.1	720.9	29.8	52.7	350	10000	1
69-120	V	69	290	179.8	429.8	875.1	23.2	68.8	350	10000	1

Table B-1. (Contd.)

Specimen Number	Orientation[a]	Heat	Test Temp. (°C)	Engineering: 0.2% Yield Stress (MPa)	Engineering: Ultimate Stress (MPa)	Fracture Stress (MPa)	Elongation (%)	Red. in Area (%)	Aging Conditions: Temp. (°C)	Aging Conditions: Time (h)	Ref.[b]
693-14	H	69	290	186.4	457.6	832.1	28.0	58.0	350	30000	1
693-15	H	69	290	195.8	444.0	639.2	32.5	46.9	350	30000	1
69-270	V	69	290	193.6	462.4	739.4	27.7	49.4	350	30000	1
692-18	H	69	290	163.9	444.8	556.4	21.8	33.2	400	2570	2
692-24	H	69	290	173.3	494.5	785.1	23.4	44.8	400	10000	1
69-110	V	69	290	196.9	481.6	802.3	26.1	51.5	400	10000	1
691-06	H	69	290	177.7	479.7	683.6	28.5	44.9	450	2570	2
692-09	H	69	290	175.7	477.1	793.4	27.4	51.0	450	2570	2
					CF-8 Grade						
18-11	C	KRB	25	306.2	554.9	1348.9	56.8	67.0	280	68000	1
18-12	C	KRB	25	288.5	555.9	1426.1	35.0	70.2	280	68000	1
18-22	C	KRB	25	291.9	568.9	1162.3	40.4	59.2	280	68000	1
13-12	C	KRB	25	317.3	567.4	1285.7	57.4	67.7	Reannealed		1
13-21	C	KRB	25	289.2	575.2	1209.1	43.4	67.0	Reannealed		1
13-22	C	KRB	25	287.7	531.2	1370.6	44.0	69.5	Reannealed		1
15-11	C	KRB	290	214.0	469.0	924.1	33.4	62.4	280	68000	1
15-12	C	KRB	290	208.4	444.5	774.1	28.9	51.1	280	68000	1
15-21	C	KRB	290	199.6	482.5	842.1	38.3	53.3	280	68000	1
15-22	C	KRB	290	180.2	434.0	710.1	35.7	51.1	280	68000	1
16-21	C	KRB	290	184.0	405.0	605.4	25.9	41.5	Reannealed		1
17-21	C	KRB	290	171.5	416.2	875.3	42.1	66.3	Reannealed		1
P13T-01	C	P1	25	244.7	584.5	1221.5	56.5	68.8	Unaged		2
P13T-03	C	P1	25	245.9	579.9	1206.6	54.6	65.9	Unaged		2
P11A-01	L	P1	25	-	584.9	1127.0	57.7	64.0	Unaged		2
P13A-01	L	P1	25	248.5	584.5	1579.5	62.4	72.9	Unaged		2
P14T-09	C	P1	25	266.2	596.2	1561.8	74.6	74.4	290	30000	1
P11A-25	L	P1	25	285.7	595.2	1660.1	70.2	71.7	290	30000	1
P14A-26	L	P1	25	276.5	[illegible]	993.2	42.7	61.6	290	30000	1
P11A-28	L	P1	25	263.5	[illegible]	1915.5	68.1	78.3	290	58000	1
P11A-29	L	P1	25	266.1	562.0	415.05	63.5	51.9	290	58000	1
P11A-10	L	P1	25	279.1	622.6	1625.9	62.5	70.7	320	30000	1
P11T-06	C	P1	25	-	569.3	1676.7	48.1	79.6	320	30000	1
P14T-08	C	P1	25	-	-	-	47.7	78.3	320	30000	1
P11A-13	L	P1	25	299.0	646.8	1100.7	61.3	53.1	320	55000	1
P12A-25	L	P1	25	287.6	688.3	1463.6	60.9	60.3	320	55000	1
P12T-05	C	P1	25	276.8	610.8	1315.5	67.2	58.9	350	10000	2
P12T-06	C	P1	25	263.4	608.7	864.7	87.2	76.1	350	10000	2
P12A-08	L	P1	25	290.5	652.9	1625.9	-	75.2	350	10000	2
P12A-09	L	P1	25	271.2	618.0	2322.0	-	80.2	350	10000	2
P12T-11	C	P1	25	266.6	617.0	1240.0	47.7	61.0	350	30000	1
P12A-13	L	P1	25	285.0	637.0	1068.7	67.8	55.8	350	30000	1
P12A-14	L	P1	25	263.5	634.9	1648.8	44.1	70.3	350	30000	1
P13T-07	C	P1	25	285.0	660.0	1351.8	46.8	55.8	400	10000	2
P13A-07	L	P1	25	286.3	677.7	1429.8	68.6	56.4	400	10000	2
P13T-02	C	P1	290	148.5	408.8	642.2	33.3	43.9	Unaged		2
P14T-01	C	P1	290	157.0	437.5	622.3	32.6	46.4	Unaged		2
P11A-02	L	P1	290	159.9	442.7	497.0	35.5	36.7	Unaged		2
P13A-02	L	P1	290	155.0	424.4	850.8	43.0	67.2	Unaged		2
P14T-10	C	P1	290	166.1	415.3	769.1	35.4	64.0	290	30000	1
P11A-26	L	P1	290	160.3	394.6	605.7	51.3	73.6	290	30000	1
P14A-27	L	P1	290	167.8	421.6	812.5	29.4	60.1	290	30000	1
P11A-27	L	P1	290	167.1	388.4	843.0	34.8	60.1	290	58000	1
P11A-30	L	P1	290	179.3	445.5	683.6	39.5	46.6	290	58000	1
P11A-09	L	P1	290	175.5	435.1	934.6	29.4	59.1	320	30000	1
P12A-19	L	P1	290	174.8	456.9	731.1	27.4	51.6	320	30000	1
P12A-22	L	P1	290	175.4	418.7	629.7	24.5	46.6	320	30000	1

Table B-1. (Contd.)

Specimen Number	Orientation[a]	Heat	Test Temp. (°C)	Engineering 0.2% Yield Stress (MPa)	Engineering Ultimate Stress (MPa)	Fracture Stress (MPa)	Elongation (%)	Red. in Area (%)	Aging Condition Temp. (°C)	Aging Condition Time (h)	Ref.[b]
P11A-12	L	P1	290	188.2	424.8	865.0	39.5	56.6	320	55000	1
P12A-26	L	P1	290	200.4	472.0	951.8	31.0	58.3	320	55000	1
P12T-08	C	P1	290	180.2	454.2	981.5	-	63.4	350	10000	2
P12A-10	L	P1	290	173.7	451.3	919.6	43.4	62.8	350	10000	2
P12A-11	L	P1	290	180.7	457.7	823.2	42.4	55.8	350	10000	2
P12T-12	C	P1	290	194.9	472.7	786.5	24.8	58.0	350	30000	1
P14A-22	L	P1	290	185.3	462.3	719.2	25.3	44.5	350	30000	1
P14A-23	L	P1	290	198.6	475.6	735.1	25.1	42.0	350	30000	1
P13T-08	C	P1	290	167.3	502.2	791.0	-	49.6	400	10000	2
P13A-08	L	P1	290	162.9	485.6	881.0	35.6	51.0	400	10000	2
683-40	H	68	25	274.1	530.0	996.8	45.4	53.4	Unaged		2
683-41	H	68	25	279.4	517.2	811.9	36.4	49.2	Unaged		2
683-33	H	68	25	263.1	502.3	2242.4	55.7	83.2	290	30000	1
684-31	H	68	25	269.2	531.6	2050.9	42.3	79.7	290	30000	1
68-145	V	68	25	278.0	566.4	1903.0	42.1	78.9	290	30000	1
684-21	H	68	25	304.5	614.1	1291.8	67.8	61.9	320	10000	1
684-22	H	68	25	281.0	571.2	1880.1	76.6	80.7	320	10000	1
682-41	H	68	25	305.7	621.0	1544.6	40.8	71.2	320	30000	1
684-39	H	68	25	[illegible]	614.[illegible]	1716.[illegible]	43.4	75.4	320	30000	1
68-264	V	68	25	296.2	572.5	1903.8	65.3	75.6	320	30000	1
681-28	H	68	25	326.9	640.3	1130.7	51.0	66.6	320	50000	1
681-29	H	68	25	303.7	608.4	1666.1	50.7	71.1	320	50000	1
68-2[illegible]0	V	68	25	294.3	578.9	1696.8	47.0	75.8	320	50000	1
682-25	H	68	25	281.5	601.6	1647.2	64.1	75.2	350	5780	2
682-26	H	68	25	294.8	599.4	1620.7	62.0	73.5	350	5780	2
684-06	H	68	25	264.5	606.5	2014.0	53.7	78.3	350	10000	1
684-07	H	68	25	299.7	601.1	1953.4	47.4	76.7	350	10000	1
684-08	H	68	25	296.8	612.0	2084.7	52.6	78.5	350	10000	1
68-129	V	68	25	287.6	595.8	1688.6	58.5	73.5	350	10000	1
684-10	H	68	25	299.0	652.8	2072.9	44.6	74.9	350	30000	1
684-11	H	68	25	281.1	628.2	1342.3	55.0	57.4	350	30000	1
68-139	V	68	25	287.4	639.0	2090.6	44.5	77.0	350	30000	1
682-16	H	68	25	294.1	657.8	1534.6	75.0	64.0	400	2570	2
682-17	H	68	25	289.8	629.5	1313.0	-	64.6	400	2570	2
682-15	H	68	25	313.4	641.0	1526.3	36.8	64.4	400	10000	1
682-22	H	68	25	299.3	650.4	1019.0	43.9	49.4	400	10000	1
682-23	H	68	25	306.0	657.4	941.5	31.8	42.2	400	10000	1
68-119	V	68	25	-	624.3	1926.8	44.0	72.9	400	10000	1
681-04	H	68	25	291.3	653.1	1030.9	41.5	38.7	450	2570	2
681-05	H	68	25	309.4	632.9	1447.0	-	68.7	450	2570	2
683-42	H	68	290	162.7	397.3	815.4	29.2	57.8	Unaged		2
684-40	H	68	290	156.4	412.3	792.0	37.9	60.6	Unaged		2
684-32	H	68	290	149.5	333.2	513.0	27.7	62.2	290	30000	1
684-33	H	68	290	155.0	399.6	784.0	43.8	62.6	290	30000	1
68-246	V	68	290	170.6	390.7	522.1	28.4	51.5	290	30000	1
684-23	H	68	290	173.4	416.6	1048.7	26.8	72.7	320	10000	1
684-24	H	68	290	164.4	442.8	869.9	32.6	58.2	320	10000	1
682-40	H	68	290	174.3	440.8	853.5	36.6	62.3	320	30000	1
682-42	H	68	290	176.9	451.6	788.3	38.1	59.6	320	30000	1
68-263	V	68	290	165.6	450.2	758.2	37.2	48.0	320	30000	1
682-28	H	68	290	203.3	479.0	1132.6	32.6	64.0	320	50000	1
682-29	H	68	290	205.3	485.6	824.2	41.4	47.1	320	50000	1
68-130	V	68	290	201.3	475.2	699.1	38.9	46.2	320	50000	1
682-27	H	68	290	185.1	452.4	826.3	41.7	57.8	350	5780	2
684-09	H	68	290	164.3	500	765.7	30.5	51.9	350	10000	1
68-130	V	68	290	168.9	447.2	765.4	27.0	49.9	350	10000	1

Table B-1. (Contd.)

Specimen Number	Orientation[a]	Heat	Test Temp. (°C)	Engineering 0.2% Yield Stress (MPa)	Engineering Ultimate Stress (MPa)	Fracture Stress (MPa)	Elongation (%)	Red. in Area (%)	Aging Condition Temp. (°C)	Aging Condition Time (h)	Ref.[b]
684-12	H	68	290	216.0	485.7	888.0	29.6	53.9	350	30000	1
684-15	H	68	290	190.4	427.3	671.2	25.3	41.7	350	30000	1
68-140	V	68	290	170.2	479.0	482.8	31.6	53.6	350	30000	1
682-18	H	68	290	161.3	463.1	711.3	32.1	47.1	400	2570	2
682-24	H	68	290	176.7	475.6	800.8	34.4	47.6	400	10000	1
68-120	V	68	290	193.9	484.4	734.0	27.8	37.1	400	10000	1
681-06	H	68	290	169.7	486.8	700.4	–	36.8	450	2570	2
682-09	H	68	290	191.6	503.8	769.0	35.5	42.6	450	2570	2
733-40	H	73	25	254.3	557.0	882.9	46.5	41.3	Unaged		1
733-41	H	73	25	249.5	530.8	988.8	54.9	55.1	Unaged		1
734-23	H	73	25	221.9	475.4	1835.0	62.7	78.0	320	10000	1
734-24	H	73	25	228.2	521.4	1675.1	72.3	78.0	320	10000	1
732-25	H	73	25	244.0	526.5	1453.0	57.3	74.2	350	2570	1
732-26	H	73	25	244.4	528.4	1109.6	45.5	65.4	350	2570	1
734-06	H	73	25	228.0	536.9	1885.1	53.5	78.0	350	10000	1
734-07	H	73	25	219.1	529.3	2005.0	67.1	79.0	350	10000	1
73-119	H	73	25	212.8	488.1	2084.8	50.8	83.0	350	10000	1
732-16	H	73	25	240.8	541.8	1390.9	59.5	72.4	400	2570	1
732-17	H	73	25	252.6	555.7	1419.0	56.1	72.1	400	2570	1
732-15	H	73	25	235.3	563.3	2183.2	58.5	79.2	400	10000	1
732-22	H	73	25	215.8	530.3	1298.3	58.4	63.6	400	10000	1
73-109	V	73	25	222.2	534.0	1719.7	69.0	74.4	400	10000	1
731-04	H	73	25	256.5	493.1	944.5	34.4	53.1	450	2570	1
731-05	H	73	25	234.0	570.4	1511.4	75.2	69.3	450	2570	1
733-42	H	73	290	138.9	366.6	970.1	40.5	75.8	Unaged		1
734-40	H	73	290	133.9	365.0	599.5	33.0	54.0	Unaged		1
734-19	H	73	290	130.4	354.0	426.4	33.6	33.8	320	10000	1
734-22	H	73	290	131.3	365.2	743.5	45.7	61.1	320	10000	1
732-27	H	73	290	139.6	419.8	833.9	44.3	62.0	350	2570	1
734-08	H	73	290	127.7	377.7	964.3	40.7	68.6	350	10000	1
734-09	H	73	290	165.0	417.5	725.9	28.9	53.3	350	10000	1
73-120	V	73	290	136.7	386.4	835.4	35.5	69.0	350	10000	1
732-18	H	73	290	–	444.1	700.7	38.0	59.3	400	2570	1
732-23	H	73	290	138.5	408.5	683.8	39.7	50.0	400	10000	
732-24	H	73	290	143.0	424.1	649.8	32.7	40.2	400	10000	
73-110	V	73	290	139.4	395.8	696.5	37.4	51.7	400	10000	
731-06	H	73	290	144.1	411.2	596.6	24.8	39.2	450	2570	1
732-09	H	73	290	136.2	436.1	730.6	43.6	51.2	450	2570	1
					CF-8M Grade						
205-26	L	205	25	248.5	670.6	1227.7	36.3	65.0	400	18000	1
205-27	L	205	25	254.0	642.4	1694.1	49.0	71.2	400	18000	1
205-30	L	205	25	248.7	646.1	1576.7	41.8	70.6	400	18000	1
205-25	L	205	290	179.4	505.9	744.1	23.6	44.6	400	18000	1
205-28	L	205	290	177.3	507.8	790.3	27.0	49.2	400	18000	1
205-29	L	205	290	168.2	495.1	700.7	24.6	44.2	400	18000	1
743-40	H	74	25	273.5	542.4	1356.5	–	65.4	Unaged		1
743-41	H	74	25	273.0	531.3	1362.7	63.0	68.3	Unaged		1
743-36	H	74	25	282.2	555.6	2157.5	42.5	53.2	290	30000	1
744-34	H	74	25	292.9	601.2	1509.6	38.1	7[illegible].1	290	30000	1
74-135	V	74	25	259.0	570.4	1832.2	55.6	77.6	290	30000	1
744-21	H	74	25	273.1	551.0	1848.3	49.9	78.1	320	10000	1
744-25	H	74	25	270.5	565.3	2107.4	69.9	80.8	320	10000	1
742-42	H	74	25	312.7	589.9	1418.6	10.2	66.4	320	30000	1
744-39	H	74	25	326.4	663.6	1400	[illegible]	63.6	320	30000	1
74-245	V	74	25	278.8	617.0	1579	[illegible]	76.7	320	30000	1

Table B-1. (Contd.)

Specimen Number	Orientation[a]	Heat	Test Temp. (°C)	Engineering 0.2% Yield Stress (MPa)	Engineering Ultimate Stress (MPa)	Fracture Stress (MPa)	Elongation (%)	Red. in Area (%)	Aging Condition Temp. (°C)	Aging Condition Time (h)	Ref.[b]
741-28	H	74	25	309.1	668.1	1056.7	42.2	52.7	320	50000	1
741-29	H	74	25	304.5	638.1	1506.5	48.3	62.9	320	50000	1
74-230	V	74	25	299.4	631.6	1623.1	47.1	68.7	320	50000	1
742-25	H	74	25	269.0	575.1	1380.5	58.9	68.1	3[illegible]	2570	1
742-26	H	74	25	261.0	536.8	1517.5	62.5	72.0	350	2570	1
744-07	H	74	25	281.7	606.1	1498.4	57.1	63.8	350	10000	1
744-08	H	74	25	278.2	619.2	1903.6	38.7	74.0	350	10000	1
74-119	V	74	25	267.5	587.8	2081.4	49.3	80.9	350	10000	1
743-13	H	74	25	265.8	647.2	1198.4	55.6	51.8	350	30000	1
743-14	H	74	25	260.3	613.5	1375.6	30.5	63.8	350	30000	1
74-130	V	74	25	272.3	624.8	1334.6	37.6	60.0	350	30000	1
742-16	H	74	25	268.6	602.3	1409.4	44.1	70.8	400	2570	1
742-17	H	74	25	267.7	579.7	1308.7	41.7	71.8	400	2570	1
742-22	H	74	25	269.8	626.3	991.8	40.7	69.1	400	10000	1
742-23	H	74	25	267.7	624.3	1170.2	46.4	72.6	400	10000	1
74-110	V	74	25	259.2	607.9	1429.6	38.5	69.6	400	10000	1
741-04	H	74	25	257.5	620.5	1294.5	43.5	60.5	450	2570	1
741-05	H	74	25	259.1	616.7	1176.2	58.8	52.9	450	2570	1
744-40	H	74	290	171.8	412.3	557.7	25.3	58.7	Unaged		1
743-42	H	74	290	164.6	442.8	674.7	33.4	42.1	Unaged		1
744-35	H	74	290	193.8	424.7	1061.2	42.8	69.9	290	30000	1
744-36	H	74	290	165.9	424.1	810.8	35.1	54.9	290	30000	1
74-236	V	74	290	179.9	436.3	1433.8	29.2	76.4	290	30000	1
744-26	H	74	290	192.7	440.1	890.9	36.3	62.6	320	10000	1
744-27	H	74	290	181.0	420.6	831.2	35.8	56.9	320	10000	1
742-40	H	74	290	153.7	452.7	915.5	31.5	57.3	320	30000	1
742-41	H	74	290	190.3	483.3	748.7	24.0	42.5	320	30000	1
74-246	V	74	290	184.4	481.7	839.4	33.5	52.5	320	30000	1
742-28	H	74	290	203.5	473.3	884.5	33.[illegible]	53.1	320	50000	1
742-29	H	74	290	215.2	474.4	743.6	24.[illegible]	41.2	320	50000	1
74-130	V	74	290	235.4	517.7	741.1	29.5	[illegible]4.2	320	50000	1
742-27	H	74	290	174.9	454.3	787.2	31.5	65.9	350	2570	1
744-06	H	74	290	185.4	448.0	677.7	2[illegible]	3[illegible].7	350	10000	1
744-09	H	74	290	197.8	507.2	889.6	3[illegible]	5[illegible].4	350	10000	1
74-120	V	74	290	176.6	453.8	751.0	33.3	48.[illegible]	350	10000	[illegible]
744-18	H	74	290	226.5	510.5	791.9	27.6	40.3	350	30000	[illegible]
743-15	H	74	290	180.0	503.8	830.7	34.0	[illegible]9	350	30000	[illegible]
74-270	H	74	290	182.2	495.0	729.9	31.2	40.2	350	30000	[illegible]
742-18	H	74	290	166.2	485.1	695.0	28.5	57.1	400	2570	1
742-15	H	74	290	178.9	516.0	–	33.7	–	400	10000	1
742-24	H	74	290	184.2	509.1	848.8	29.9	48.9	400	10000	1
7[illegible]-109	V	74	290	172.0	476.8	546.4	[illegible]3	48.7	400	10000	1
741-06	H	74	290	172.[illegible]	500.7	678.6	[illegible]9	45.5	450	2570	1
742-09	H	74	290	170.3	485.2	697.5	[illegible]3	35.8	450	2570	1
753-40	H	75	25	313.5	610.4	1056.6	47.4	67.9	Unaged		1
753-41	H	75	25	330.5	589.8	931.7	39.9	74.9	Unaged		1
753-30	H	75	25	315.6	609.0	1668.9	37.2	75.0	290	30000	1
754-28	H	75	25	321.7	619.2	1140.2	48.3	70.5	290	30000	1
75-135	V	75	25	310.6	630.4	1448.9	48.3	69.7	290	30000	1
754-21	H	75	25	355.9	693.7	1822.0	58.5	75.0	320	100[illegible]	1
754-25	H	75	25	[illegible]06.3	706.0	1763.9	46.4	71.2	320	1000[illegible]	[illegible]
752-41	H	75	25	357.9	726.8	12[illegible].7	38.8	52.4	320	30000	1
754-39	H	75	25	395.1	722.5	1203.2	39.2	52.5	320	30000	1
75-245	V	75	25	323.1	691.3	1418.1	47.5	62.2	320	30000	1
751-28	H	75	25	334.7	689.5	1118.9	28.1	40.8	320	50000	1
751-29	H	75	25	352.0	729.8	1166.6	27.0	43.2	320	50000	1
75-230	V	75	25	378.4	759.5	1179.8	32.7	38.6	320	50000	1

Table B–1. (Contd.)

Specimen Number	Orientation[a]	Heat	Test Temp. (°C)	Engineering: 0.2% Yield Stress (MPa)	Engineering: Ultimate Stress (MPa)	Fracture Stress (MPa)	Elongation (%)	Red. in Area (%)	Aging Condition: Temp. (°C)	Aging Condition: Time (h)	Ref.[b]
752-25	H	75	25	–	667.8	1677.6	37.5	[illegible]	350	2570	1
752-26	H	75	25	346.5	688.9	1522.3	37.6	[illegible]	350	2570	1
754-06	H	75	25	332.7	741.1	1543.1	41.4	59.6	350	10000	1
754-07	H	75	25	352.5	728.5	1159.6	39.5	54.2	350	10000	1
754-08	H	75	25	308.6	718.8	1455.1	42.3	56.1	350	10000	1
75-119	V	75	25	354.0	742.8	1437.7	44.4	52.6	350	10000	1
753-10	H	75	25	316.1	766.4	1256.0	31.5	41.4	350	30000	1
753-11	H	75	25	344.3	748.2	1051.8	26.3	31.6	350	30000	1
75-130	V	75	25	300.8	711.0	1061.3	30.5	34.9	350	30000	1
752-16	H	75	25	326.7	703.6	1531.0	38.5	64.3	400	2570	1
752-17	H	75	25	353.1	731.5	1441.4	33.5	64.0	400	2570	1
752-15	H	75	25	405.3	777.1	1305.1	36.4	45.0	400	10000	1
752-22	H	75	25	–	749.1	1093.5	28.1	37.6	400	10000	1
752-23	H	75	25	338.9	726.6	1328.9	26.7	53.6	400	10000	1
75-109	V	75	25	359.0	736.8	1171.8	38.1	46.3	400	10000	1
751-04	H	75	25	311.7	721.2	1094.2	25.1	38.4	450	2570	1
751-05	H	75	25	314.7	746.4	[illegible]	32.0	41.0	450	2570	1
754-40	H	75	290	196.8	470.8	652.0	26.1	63.1	Unaged		1
753-42	H	75	290	191.5	474.8	620.7	30.5	45.0	Unaged		1
754-29	H	75	290	193.3	528.3	1051.1	33.5	60.5	290	30000	1
754-30	H	75	290	202.6	495.3	784.9	31.1	58.5	290	30000	1
75-236	V	75	290	211.8	486.2	924.1	32.0	58.2	290	30000	1
754-26	H	75	290	205.6	538.0	945.5	28.9	64.7	320	10000	1
754-27	H	75	290	212.2	534.3	957.8	29.2	64.6	320	10000	1
752-40	H	75	290	231.7	589.3	852.7	26.0	38.4	320	30000	1
752-42	H	75	290	268.5	575.8	893.6	22.9	46.0	320	30000	1
75-246	V	75	290	213.0	521.8	881.3	26.7	54.2	320	30000	1
[illegible]2-28	H	75	290	258.9	587.9	933.6	24.4	43.2	320	50000	1
752-29	H	75	290	264.1	581.7	969.4	23.2	48.5	320	50000	1
75-130	V	75	290	239.6	557.8	889.5	24.7	38.9	320	50000	1
752-27	H	75	290	204.7	528.8	843.9	25.8	49.4	350	2570	1
754-09	H	75	290	219.8	614.1	918.6	24.5	44.8	350	10000	1
75-120	V	75	290	209.9	595.6	854.7	32.7	35.4	350	10000	1
753-12	H	75	290	264.4	615.9	809.3	23.0	30.2	350	30000	1
754-12	H	75	290	227.2	613.8	839.4	24.2	31.2	350	30000	1
75-270	V	75	290	209.0	584.6	823.5	26.2	32.9	350	30000	1
752-18	H	75	290	203.2	591.1	799.6	26.4	41.0	400	2570	1
752-24	H	75	290	208.2	630.4	858.4	23.7	31.4	400	10000	1
75-110	V	75	290	206.7	593.1	884.1	25.3	42.4	400	10000	1
751-06	H	75	290	218.7	598.2	749.6	24.3	24.7	450	2570	1
752-09	H	75	290	197.7	606.2	888.1	25.5	33.0	450	2570	1

[a] Designation L = longitudinal or axial direction, C = circumferential direction, H = horizontal direction in the plane of the slab, and V = vertical direction transverse to the plane of the slab.

[b] 1) Argonne National Laboratory
2) Materials Engineering Associates

Appendix C

J–R Curve Characterization

The J–R curve tests were conducted at MEA and at ANL. Details of the test procedure and results for the tests at MEA have been presented earlier.[C-1,C-2] Tests at ANL were performed according to ASTM Specifications E 813-85 (Standard Test Method for J_{IC}, a Measure of Fracture Toughness) and E 1152-87 (Standard Test Method for Determining J–R Curve). Compact-tension (CT) specimens, 25.4 mm (1 in.) thick with 10% side grooves, were used for the tests. The CT specimen design, shown in Fig. C-1, is similar to the specimen of ASTM Specification E 399, the notch region is modified in accordance with [illegible] 81 and E 5112, to permit measurement of load-line displacement by axial extensometer. The extensometer was mounted on razor blades that were screwed onto the specimen along the load line.

Prior to testing, the specimens were fatigue-precracked at room temperature and at load levels within the linear elastic range. The final ratio of crack length to width (a/W) after precracking was ≈0.55. The final 1-mm (≈0.04-in.) crack extension was carried out at a load range of 13 kN (2.92 kip) to 1.3 kN (0.292 kip), i.e., during precracking K_{max} was <25 MPa·m$^{1/2}$ (22.6 ksi·in.$^{1/2}$). After precracking, all specimens were side-grooved by 20% of the total specimen thickness, i.e., 10% per side, to ensure uniform crack growth during testing.

The J–R curve tests were performed on an Instron testing machine with 90 kN (20 kip) maximum load capacity. The load and load-line displacement data were digitized with digital voltmeters and stored on a disk for post-test analysis and correction of the test data. The single-specimen compliance procedure was used to estimate the crack extension. Rotation and modulus corrections were applied to the compliance data. Both deformation theory and modified forms of the J integral were evaluated for each test.

After each test, the specimen was heated to 350°C to heat-tint the exposed fracture surface. The specimen was then fractured at liquid nitrogen temperature. The initial (i.e., fatigue precrack) and final (test) crack lengths were measured optically for both halves of the fractured specimen. The crack lengths were determined by the 9/8 averaging technique, i.e., the two near-surface measurements were averaged and the resultant value averaged with the remaining seven measurements.

The fracture toughness J_{IC} values were determined in accordance with ASTM Specification E 813-81 and E 813-85. For the former, J_{IC} is defined as the intersection of the blunting line given by $J = 2\sigma_f \Delta a$, and the linear fit of the J-vs-Δa test data between the 0.15-mm and 1.5-mm exclusion lines. The flow stress, σ_f, is the average of the 0.2% yield stress and the ultimate stress. The ASTM Specification E 813-85 procedure defines J_{IC} as the intersection of the 0.2-mm offset line with the power law-fit (of the form $J = C\Delta a^n$) of the test data between the exclusion lines. J–R curve tests on cast stainless steels indicate that a slope of four times the flow stress ($4\sigma_f$) for the blunting line expresses the J vs Δa data better than the slope of $2\sigma_f$ defined in E 813-81 or E 813-85. The fracture toughness J_{IC} values were determined using the $4\sigma_f$ slope.

The tearing modulus was also evaluated for each test. The tearing modulus is given by $T = E(dJ/da)/\sigma_f^2$, where E is the Young's modulus and σ_f is the flow stress. The ASTM E 813-81 value of tearing modulus is determined from the slope dJ/da of the linear fit to the J-vs-Δa data. For the power law curve fits, an average value of dJ/da was calculated[C-3] to obtain average tearing modulus.

The fracture toughness results for four commercial and four experimental heats of cast stainless steel aged up to 30,000 h at 320, 350, 400, and 450°C, and for the service-aged KBR pump cover plate material, are given in Table C-1. The test data as well as an analysis and qualification of the data for 47 J-R curve tests have been presented earlier.[C-4] Data analysis and qualification for an additional 24 J-R curve tests at 290°C are presented in this Appendix.

Data Analysis Procedures

The compliance method was used to determine the crack length during the tests. The Hudak-Saxena calibration equation[C-5] is used to relate the specimen load line elastic compliance C_i on an unloading/loading sequence with the crack length a_i. The compliance, i.e., slope $(\Delta\delta/\Delta P)$ of the load-line displacement versus load record obtained during the unloading/loading sequence, is given by

$$U_{LL} = \frac{1}{(B_e E_e C_i)^{1/2} + 1} \qquad (C-1)$$

and

$$a_i/W = 1.000196 - 4.06319(U_{LL}) + 11.242(U_{LL})^2 - 106.043(U_{LL})^3 + 464.335(U_{LL})^4 - 650.677(U_{LL})^5 \qquad (C-2)$$

where E_e is the effective elastic modulus, B_e is the effective specimen thickness expressed as $B - (B - B_N)^2/B$, and W is specimen width.

Both rotation and modulus corrections are applied to the compliance data. The modulus correction[C-5] is used to account for the uncertainties in testing, i.e., in the values of initial crack length determine by compliance and measured optically. The effective modulus E_M is determined from

$$E_e = \frac{1}{C_0 B_e}\left(\frac{W + a_o}{W - a_o}\right)^{1/2} f(a_o/W) \qquad (C-3)$$

and

$$f(a_e/W) = 2.163 + 12.219(a_o/W) - 20.065(a_o/W)^2 - 0.9925(a_o/W)^3 + 20.609(a_o/W)^4 - 9.9314(a_o/W)^5 \qquad (C-4)$$

where C_o is initial compliance, B_e is effective specimen thickness, and a_o is the initial physical crack size measured optically.

To account for crack opening displacement in CT specimen, the crack size should be corrected for rotation.[C-6] The corrected compliance is calculated from

$$\theta = \mathrm{Sin}^{-1} [(\frac{d_m}{2} + D)/(D^2 + R^2)^{1/2}] - \tan^{-1} (\frac{D}{R}) \quad \text{(C-5)}$$

and

$$C_c = C_m/[(\frac{H^*}{R}\mathrm{Sin}\theta - \mathrm{Cos}\theta)(\frac{D}{R}\mathrm{Sin}\theta - \mathrm{Cos}\theta)] \quad \text{(C-6)}$$

where C_c and C_m are the corrected and measured elastic compliance at the load line, H^* is initial half span of load points (i.e., center of pinholes), R is radius of rotation of crack centerline (=(W+a)/2), a is the updated crack length, D is one-half of the initial distance between the displacement points (i.e., half gauge length), d_m is total measured load line displacement, and θ is the angle of rotation of a rigid body element about the unbroken midsection line.

The J value is calculated at any point on the load versus load-line displacement record using the relationship

$$J = J_{el} + J_{pl} \quad \text{(C-7)}$$

where J_{el} is the elastic component of J and J_{pl} is the plastic component of J. For a CT specimen, at a point corresponding to the coordinates P_i and δ_i on the specimen load versus load-line displacement record and a_i is $(a_0 + \Delta a_i)$, the deformation J is given by

$$J_{D(i)} = (K_i)^2 \, (1-\nu^2)/E_e + J_{pl(i)} \quad \text{(C-8)}$$

where from ASTM method E 399:

$$K_i = [P_i/(BB_N W_e)^{1/2}] \, f(a_i/W) \quad \text{(C-9)}$$

with

$$f(a_i/W) = [2 + (a_i/W)] \, [0.886 + 4.64(a_i/W) - 13.32(a_i/W)^2 + 14.72(a_i/W)^3 - 5.6(a_i/W)^4]/[1 - (a_i/W)]^{3/2} \quad \text{(C-10)}$$

and:

$$J_{pl(i)} = [J_{pl(i-1)} + (\frac{\eta_i}{b_i}) \frac{A_{pl(i)} - A_{pl(i-1)}}{B_N}] \, [1 - (\frac{\gamma_i}{b_i})(a_i - a_{i-1})] \quad \text{(C-11)}$$

where ν is Poisson's ratio, b is the uncracked ligament, A_{pl} is the plastic component of the area under the load versus load-line displacement record, and η a factor that accounts for the tensile component of the load as given by

$$\eta_i = 2 + 0.522 b_i/W, \quad \text{(C-12)}$$

and γ a factor that accounts for limited crack growth as given by

$$\gamma_i = 1 + 0.76 b_i/W \quad \text{(C-13)}$$

The modified J values (J_M) are calculated from the relationships (from Ref. C-7)

$$J_{M(i)} = J_{D(i)} + \Delta J_i \quad \text{(C-14)}$$

where

$$\Delta J_i = \Delta J_{i-1} + \left(\frac{\gamma_i}{b_i}\right) J_{pl(i)} (a_i - a_{i-1}) \quad \text{(C-15)}$$

According to ASTM Specification E 1152-87, the J_D-R curves are valid only for crack growth up to 10% of the initial uncracked ligament. Also, they show a dependence on specimen size. The J_M-R curves have been demonstrated to be independent of specimen size and yield valid results for larger crack growth.

Data Qualification

The various validity criteria specified in ASTM Specification E 813-85 for J_{IC} and in ASTM Specification E 1152-87 for J-R curve, were used to qualify the results from each test. The various criteria include maximum values of crack extension and J-integral; limits for initial uncracked ligament, effective elastic modulus, and optically measured physical crack length; and spacing of J-Δa data points. The ω criteria (from Ref. C-8) was also used to ensure that a region of J dominance exists.

For the present investigation, most of the unaged or short-term-aged specimens yielded invalid J_{IC} values because of the relatively high toughness of the material. The reasons for the discrepancies are data-point spacing, shape of the final crack front, or size of the uncracked ligament. In general, the size of the uncracked ligament or the specimen thickness was inadequate for the unaged or short-term-aged specimens because of the relatively high toughness of the material. The J_{max} limit for the J-vs.-Δa data was ignored in most tests to obtain a good power-law fit of the test data.

The shape of the crack front was also very irregular for most cast stainless steels. This may be attributed to the coarse grain structure of the casting and differences in ferrite morphology. Cast stainless steels with large columnar grains, in particular, showed significant variation in crack length along the width of a specimen. Furthermore, the crack front always had a leading crack near the edges of the specimen. The near-surface measurements of the final physical crack length were often >±1.02 mm, the maximum value allowed for data qualification.

The fracture surfaces often showed uncracked ridges or ligaments along the direction of crack extension. The uncracked ligaments add significant error to the estimation of crack length by compliance. Therefore, the difference between the crack extension predicted from elastic compliance and the average measured physical crack extension is more than the maximum value allowed by ASTM E 1152.

All tests showed significant load relaxation during the unloading/reloading cycle for estimating the crack length by elastic compliance. All unloadings were 25% of the load. The load at the end of the unloading/reloading cycle is always lower than it was at the start of the unloading cycle. The difference is appreciable for the room-temperature test. Therefore, the initial 20-30% of the unloading curve was ignored in estimating the crack length.

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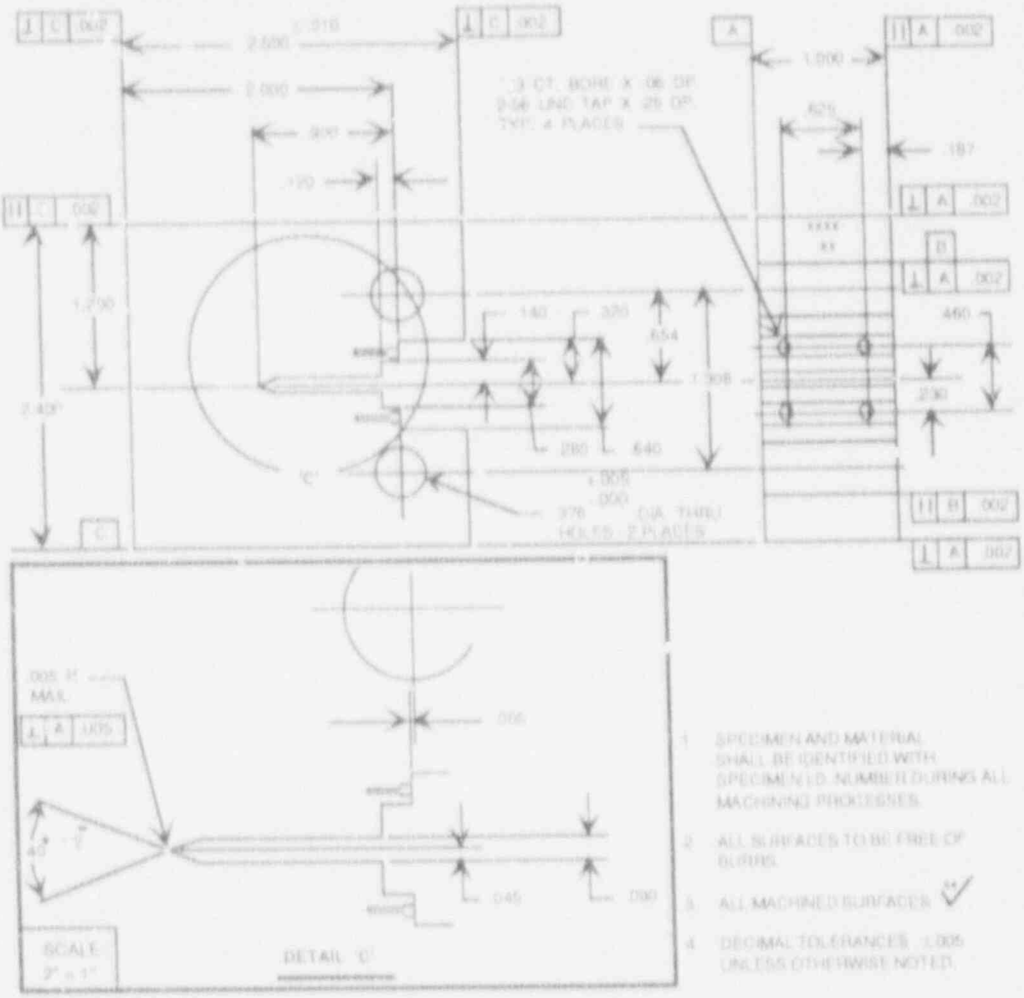

Figure C–1. Configuration of compact–tension test specimen

Table C-1. *Results from fracture toughness tests conducted at ANL and MEA on nine heats of cast stainless steel*

Specimen Number	Heat	Orientation[a]	Test Temp.	a/W	Δa Final[b] Comp. (mm)	Δa Final[b] Opt. (mm)	Deformation J[c] J_{IC} (kJ/m²)	Deformation J[c] T_{av}	Deformation J[c] C (kJ/m²)	Deformation J[c] n	Modified J[c] J_{IC} (kJ/m²)	Modified J[c] T_{av}	Modified J[c] C (kJ/m²)	Modified J[c] n	Flow Stress (MPa)	Impact Energy (J/cm²)	Condition Time (h)	Condition Temp. (°C)	Ref.[d]
									CF-3										
I1S-03	I	C-L	25	0.530	13.50	12.90	475.9	604	781.5	0.694	435.2	712	796.0	0.788	411.2	179.7	Unaged		2
I1S-01	I	L-C	25	0.538	15.20	13.77	623.9	541	861.5	0.591	639.2	610	896.5	0.638	411.2	179.7	Unaged		2
I2S-01	I	L-C	25	0.534	12.18	13.66	478.2	675	811.6	0.743	483.6	741	840.7	0.784	411.2	179.7	Unaged		2
I1S-07	I	L-C	25	0.561	6.44	6.75	[illegible]	353	707.5	0.560	473.3	380	739.7	0.580	450.6	214.4	30000	320	1
I1S-76	I	C-L	25	0.527	12.69	14.72	497.8	336	741.1	0.522	506.7	373	771.1	0.558	466.8	141.2	10000	350	2
I1S-04	I	L-C	25	0.535	12.86	14.04	455.9	334	705.8	0.539	462.9	369	733.9	0.574	466.8	141.2	10000	350	2
I2S-03	I	L-C	25	0.544	12.93	14.17	330.2	463	684.2	0.747	333.6	501	716.1	0.778	466.8	141.2	10000	350	2
I1S-02	I	L-C	290	0.525	13.18	14.83	386.1	491	512.6	0.459	393.4	563	534.3	0.506	284.2	140.7	Unaged		2
I2S-02	I	L-C	290	0.532	6.21	7.23	[illegible]	633	536.9	0.561	393.0	670	557.0	0.576	284.2	140.7	Unaged		2
I1S-08	I	L-C	290	0.566	10.51	11.43	251.8	344	394.2	0.494	252.1	400	414.8	0.549	309.5	194.1	30000	320	1
I1S-05	I	L-C	290	0.541	12.45	13.62	249.9	367	385.5	0.480	252.9	411	402.2	0.515	303.7	130.1	10000	350	2
I2S-04	I	L-C	290	0.538	12.65	13.91	274.5	425	425.0	0.512	277.5	476	443.2	0.552	303.7	130.1	10000	350	2
P2B-03	P2	C-L	25	0.538	6.92	7.95	1271.7	1194	1250.6	0.817	1301.3	1393	1256.5	0.898	381.0	385.8	Unaged		2
P2B-01	P2	L-C	25	0.541	6.25	7.18	1300.1	1400	1241.6	0.890	1245.6	1592	1225.2	0.961	381.0	385.8	Unaged		2
P2T-01	P2	L-C	25	0.539	3.18	2.92	1365.3	1104	1274.3	0.754	1480.4	1113	1315.3	0.747	381.0	385.8	Unaged		2
P2T-06	P2	L-C	25	0.719	3.31	4.17	935.4	988	1178.3	0.829	1025.5	1140	1236.9	0.879	421.7	360.4	3000	350	2
P2T-08	P2	L-C	25	0.531	9.52	10.76	913.3	1091	1221.9	0.897	989.9	1154	1261.8	0.913	436.8	286.7	10000	350	2
P2T-10	P2	L-C	25	0.531	8.53	8.39	1468.0	903	1426.5	0.728	1647.8	1000	1487.1	0.767	436.8	286.7	10000	350	2
P2B-11	P2	C-L	25	0.556	2.58	4.00	688.4	575	960.6	0.643	710.3	639	998.1	0.686	434.7	224.2	30000	350	1
P2B-06	P2	L-C	25	0.527	11.83	13.04	747.1	808	1053.6	0.765	787.2	893	1097.5	0.804	426.4	159.5	10000	400	2
P2T-04	P2	L-C	25	0.528	11.26	12.18	820.2	681	1059.3	0.666	849.6	758	1096.7	0.711	426.4	159.5	10000	400	2
P2B-02	P2	L-C	290	0.531	6.51	8.03	1483.5	1435	1080.9	0.691	1749.4	1682	1102.3	0.765	268.5	300.5	Unaged		2
P2T-02	P2	L-C	290	0.534	3.62	3.98	892.3	1272	873.7	0.694	949.6	1524	891.3	0.782	268.5	300.5	Unaged		2
P2T-07	P2	L-C	290	0.525	8.36	9.50	1060.3	1208	980.8	0.689	1154.4	1397	1004.8	0.736	288.2	347.5	3000	350	2
P2T-09	P2	L-C	290	0.529	8.44	10.47	1033.8	1272	964.9	0.717	1182.9	1382	1013.5	0.743	286.8	321.5	10000	350	2
P2B-12	P2	L-C	290	0.568	4.84	5.58	650.7	1078	796.5	0.726	686.7	1192	824.8	0.768	292.1	334.5	30000	350	1
P2T-05	P2	L-C	290	0.515	11.85	13.62	874.6	732	893.1	0.484	917.2	866	920.0	0.548	288.6	159.5	10000	400	2
692-08B	69	H-H	25	0.530	13.72	16.07	204.4	[illegible]	405.4	0.597	205.3	287	421.6	0.628	435.5	207.1	Unaged		2
692-08T	69	H-H	25	0.537	13.34	14.60	267.0	408	552.9	0.700	268.8	438	571.9	0.728	435.5	207.1	Unaged		2
691-06T	69	H-H	25	0.552	9.18	10.02	567.2	434	834.2	0.586	574.9	486	866.5	0.631	446.4	187.0	30000	320	1
691-04B	69	H-H	25	0.519	12.47	13.61	702.9	307	888.8	0.425	720.9	350	925.5	0.466	467.7	154.1	2570	350	2
691-01T	69	H-H	25	0.552	10.97	10.33	514.0	385	770.8	0.559	520.4	431	801.4	0.601	452.1	188.6	10000	350	1
691-04T	69	H-H	25	0.548	11.30	12.07	406.7	277	626.2	0.497	412.1	309	652.7	0.534	463.2	129.1	30000	350	1

Table C-1. (Contd.)

Specimen Number	Heat	Orientation[a]	Test Temp.	a/W	Δa Final[b] Comp. (mm)	Δa Final[b] Opt. (mm)	Deformation J^c J_{IC} (kJ/m²)	Deformation J^c T_{av}	Deformation J^c C (kJ/m²)	Deformation J^c n	Modified J^c J_{IC} (kJ/m²)	Modified J^c T_{as}	Modified J^c C (kJ/m²)	Modified J^c n	Flow Stress (MPa)	Impact Energy (J/cm²)	Condition Time (h)	Condition Temp. (°C)	R
691-03B	69	H-H	25	0.514	12.86	13.65	454.9	200	614.2	0.368	459.3	229	639.4	0.408	469.1	141.6	2570	400	
696-01T	69	H-H	25	0.566	5.11	5.90	323.1	244	548.3	0.527	328.9	268	573.1	0.558	484.0	96.9	10000	400	
691-05B	69	H-H	25	0.517	12.85	14.04	495.1	212	661.4	0.375	503.7	243	690.3	0.413	472.7	121.1	2570	450	
693-07T	69	H-H	290	0.532	12.87	14.50	700.1	378	756.3	0.312	723.6	467	785.8	0.370	301.4	257.6	Unaged		
693-01V	69	V-H	290	0.582	12.53	13.56	266.3	423	424.8	0.540	252.3	504	439.5	0.621	301.4	257.6	Unaged		
691-07T	69	H-H	290	0.571	10.30	11.33	376.5	375	492.9	0.410	376.5	453	514.4	0.475	295.4	213.0	30000	320	
691-06T	69	H-H	290	0.530	12.97	14.17	456.9	201	523.7	0.259	465.1	280	550.0	0.301	312.2	261.1	2570	350	
691-02T	69	H-H	290	0.562	10.16	11.07	158.4	562	362.6	0.756	158.8	609	376.8	0.789	294.8	169.3	10000	350	
691-03T	69	H-H	290	0.560	10.38	11.03	210.3	339	365.5	0.545	212.5	375	321.7	0.580	323.3	159.8	30000	350	
691-05T	69	H-H	290	0.526	12.47	13.42	255.0	301	368.5	0.412	256.5	345	384.7	0.456	304.4	140.6	2570	400	
697-01T	69	H-H	290	0.564	9.91	10.16	166.8	243	296.4	0.510	168.7	268	309.9	0.541	336.6	135.9	10000	400	
691-03T	69	H-H	290	0.519	12.77	13.75	261.9	256	376.0	0.395	264.3	291	392.3	0.433	327.6	123.8	2570	450	
									CF-8										
C1B-03	C1	C-L	25	0.531	13.47	15.20	306.3	557	549.0	0.664	310.3	606	569.8	0.696	356.2	59.7	Unaged		
C1B-01	C1	L-C	25	0.526	12.87	14.45	291.9	230	404.6	0.361	295.2	264	422.5	0.399	356.2	59.7	Unaged		
C1B-02	C1	L-C	25	0.537	11.60	12.65	185.3	455	416.5	0.724	186.1	489	431.3	0.752	356.2	59.7	Unaged		
C1B-04	C1	L-C	290	0.529	12.89	14.44	-	-	-	-	254.0	625	384.5	0.539	241.1	-	Unaged		
C1B-05	C1	L-C	290	0.529	13.21	14.85	236.4	583	362.4	0.527	254.3	300	360.3	0.523	241.4	-	Unaged		
KRB-06	KRB	C-R	25	0.617	5.63	7.51	263.4	564	639.4	0.853	264.5	616	666.1	0.890	428.4	131.1	68000	284	
KRB-01	KRB	R-C	25	0.553	6.58	6.49	396.2	403	657.1	0.602	400.4	447	684.6	0.642	428.4	131.1	68000	284	
KRB-04	KRB	R-C	25	0.576	6.69	7.29	531.6	626	843.9	0.687	536.9	698	875.9	0.734	428.0	232.0	Annealed		
KRB-05	KRB	C-R	290	0.609	9.10	10.58	681.1	337	764.3	0.346	707.5	420	802.1	0.411	329.0	321.2	68000	284	
P1B-03	P1	C-L	25	0.526	10.27	12.53	592.2	603	866.5	0.652	602.6	670	898.0	0.697	413.8	228.3	Unaged		
P1B-01	P1	L-C	25	0.524	8.42	9.07	413.3	678	776.1	0.785	419.8	733	803.4	0.818	416.5	228.3	Unaged		
P1T-01	P1	L-C	25	0.537	9.25	10.42	560.3	1124	1017.4	0.958	610.7	1132	1045.3	0.946	416.5	228.3	Unaged		
P1B-11	P1	L-C	25	0.551	-	8.28	1002.3	407	1105.6	0.429	1069.2	465	1163.1	0.468	420.7	207.3	30000	320	
P1T-08	P1	C-L	25	0.519	13.90	13.07	209.1	445	526.3	0.808	202.0	493	546.4	0.861	439.8	156.4	10000	350	
P1B-06	P1	L-C	25	0.523	3.88	3.07	707.3	437	945.8	0.544	720.2	497	982.0	0.594	458.1	156.4	10000	350	
P1T-06	P1	L-C	25	0.525	12.58	13.79	468.0	565	837.6	0.740	468.4	622	866.5	0.783	458.1	156.4	10000	350	
P1B-09	P1	L-C	25	0.562	7.70	9.78	409.0	420	708.2	0.644	414.7	460	735.7	0.679	451.4	87.7	30000	350	
P1B-05	P1	L-C	25	0.535	12.35	14.13	228.7	231	445.0	0.582	230.8	249	462.2	0.609	481.8	51.7	10000	400	
P1T-04	P1	L-C	25	0.558	11.75	12.22	186.8	187	368.0	0.558	188.1	203	382.7	0.586	481.8	51.7	10000	400	
P1B-02	P1	L-C	290	0.522	12.79	14.84	554.7	534	664.1	0.448	571.2	624	691.7	0.501	295.8	255.8	Unaged		
P1T-02	P1	L-C	290	0.533	12.38	14.46	630.9	630	733.8	0.458	674.5	688	771.2	0.512	295.8	255.8	Unaged		

Table C-1. (Contd.)

Specimen Number	Heat	Orientation[a]	Test Temp.	a/W	Δa Final[b] Comp. (mm)	Δa Final[b] Opt. (mm)	Deformation J[c] J_{IC} (kJ/m²)	Deformation J[c] T_{av}	Deformation J[c] C (kJ/m²)	Deformation J[c] n	Modified J[c] J_{IC} (kJ/m²)	Modified J[c] T_{av}	Modified J[c] C (kJ/m²)	Modified J[c] n	Flow Stress (MPa)	Impact Energy (J/cm²)	Condition Time (h)	Condition Temp. (°C)	Ref[d]
P1B-12	P1	L-C	290	0.571	9.05	10.43	456.3	366	571.2	0.403	467.6	429	597.6	0.453	306.1	-	30000	320	1
P1B-07	P1	L-C	290	0.527	7.19	9.63	400.7	384	529.9	0.[illegible]24	428.2	410	559.7	0.434	315.8	244.7	10000	350	2
P1T-07	P1	L-C	290	0.526	12.36	14.10	542.1	469	663.3	0.435	558.4	537	691.7	0.484	315.8	244.7	10000	350	2
P1B-10	P1	L-C	290	0.551	10.11	11.17	294.0	440	491.5	0.595	299.2	488	513.9	0.633	331.6	-	30000	350	1
P1T-05	P1	L-C	290	0.513	12.48	13.47	290.7	391	451.7	0.505	298.7	431	470.[illegible]	0.538	324.2	133.5	10000	400	2
683-05B	68	H-H	25	0.527	13.04	14.68	324.4	396	552.8	0.586	327.0	432	572.9	0.619	400.2	245.4	Unaged		2
683-05T	68	H-H	25	0.519	13.88	16.29	282.3	335	485.5	0.554	284.0	369	504.1	0.590	400.2	245.4	Unaged		2
683-03V	68	V-H	25	0.528	12.81	15.00	311.8	364	526.0	0.562	315.5	398	546.3	0.594	400.2	245.4	Unaged		2
683-06T	68	H-H	25	0.572	4.76	5.83	1097.4	567	1170.2	0.529	1157.0	667	1213.5	0.593	400.2	237.4	Annealed		1
682-06T	68	H-H	25	0.578	8.62	9.69	647.3	328	864.1	0.484	657.1	380	901.3	0.539	461.4	135.1	30000	320	1
681-04B	68	H-H	25	0.543	10.22	11.65	798.0	560	1037.7	0.608	832.0	607	1075.5	0.636	444.3	192.9	2570	350	2
682-02T	68	H-H	25	0.560	8.08	8.35	475.2	367	719.1	0.546	488.3	397	746.2	0.571	442.5	100.0	10000	350	1
682-04T	68	H-H	25	0.562	8.18	8.63	205.1	244	430.4	0.634	204.7	265	446.3	0.666	464.6	80.6	30000	350	1
681-06V	68	V-H	25	0.575	9.00	10.20	206.0	159	357.5	0.472	207.4	175	372.3	0.502	464.6	80.6	30000	350	1
681-03B	68	H-H	25	0.548	10.73	12.13	408.4	307	648.6	0.531	412.6	338	673.6	0.566	467.8	74.1	2570	400	2
681-01T	68	H-H	25	0.553	7.08	6.85	260.5	253	487.6	0.578	266.1	265	503.6	0.590	472.5	46.4	10000	400	1
681-03V	68	V-H	25	0.548	10.96	11.66	214.0	244	443.4	0.626	216.2	258	456.9	0.645	476.1	46.4	10000	400	1
681-04T	68	H-H	25	0.531	12.92	14.52	294.7	193	467.7	0.448	296.6	214	486.1	0.480	471.7	54.2	2570	450	2
681-05B	68	H-H	25	0.540	-	-	252.6	330	532.9	0.680	253.2	356	551.9	0.711	471.7	54.2	2570	450	2
683-07T	68	H-H	290	0.536	12.59	14.50	753.1	368	783.0	0.271	752.5	545	795.3	0.384	282.2	287.1	Unaged		2
683-06B	68	H-H	290	0.564	7.05	8.22	413.0	550	553.1	0.513	425.8	631	579.9	0.562	282.2	220.5	Annealed		1
682-07T	68	H-H	290	0.570	10.35	11.48	225.3	432	401.9	0.601	225.9	477	418.1	0.640	30[illegible].9	221.2	30000	320	1
681-06T	68	H-H	290	0.544	13.40	15.28	406.3	573	592.8	0.575	413.7	642	617.0	0.619	318.8	147.5	2570	350	2
682-03T	68	H-H	290	0.563	10.13	10.69	281.6	423	451.5	0.544	283.0	472	469.5	0.585	320.2	207.6	10000	350	1
682-05T	68	H-H	290	0.572	10.27	11.24	303.8	291	438.6	0.437	311.8	322	458.3	0.466	328.1	187.7	30000	350	1
681-05T	68	H-H	290	0.550	12.69	14.66	335.4	362	464.9	0.431	343.1	4[illegible]4	487.9	0.473	312.2	139.6	2570	400	2
681-02T	68	H-H	290	0.569	10.55	11.38	242.5	312	396.2	0.510	245.7	347	413.7	0.546	332.7	144.0	10000	400	1
681-03T	68	H-H	290	0.529	12.69	13.77	312.2	319	454.9	0.446	316.5	361	475.1	0.486	338.5	124.8	2570	450	2
									Weld										
205-23C	205	L-C	290	0.511	15.71	15.36	185.0	149	328.1	0.482	186.7	161	339.7	0.506	440.2[e]	123.5	18000	400	1
									CF-8M										
205-25C	205	L-C	25	0.569	16.45	11.65	275.8	248	493.9	0.555	274.9	274	513.4	0.593	461.1[e]	113.8	18000	400	1
205-24C	205	L-C	290	0.581	9.93	11.14	207.2	256	340.0	0.475	208.1	285	354.3	0.512	339.0	116.3	18000	400	1
207-09C	207	L-C	290	0.564	10.76	11.09	615.1	409	718.8	0.405	64[illegible].9	483	755.8	0.456	320.5[e]	271.6	Unaged		1

Table C-1. (Contd.)

Specimen Number	Heat	Orientation[a]	Test Temp.	a/W	Δa Final[b] Comp. (mm)	Δa Final[b] Opt. (mm)	Deformation J[c] J_{IC} (kJ/m²)	Deformation J[c] T_{av}	Deformation J[c] C (kJ/m²)	Deformation J[c] n	Modified J[c] J_{IC} (kJ/m²)	Modified J[c] T_{av}	Modified J[c] C (kJ/m²)	Modified J[c] n	Flow Stress (MPa)	Impact Energy (J/cm²)	Condition Time (h)	Condition Temp. (°C)	Ref.[d]
207-10C	207	L-C	290	0.573	9.47	10.78	473.9	508	637.0	0.526	484.5	578	663.9	0.574	320.5[e]	271.6	Unaged		1
743-05B	74	H-H	25	0.528	12.61	14.71	610.3	415	795.4	0.481	633.5	451	826.1	0.5[illegible]	405.1	210.1	Unaged		2
743-05T	74	H-H	25	0.523	12.44	14.04	577.1	276	710.6	0.355	595.4	323	746.0	0.398	405.1	210.1	Unaged		2
743-03V	74	V-H	25	0.601	7.56	8.28	418.5	326	599.0	0.460	426.7	371	627.7	0.502	405.1	210.1	Unaged		1
741-06T	74	H-H	25	0.532	12.55	14.31	692.1	385	852.6	0.439	724.7	437	895.6	0.476	410.5	138.1	2570	350	2
742-05T	74	H-H	25	0.570	11.41	12.00	208.6	220	391.6	0.548	209.8	241	407.9	0.579	447.3	63.0	30000	350	1
741-03B	74	H-H	25	0.514	12.35	15.17	389.0	248	556.5	0.420	394.0	277	578.7	0.455	429.6	128.9	2570	400	2
741-01T	74	H-H	25	0.564	10.93	11.53	218.7	233	409.0	0.555	219.9	255	425.0	0.585	442.5	76.5	10000	400	1
741-03T	74	H-H	25	0.522	13.08	14.57	238.8	210	404.0	0.483	241.7	225	418.0	0.505	438.5	84.6	2570	450	2
741-05B	74	H-H	25	0.533	12.91	13.74	289.4	288	502.9	0.545	296.2	297	514.8	0.554	438.5	84.6	2570	450	2
741-05T	74	H-H	290	0.577	10.18	10.89	309.3	285	438.2	0.421	314.5	325	459.1	0.462	325.7	135.2	2570	400	1
741-02T	74	H-H	290	0.560	10.57	10.92	195.3	303	348.9	0.546	196.5	334	363.5	0.580	335.5	142.9	10000	400	1
741-04T	74	H-H	290	0.577	10.45	11.31	100.7	239	232.9	0.651	101.3	257	242.2	0.678	332.1	94.4	3000	450	1
752-08T	75	H-H	25	0.584	10.80	11.92	463.2	226	639.4	0.405	471.9	259	670.1	0.447	461.0	236.9	Unaged		1
753-05T	75	H-H	25	0.552	11.12	12.63	537.4	416	817.6	0.591	541.3	467	849.1	0.638	461.0	228.3	Annealed		1
751-07T	75	H-H	25	0.563	10.20	11.27	515.2	305	749.3	0.501	441.6	342	782.1	0.541	479.5	266.0	30000	290	1
752-06T	75	H-H	25	0.557	10.61	12.00	281.2	173	493.4	0.509	282.8	190	514.1	0.542	536.1	185.2	30000	320	1
752-02T	75	H-H	25	0.548	11.92	12.16	274.2	164	478.0	0.496	276.6	178	495.9	0.523	542.8	46.0	10000	350	1
752-04T	75	H-H	25	0.571	11.05	12.35	104.3	63	189.4	0.429	104.2	69	196.5	0.456	531.2	30.5	30000	350	1
751-06V	75	V-H	25	0.553	11.50	12.29	90.9	60	172.2	0.451	91.3	65	177.8	0.471	531.2	30.5	30000	350	1
751-03B	75	H-H	25	0.563	11.55	12.31	238.4	136	407.3	0.461	241.1	149	424.1	0.488	528.7	46.3	2570	400	1
751-01B	75	H-H	25	0.547	11.23	11.66	123.8	109	281.2	0.599	123.6	117	290.3	0.624	569.6	35.8	10000	400	1
751-01T	75	H-H	25	0.565	11.39	13.13	88.9	105	231.4	0.670	88.2	112	238.8	0.696	569.6	35.8	10000	400	1
751-03V	75	V-H	25	0.557	11.03	11.98	149.6	114	309.2	0.548	123.6	124	320.3	0.575	569.6	35.8	10000	400	1
751-04T	75	H-H	25	0.567	10.85	11.19	170.4	151	348.1	0.563	171.7	162	360.6	0.586	523.5	51.1	2570	450	1
752-08B	75	H-H	290	0.579	7.83	8.49	436.8	386	583.3	0.453	448.2	444	611.6	0.498	333.5	164.8	Unaged		1
752-03V	75	V-V	290	0.565	8.32	9.21	493.4	289	600.0	0.347	500.4	365	630.5	0.418	333.5	164.8	Unaged		1
753-05B	75	H-H	290	0.568	10.29	11.30	329.6	452	518.5	0.562	335.0	500	539.8	0.599	333.5	201.5	Annealed		1
752-07T	75	H-H	290	0.565	10.53	11.08	210.0	212	358.9	0.488	213.2	232	373.1	0.515	389.0	160.0	30000	320	1
752-03T	75	H-H	290	0.551	10.12	10.68	129.5	206	288.2	0.627	129.7	221	298.7	0.654	409.9	151.5	10000	350	1
752-05T	75	H-H	290	0.574	10.09	10.49	108.4	202	262.6	0.669	108.3	217	272.3	0.697	408.7	111.9	30000	350	1
751-05T	75	H-H	290	0.563	10.23	10.56	150.2	206	301.9	0.571	151.4	223	313.7	0.597	397.2	115.5	2570	400	1
751-02T	75	H-H	290	0.568	10.40	10.53	156.1	145	274.2	0.462	154.8	161	284.4	0.497	409.6	135.8	10000	400	1

Table C-1. (Contd.)

Specimen Number	Heat	Orientation[a]	Test Temp.	a/W	Δa Final[b] Comp. (mm)	Δa Final[b] Opt. (mm)	Deformation J^c: J_{IC} (kJ/m^2)	Deformation J^c: T_{av}	Deformation J^c: C (kJ/m^2)	Deformation J^c: n	Modified J^c: J_{IC} (kJ/m^2)	Modified J^c: T_{av}	Modified J^c: C (kJ/m^2)	Modified J^c: n	Flow Stress (MPa)	Impact Energy (J/cm^2)	Condition Time (h)	Condition Temp. (°C)	Ref.[d]
751-02V	75	V–V	290	0.569	10.33	11.14	262.0	121	363.6	0.329	266.6	140	382.5	0.356	409.6	135.8	10000	400	1
751-03T	75	H–H	290	0.559	10.06	10.36	107.1	151	230.1	0.577	197.2	165	240.0	0.609	405.2	82.0	2570	450	1
758-02C	758	L–C	25	0.582	10.84	10.39	91.2	101	209.0	0.591	91.5	108	216.6	0.613	501.0[e]	69.6	18000	400	1
758-03C	758	L–C	25	0.568	11.57	13.56	103.4	116	239.1	0.607	103.4	124	247.3	0.632	501.0[e]	69.6	18000	400	1
758-01C	758	L–C	290	0.567	11.90	12.37	167.2	128	268.8	0.400	167.8	142	279.8	0.432	397.1[e]	118.1	18000	400	1

[a] The first digit represents the direction normal to the plane of the crack and second digit is the direction of crack propagation. For pipe and pump cover plate materials L = longitudinal or axial, C = circumferential, and R = radial directions. For slabs H = horizontal direction in the plane of the slab and V = vertical direction transverse to the plane of the crack.

[b] Final crack extension: Comp. determined from compliance and Opt. measured optically.

[c] According to ASTM E-813 but with a slope of 4 times the flow stress for the blunting line.

[d] Tests conducted at :1 ANL and 2 MEA.

[e] Estimated from Charpy-impact data.

Table C-2. Test data for specimen 11S-08

Test Number	: 0076	Test Temp.	: 290°C
Material Type	: CF-3	Heat Number	: I
Aging Temp.	: 320°C	Aging Time	: 30,000 h
Spec. Thickness	: 25.35 mm	Net Thickness	: 20.31 mm
Spec. Width	: 50.83 mm	Flow Stress	: 309.50 MPa

Unload Number	J_d (kJ/m^2)	J_m (kJ/m^2)	Δa (mm)	Load (kN)	Deflection (mm)
1	15.16	15.17	0.0180	16.288	0.304
2	42.48	42.45	-0.0014	19.437	0.607
3	73.13	73.26	0.0424	21.271	0.907
4	111.70	111.82	0.0404	22.718	1.258
5	151.59	153.85	0.3008	23.862	1.609
6	194.27	195.66	0.2207	24.702	1.960
7	237.00	241.25	0.4349	25.511	2.309
8	281.88	286.95	0.4866	26.142	2.662
9	325.27	334.42	0.7044	26.576	3.008
10	366.58	374.76	0.6565	26.805	3.310
11	401.02	418.82	1.0665	26.943	3.612
12	438.17	458.98	1.1826	26.905	3.907
13	472.08	503.20	1.5449	26.876	4.210
14	508.69	544.96	1.7112	26.567	4.511
15	542.48	588.46	2.0020	26.484	4.811
16	583.84	629.76	2.0000	26.561	5.109
17	614.36	675.75	2.4014	26.402	5.412
18	653.25	717.59	2.4741	26.059	5.714
19	684.57	762.09	2.7738	25.984	6.011
20	716.29	813.60	3.1987	25.600	6.362
21	757.45	862.50	3.3542	25.347	6.709
22	792.80	914.87	3.6755	25.151	7.060
23	828.24	965.24	3.9439	24.561	7.408
24	860.68	1024.22	4.3914	23.644	7.811
25	903.62	1093.62	4.8075	22.550	8.307
26	925.99	1163.31	5.5103	21.630	8.808
27	963.53	1230.34	5.9225	20.867	9.314
28	1005.46	1310.63	6.4226	19.899	9.908
29	1047.22	1389.68	6.8778	19.042	10.507
30	1052.26	1467.07	7.7109	17.534	11.108
31	1077.23	1537.04	8.2113	16.255	11.710
32	1093.22	1608.88	8.7944	15.228	12.512
33	1102.49	1676.77	9.3785	14.070	12.911
34	1112.28	1741.95	9.9058	13.001	13.512
35	1107.92	1803.55	10.5091	11.852	14.110

Table C-3. Deformation J_{IC} and J-R curve results for specimen 11S-08

Test Number	: 0076	Test Temp.	: 290°C
Material Type	: CF-3	Heat Number	: I
Aging Temp.	: 320°C	Aging Time	: 30,000 h
Spec. Thickness	: 25.35 mm	Net Thickness	: 20.31 mm
Spec. Width	: 50.83 mm	Flow Stress	: 309.50 MPa
Modulus E	: 176.59 GPa	(Effective)	
Modulus E	: 180.00 GPa	(Nominal)	
Init. Crack	: 28.7750 mm	Init. a/w	: 0.5661 (Measured)
Final Crack	: 40.2031 mm	Final a/w	: 0.7909 (Measured)
Final Crack	: 39.2841 mm	Final a/w	: 0.7728 (Compliance)
Linear Fit	**$J = B+M(\Delta a)$**		
Intercept B	: 195.479 kJ/m^2	Slope M	: 188.31 kJ/m^{2}mm
Fit Coeff. R	: 0.9623	(8 Data Points)	
J_{IC}	: 230.5 kJ/m^2	(1316.5 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.186 mm	(0.0073 in)	
T average	: 347.1	(J_{IC} at 0.15)	
Power-Law Fit	**$J = C(\Delta a)^n$**		
Coeff. C	: 394.23 kJ/m^2	Exponent n	: 0.4938
Fit Coeff. R	: 0.9683	(8 Data Points)	
J_{IC}(0.20)	: 251.8 kJ/m^2	(1437.9 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.403 mm	(0.0159 in)	
T average	: 343.8	(J_{IC} at 0.20)	
J_{IC}(0.15)	: 230.0 kJ/m^2	(1313.3 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.336 mm	(0.0132 in)	
T average	: 351.4	(J_{IC} at 0.15)	
K_{jc}	: 310.8 MPa-m$^{0.5}$		
J_{IC} Validity & Data Qualification (E 813-85)			
J_{max} allowed	: 455.13 kJ/m^2	($J_{max}=b_o\sigma_f/15$)	
Data Limit	: J_{max} Ignored		
Δa (max) allowed	: 1.942 mm	(at 1.5 exclusion line)	
Data Limit	: 1.5 Exclusion line		
Data Points	: Zone A = 4	Zone B = 2	
Data point spacing	: OK		
b_{net} and b_o size	: OK		
dJ/da at J_{IC}	: OK		
a_f Measurement	: Near-surface	outside limit	
Initial crack shape	: OK		
Crack size estimate	: Inadequate	(by compliance)	
E Effective	: OK		
J_{IC} Estimate	: INVALID		
J-R Curve Validity & Data Qualification (E 1152-86)			
J_{max} allowed	: 314.33 kJ/m^2	($J_{max}=b_{net}\sigma_f/20$)	
Δa (max) allowed	: 2.206 mm	($\Delta a=0.1*b_o$)	
Δa (max) allowed	: 4.569 mm	($\omega=5$)	
Data Points	: Zone A = 9	Zone B = 6	
Data point spacing	: Inadequate		
J-R Curve Data	: INVALID		

Table C-4. Modified J_{IC} and J-R curve results for specimen I1S-08

Linear Fit	**J = B+M(Δa)**		
Intercept B	: 183.374 kJ/m^2	Slope M	: 218.88 kJ/m^2mm
Fit Coeff. R	: 0.982[illegible]	(9 Data Points)	
J_{IC}	: 222.8 kJ/m^2	(1272.0 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.180 mm	(0.0071 in)	
T average	: 403.5	(J_{IC} at 0.15)	
Power-Law Fit	**J = C(Δa)^n**		
Coeff. C	: 414.79 kJ/m^2	Exponent n	: 0.5489
Fit Coeff. R	: 0.9808	(9 Data Points)	
J_{IC}(0.20)	: 252.1 kJ/m^2	(1439.5 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.404 mm	(0.0159 in)	
T average	: 400.1	(J_{IC} at 0.20)	
J_{IC}(0.15)	: 226.9 kJ/m^2	(1295.9 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.333 mm	(0.0131 in)	
T average	: 408.1	(J_{IC} at 0.15)	
K_{Jc}	: 326.8 MPa·m$^{0.5}$		

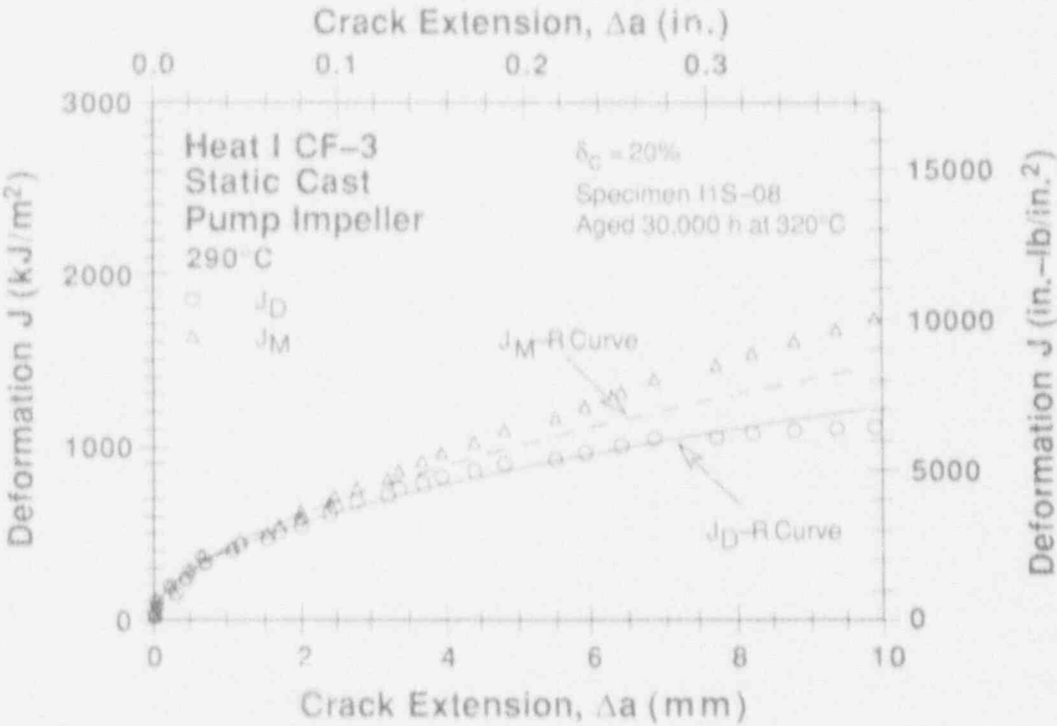

Figure C-2. Deformation and modified J-R curves at 290°C for Heat I aged 30,000 h at 320°C.

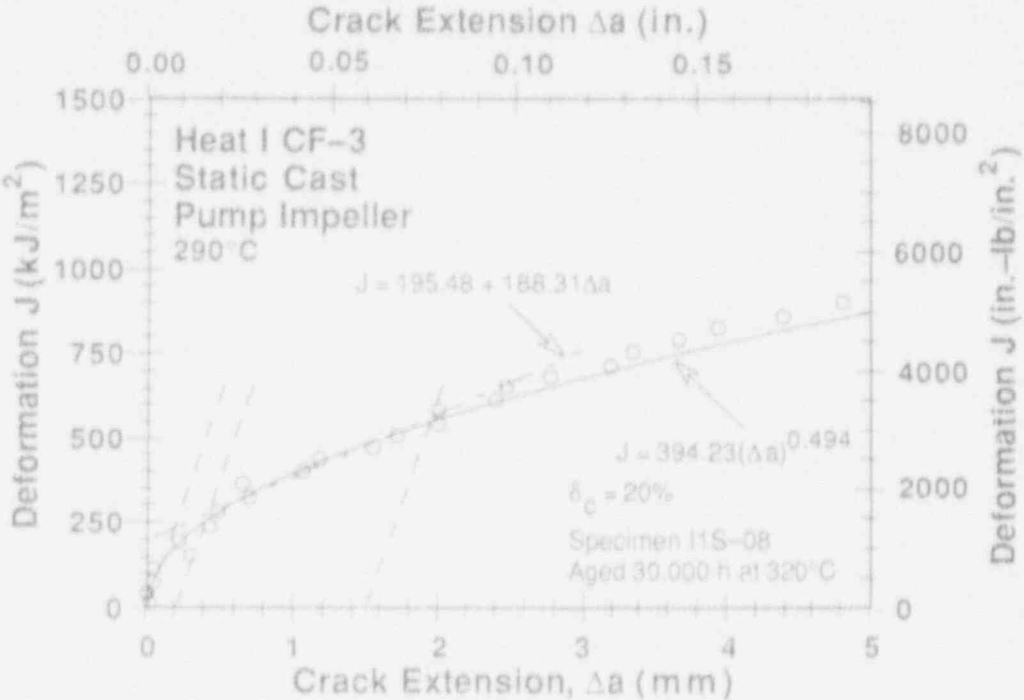

Figure C-3. Deformation J_{IC} at 290°C for Heat I aged 30,000 h at 320°C.

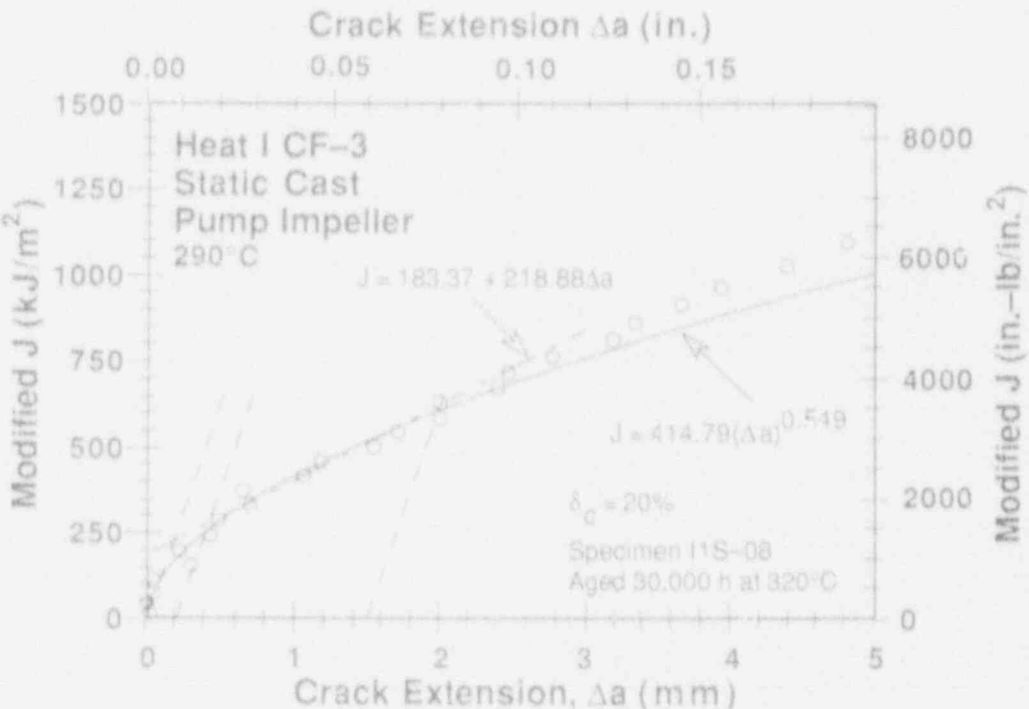

Figure C-4. Modified J_{IC} at 290°C for Heat I aged 30,000 h at 320°C.

Table C-5. Test data for specimen P2B-12

Test Number	: 0058	Test Temp.	: 290°C
Material Type	: CF-3	Heat Number	: P2
Aging Temp.	: 350°C	Aging Time	: 30,000 h
Spec. Thickness	: 25.30 mm	Net Thickness	: 20.30 mm
Spec. Width	: 50.78 mm	Flow Stress	: 292.10 MPa

Unload Number	J_d (kJ/m²)	J_m (kJ/m²)	Δa (mm)	Load (kN)	Deflection (mm)
1	23.99	24.01	0.0200	16.493	0.429
2	30.39	39.23	-0.0747	17.870	0.607
3	62.89	62.79	-0.0590	19.239	0.858
4	87.56	87.42	-0.0655	20.385	1.105
5	118.97	110.35	0.0465	21.494	1.407
6	151.33	152.54	0.1217	22.469	1.705
7	186.70	187.54	0.0854	23.315	2.010
8	221.72	223.07	0.1983	24.034	2.309
9	257.90	261.68	0.3024	24.749	2.613
10	293.51	290.14	0.4120	25.412	2.905
11	335.15	338.19	0.2777	26.065	3.209
12	370.57	379.83	0.5654	26.670	3.505
13	412.18	419.91	0.5021	27.208	3.806
14	451.83	463.41	0.6473	27.742	4.106
15	495.73	505.78	0.5947	28.239	4.406
16	540.80	550.30	0.5775	28.696	4.707
17	586.19	596.42	0.5987	29.203	5.014
18	624.97	642.94	0.8063	29.543	5.314
19	669.15	687.90	0.8256	30.034	5.611
20	709.65	735.70	0.9906	30.378	5.909
21	760.35	782.64	0.9142	30.773	6.212
22	804.01	832.12	1.0340	31.090	6.509
23	857.72	898.78	1.0908	31.303	6.856
24	917.38	946.85	1.0622	31.780	7.209
25	981.32	1015.78	1.1455	32.026	7.613
26	1053.53	1101.94	1.3608	32.374	8.113
27	1137.38	1206.72	1.6566	32.592	8.712
28	1238.90	1310.29	1.6818	32.760	9.312
29	1320.54	1419.40	2.0118	32.907	9.911
30	1408.70	1528.24	2.2418	32.837	10.518
31	1484.00	1638.89	2.6094	32.880	11.117
32	1590.17	1745.40	2.6128	32.824	11.713
33	1654.26	1859.98	3.0742	32.459	12.31'
34	1729.23	1970.07	3.3774	32.232	12.91ı
35	1815.93	2081.07	3.5751	31.716	13.512
36	1902.05	2212.78	3.9239	31.080	14.213
37	1969.43	2342.49	4.3751	30.258	14.911
38	2047.25	2487.84	4.8354	29.285	15.707

Table C-6. Deformation J_{IC} and J-R curve results for specimen P2B-12

Test Number	: 0058	Test Temp.	: 290°C
Material Type	: CF-3	Heat Number	: P2
Aging Temp.	: 350°C	Aging Time	: 30,000 h
Spec. Thickness	: 25.30 mm	Net Thickness	: 20.30 mm
Spec. Width	: 50.78 mm	Flow Stress	: 292.10 MPa
Modulus E	: 186.82 GPa	(Effective)	
Modulus E	: 180.00 GPa	(Nominal)	
Init. Crack	: 28.8625 mm	Init. a/w	: 0.5684 (Measured)
Final Crack	: 34.4375 mm	Final a/w	: 0.6782 (Measured)
Final Crack	: 33.6979 mm	Final a/w	: 0.6637 (Compliance)
Linear Fit	**$J = B+M(\Delta a)$**		
Intercept B	: 326.499 kJ/m²	Slope M	: 483.46 kJ/m²mm
Fit Coeff. R	: 0.9763	(15 Data Points)	
J_{IC}	: 557.0 kJ/m²	(3180.3 in.-lb/in.²)	
Δa (J_{IC})	: 0.477 mm	(0.0188 in)	
T average	: 1058.6	(J_{IC} at 0.15)	
Power-Law Fit	**$J = C(\Delta a)^n$**		
Coeff. C	: 796.53 kJ/m²	Exponent n	: 0.7260
Fit Coeff. R	: 0.9776	(15 Data Points)	
J_{IC}(0.20)	: 650.7 kJ/m²	(3715.9 in.-lb/in.²)	
Δa (J_{IC})	: 0.757 mm	(0.0298 in)	
T average	: 1078.4	(J_{IC} at 0.20)	
J_{IC}(0.15)	: 580.6 kJ/m²	(3315.5 in.-lb/in.²)	
Δa (J_{IC})	: 0.647 mm	(0.0255 in)	
T average	: 1090.0	(J_{IC} at 0.15)	
K_{JC}	: 576.2 MPa-m$^{0.5}$		
J_{IC} Validity & Data Qualification (E 813-85)			
J_{max} allowed	: 426.71 kJ/m²	($J_{max}=b_0\sigma_f/15$)	
Data Limit	: J_{max} Ignored		
Δa (max) allowed	: 3.021 mm	(at 1.5 exclusion line)	
Data Limit	: 1.5 Exclusion line		
Data Points	: Zone A = 9	Zone B = 3	
Data point spacing	: OK		
b_{net} or b_0 size	: Inadequate		
dJ/da at J_{IC}	: OK		
Initial crack shape	: OK		
Final crack shape	: OK		
Crack size estimate	: Inadequate	(by compliance)	
E Effective	: OK		
J_{IC} Estimate	: INVALID		
J-R Curve Validity & Data Qualification (E 1152-86)			
J_{max} allowed	: 296.48 kJ/m²	($J_{max}=b_{net}\sigma_f/20$)	
Δa (max) allowed	: 2.191 mm	($\Delta a=0.1*b_0$)	
Δa (max) allowed	: 6.437 mm	($\omega=5$)	
Data Points	: Zone A = 35	Zone B = 0	
Data point spacing	: Inadequate		
J-R Curve Data	: INVALID		

Table C-7. Modified J_{IC} and J-R curve results for specimen P2B-12

Linear Fit	**$J = B+M(\Delta a)$**		
Intercept B	: 307.792 kJ/m^2	Slope M	: 534.10 kJ/m^{2}mm
Fit Coeff. R	: 0.9849	(16 Data Points)	
J_{IC}	: 567.0 kJ/m^2	(3237.4 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.485 mm	(0.0191 in)	
T average	: 1169.4	(J_{IC} at 0.15)	
Power-Law Fit	**$J = C(\Delta a)^n$**		
Coeff. C	: 824.76 kJ/m^2	Exponent n	: 0.7678
Fit Coeff. R	: 0.9853	(16 Data Points)	
J_{IC}(0.20)	: 686.7 kJ/m^2	(3921.1 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.788 mm	(0.0310 in)	
T average	: 1192.4	(J_{IC} at 0.20)	
J_{IC}(0.15)	: 604.8 kJ/m^2	(3453.4 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.668 mm	(0.0263 in)	
T average	: 1203.5	(J_{IC} at 0.15)	
K_{Jc}	: 616.5 MPa-m$^{0.5}$		

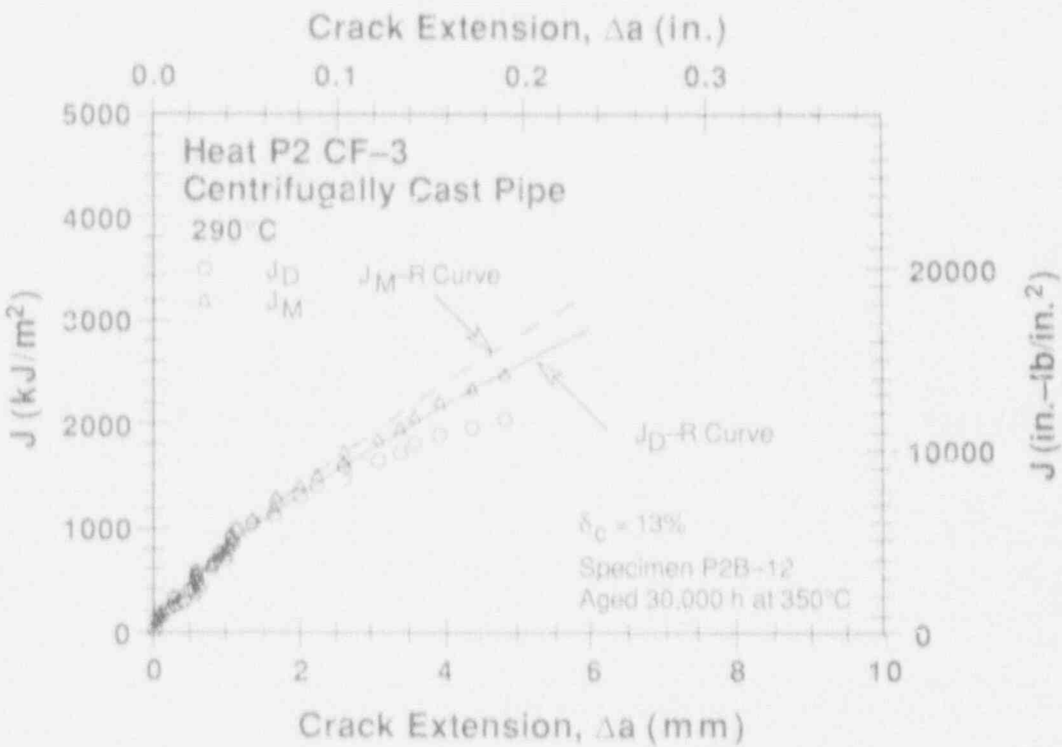

Figure C-5. Deformation and modified J-R curves at 290°C for Heat P2 aged 30,000 h at 350°C.

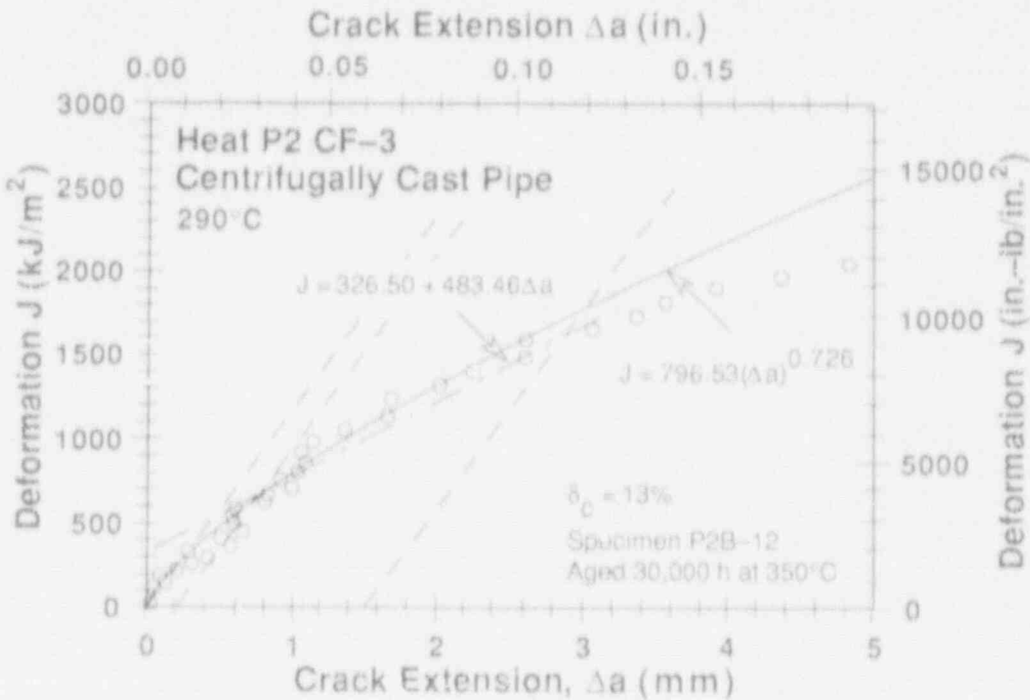

Figure C-6. Deformation J_{IC} at 290°C for Heat P2 aged 30,000 h at 350°C.

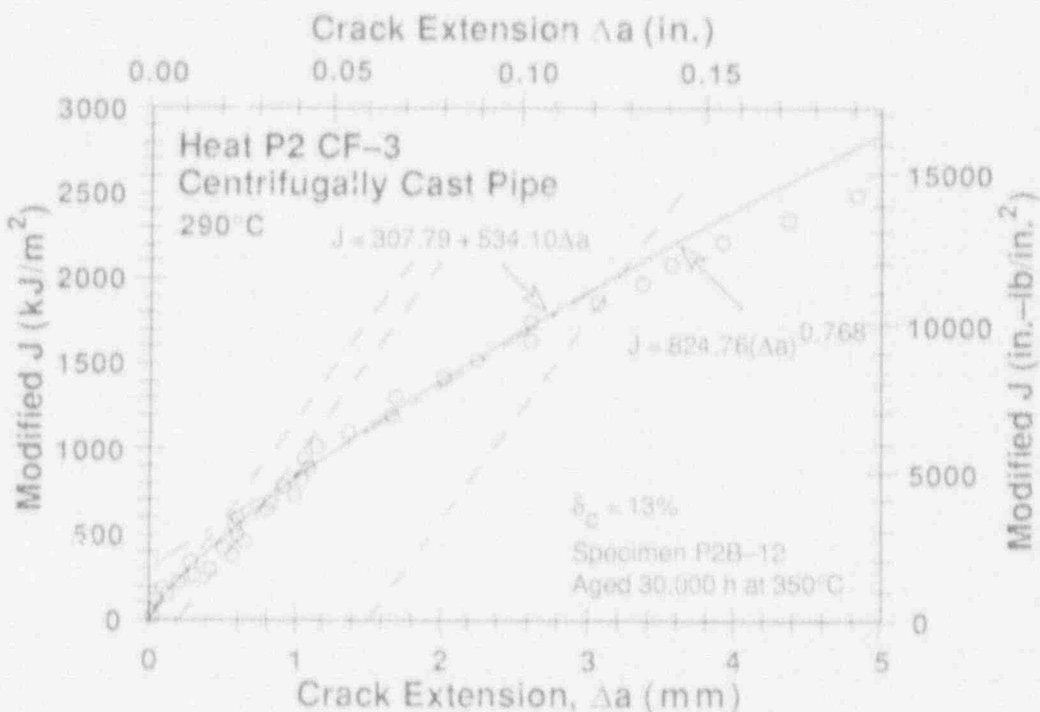

Figure C-7. Modified J_{IC} at 290°C for HeatP2 aged 30,000 h at 350°C.

Table C-8. Test data for specimen 691-07T

Test Number	: 0072	Test Temp.	: 290°C
;aterial Type	: CF-3	Heat Number	: 69
Aging Temp.	: 320°C	Aging Time	: 30,000 h
Spec. ?kness	: 25.35 mm	Net Thickness	: 20.21 ı .m
Spec. Width	: 50.75 mm	Flow Stress	: 295.40 MPa

Unload Number	J_d (kJ/m^2)	J_m (kJ/m^2)	Δa (mm)	Load (kN)	Deflection (mm)
1	15.06	15.09	0.0724	16.028	0.304
2	42.51	42.99	0.3027	19.486	0.606
3	74.08	73.55	0.0316	21.518	0.908
4	108.88	108.55	0.0660	22.935	1.209
5	144.28	145.17	0.2225	24.179	1.509
6	182.16	183.43	0.2602	25.050	1.816
7	221.50	221.51	0.1584	25.885	2.112
8	260.11	262.55	0.3241	26.491	2.409
9	303.07	302.28	0.1362	26.925	2.709
10	340.28	347.18	0.5276	27.503	3.011
11	384.40	387.31	0.3486	27.832	3.311
12	423.24	434.13	0.6702	28.142	3.616
13	459.32	477.05	0.9214	28.313	3.910
14	502.40	521.32	0.9600	28.444	4.213
15	534.20	568.63	1.4399	28.551	4.511
16	578.73	611.69	1.3080	28.551	4.812
17	614.19	661.35	1.7723	28.347	5.117
18	656.91	704.42	1.7809	28.255	5.411
19	690.16	752.57	2.1244	28.166	5.708
20	729.00	798.07	2.2698	27.864	6.009
21	761.92	854.31	2.7428	27.531	6.358
22	790.96	908.16	3.2193	27.041	6.705
23	848.11	967.72	3.2621	26.318	7.109
24	882.63	1032.07	3.7417	25.933	7.507
25	937.24	1107.45	4.0832	24.698	8.007
26	971.42	1199.20	4.0119	23.575	8.609
27	1023.24	1285.05	5.3661	22.795	9.211
28	1049.17	1372.82	6.1402	21.200	9.811
29	1102.97	1467.85	6.6178	19.963	10.509
30	1134.73	1564.21	7.3173	18.738	11.211
31	1176.72	1655.93	7.8212	17.808	11.913
32	1203.50	1747.98	8.4437	16.747	12.613
33	1235.64	1834.80	8.9351	15.496	13.311
34	1246.10	1919.71	9.5708	14.378	14.011
35	1235.89	1998.36	10.2970	12.963	14.711

Table C-9. Deformation J_{IC} and J-R curve results for specimen 691-07T

Test Number	: 0072	Test Temp.	: 290°C
Material Type	: CF-3	Heat Number	: 69
Aging Temp.	: 320°C	Aging Time	: 30,000 h
Spec. Thickness	: 25.35 mm	Net Thickness	: 20.21 mm
Spec. Width	: 50.75 mm	Flow Stress	: 295.40 MPa
Modulus E	: 181.08 GPa	(Effective)	
Modulus E	: 180.00 GPa	(Nominal)	
Init. Crack	: 28.9781 mm	Init. a/w	: 0.5710 (Measured)
Final Crack	: 40.3031 mm	Final a/w	: 0.7941 (Measured)
Final Crack	: 39.2751 mm	Final a/w	: 0.7738 (Compliance)
Linear Fit	**$J = B+M(\Delta a)$**		
Intercept B	: 301.094 kJ/m^2	Slope M	: 185.76 kJ/m^{2}mm
Fit Coeff. R	: 0.9628	(7 Data Points)	
J_{IC}	: 357.3 kJ/m^2	(2040.0 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.302 mm	(0.0119 in)	
T average	: 385.5	(J_{IC} at 0.15)	
Power-Law Fit	**$J = C(\Delta a)^n$**		
Coeff. C	: 492.89 kJ/m^2	Exponent n	: 0.4104
Fit Coeff. R	: 0.9630	(7 Data Points)	
J_{IC}(0.20)	: 376.5 kJ/m^2	(2149.7 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.519 mm	(0.0204 in)	
T average	: 375.1	(J_{IC} at 0.20)	
J_{IC}(0.15)	: 355.4 kJ/m^2	(2029.5 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.451 mm	(0.0177 in)	
T average	: 383.5	(J_{IC} at 0.15)	
K_{Jc}	: 346.6 MPa-m$^{0.5}$		
J_{IC} Validity & Data Qualification (E 813-85)			
J_{max} allowed	: 428.82 kJ/m^2	($J_{max}=b_o\sigma_f/15$)	
Data Limit	: J_{max} Ignored		
Δa (max) allowed	: 2.061 mm	(at 1.5 exclusion line)	
Data Limit	: 1.5 Exclusion line		
Data Points	: Zone A = 1	Zone B = 2	
Data point spacing	: OK		
b_{net} or b_o size	: Inadequate		
dJ/da at J_{IC}	: OK		
Initial crack shape	: OK		
Final crack shape	: OK		
Crack size estimate	: Inadequate	(by compliance)	
E Effective	: OK		
J_{IC} Estimate	: INVALID		
J-R Curve Validity & Data Qualification (E 1152-86)			
J_{max} allowed	: 298.52 kJ/m^2	($J_{max}=b_{net}\sigma_f/20$)	
Δa (max) allowed	: 2.177 mm	($\Delta a=0.1*b_o$)	
Δa (max) allowed	: 3.850 mm	($\omega=5$)	
Data Points	: Zone A = 13	Zone B = 6	
Data point spacing	: Inadequate		
J-R Curve Data	: INVALID		

Table C-10. Modified J_{IC} and J-R curve results for specimen 691-07T

Linear Fit	**J = B+M(Δa)**		
Intercept B	: 289.027 kJ/m²	Slope M	: 218.55 kJ/m²mm
Fit Coeff. R	: 0.9820	(8 Data Points)	
J_{IC}	: 354.6 kJ/m²	(2024.9 in.-lb/in.²)	
Δa (J_{IC})	: 0.300 mm	(0.0118 in)	
T average	: 453.5	(J_{IC} at 0.15)	
Power-Law Fit	**J = C(Δa)ⁿ**		
Coeff. C	: 514.35 kJ/m²	Exponent n	: 0.4752
Fit Coeff. R	: 0.9788	(8 Data Points)	
J_{IC}(0.20)	: 376.5 kJ/m²	(2149.9 in.-lb/in.²)	
Δa (J_{IC})	: 0.519 mm	(0.0204 in)	
T average	: 453.1	(J_{IC} at 0.20)	
J_{IC}(0.15)	: 350.8 kJ/m²	(2003.0 in.-lb/in.²)	
Δa (J_{IC})	: 0.447 mm	(0.0176 in)	
T average	: 462.4	(J_{IC} at 0.15)	
K_{Jc}	: 364.9 MPa·m$^{0.5}$		

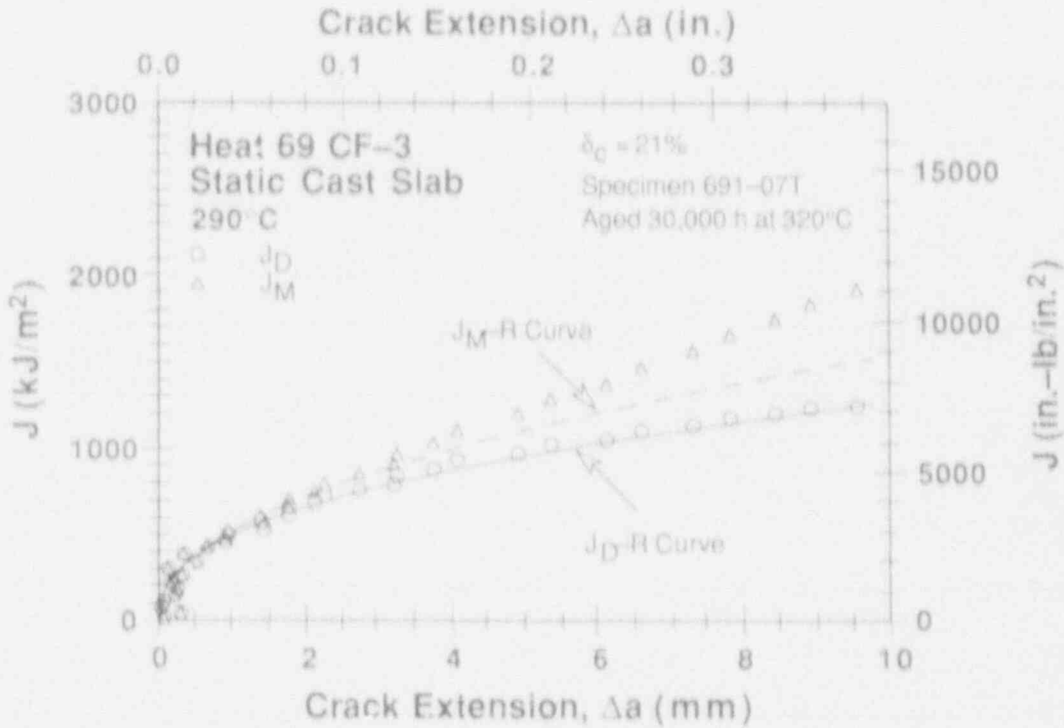

Figure C-8. Deformation and modified J-R curves at 290°C for Heat 69 aged 30,000 h at 320°C.

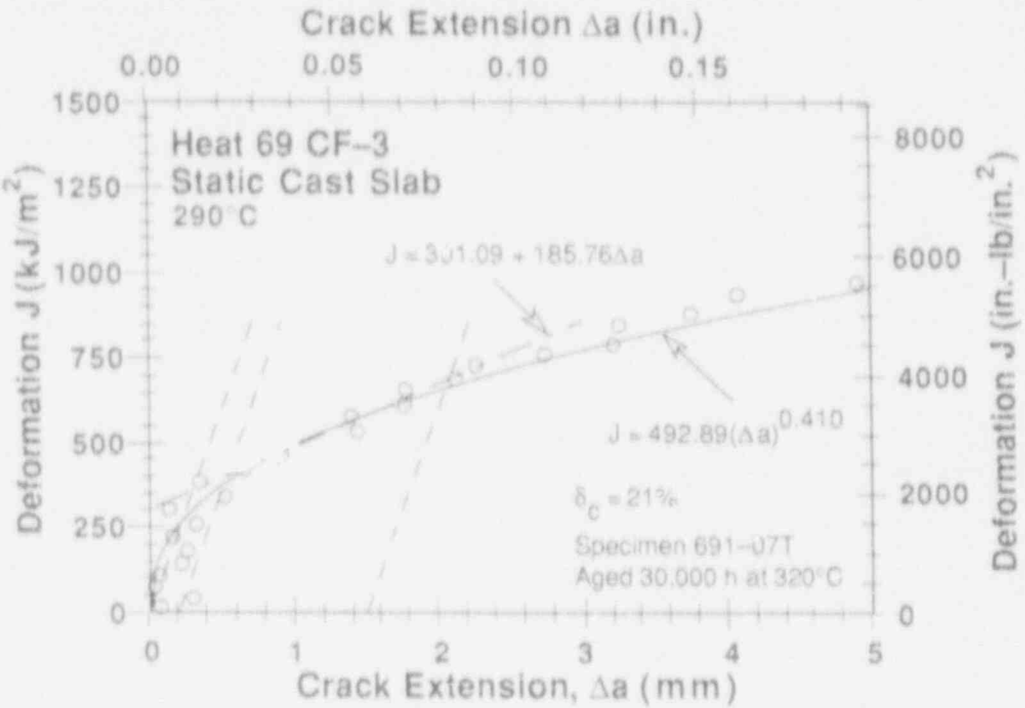

Figure C-9. Deformation J_{IC} at 290°C for Heat 69 aged 30,000 h at 320°C.

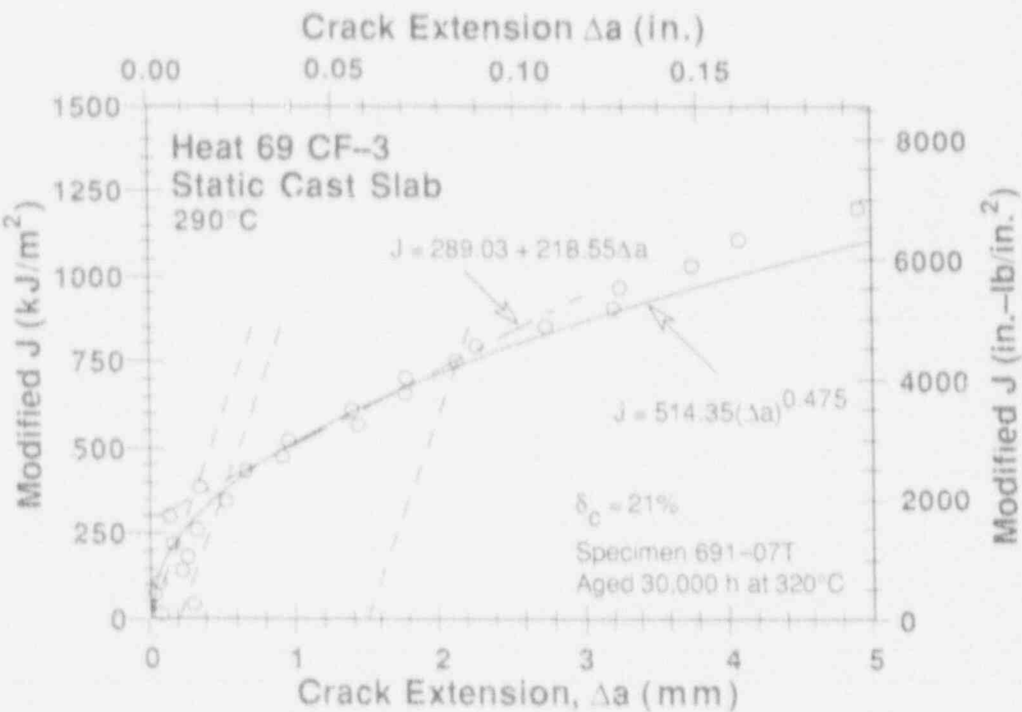

Figure C-10. Modified J_{IC} at 290°C for Heat 69 aged 30,000 h at 320°C.

Table C-11. Test data for specimen 691-02T

Test Number	: 0057	Test Temp.	: 290°C
Material Type	: CF-3	Heat Number	: 69
Aging Temp.	: 350°C	Aging Time	: 10,000 h
Spec. Thickness	: 25.34 mm	Net Thickness	: 20.29 mm
Spec. Width	: 50.78 mm	Flow Stress	: 294.80 MPa

Unload Number	J_d (kJ/m^2)	J_m (kJ/m^2)	Δa (mm)	Load (kN)	Deflection (mm)
1	20.93	20.95	0.0217	17.770	0.370
2	38.29	[illegible]	0.0053	20.035	0.556
3	64.90	[illegible]	0.1244	22.097	0.810
4	92.67	92.77	0.0679	23.590	1.056
5	122.24	123.41	0.2358	24.758	1.305
6	153.43	153.98	0.1602	25.667	1.554
7	184.51	188.21	0.4754	26.471	1.804
8	217.51	220.99	0.4563	27.144	2.056
9	251.45	256.65	0.5800	27.803	2.307
10	283.75	293.01	0.8335	28.393	2.557
11	323.40	333.87	0.8995	28.803	2.841
12	355.96	366.31	0.8936	29.136	3.060
13	387.46	405.25	1.2242	29.406	3.307
14	426.79	441.57	1.1028	29.686	3.560
15	462.49	481.62	1.2632	29.861	3.807
16	496.40	521.23	1.4577	29.70[illegible]	4.060
17	530.01	559.91	1.6168	29.590	4.309
18	559.68	600.47	1.9377	29.475	4.562
19	597.47	637.26	1.9084	29.469	808
20	624.34	679.86	2.3181	29.183	061
21	659.76	718.88	2.4059	28.687	22
22	683.70	760.81	2.8217	28.357	577
23	714.51	795.17	2.9002	28.114	811
24	739.66	835.55	3.2199	27.831	[illegible]
25	775.11	882.66	3.4506	27.403	6.362
26	809.62	938.38	3.8400	26.786	6.711
27	851.41	999.53	4.1831	26.013	7.108
28	897.21	1077.08	4.6960	25.254	7.606
29	938.76	1152.46	5.2052	24.107	8.108
30	985.39	1241.64	5.7972	22.8[illegible]3	8.708
31	1016.94	1328.63	6.5177	21.385	9.313
32	1049.12	1409.59	7.1117	19.73[illegible]	9.911
33	1068.91	1489.22	7.8014	18.481	10.511
34	1079.02	1566.43	8.5220	16.956	11.111
35	1101.80	1637.16	9.0277	15.7[illegible]9	11.711
36	1112.91	1706.27	9.6298	14.802	12.313
37	1135.83	1789.58	10.1638	13.748	13.008

Table C-12. Deformation J_{IC} and J-R curve results for specimen 691-02T

Test Number	: 0057	Test Temp.	: 290°C
Material Type	: CF-3	Heat Number	: 69
Aging Temp.	: 350°C	Aging Time	: 10,000 h
Spec. Thickness	: 25.34 mm	Net Thickness	: 20.29 mm
Spec. Width	: 50.78 mm	Flow Stress	: 294.80 MPa
Modulus E	: 182.03 GPa	(Effective)	
Modulus E	: 180.00 GPa	(Nominal)	
Init. Crack	: 28.5250 mm	Init. a/w	: 0.5617 (Measured)
Final Crack	: 39.5938 mm	Final a/w	: 0.7797 (Measured)
Final Crack	: 38.6888 mm	Final a/w	: 0.7619 (Compliance)

Linear Fit	**$J = B+M(\Delta a)$**		
Intercept B	: 94.262 kJ/m²	Slope M	: 262.92 kJ/m²mm
Fit Coeff. R	: 0.9785	(13 Data Points)	
J_{IC}	: 121.3 kJ/m²	(692.7 in.-lb/in.²)	
Δa (J_{IC})	: 0.103 mm	(0.0041 in)	
T average	: 550.7	(J_{IC} at 0.15)	

Power-Law Fit	**$J = C(\Delta a)^n$**		
Coeff. C	: 362.56 kJ/m²	Exponent n	: 0.7559
Fit Coeff. R	: 0.9808	(13 Data Points)	
J_{IC}(0.20)	: 158.4 kJ/m²	(904.4 in.-lb/in.²)	
Δa (J_{IC})	: 0.334 mm	(0.0132 in)	
T average	: 561.5	(J_{IC} at 0.20)	
J_{IC}(0.15)	: 131.6 kJ/m²	(751.3 in.-lb/in.²)	
Δa (J_{IC})	: 0.262 mm	(0.0103 in)	
T average	: 567.8	(J_{IC} at 0.15)	
K_{JC}	: 335.3 MPa-m^0.5		

J_{IC} Validity & Data Qualification (E 813-87)		
J_{max} allowed	: 437.42 kJ/m²	($J_{max}=b_o\sigma_f/15$)
Data Limit	: J_{max} ignored	
Δa (max) allowed	: 2.024 mm	(at 1.5 exclusion line)
Data Limit	: 1.5 Exclusion line	
Data Points	: Zone A = 3	Zone B = 4
Data point spacing	: OK	
b_{net} and b_o size	: OK	
dJ/da at J_{IC}	: OK	
Initial crack shape	: OK	
Final crack shape	: OK	
Crack size estimate	: Inadequate	(by compliance)
E Effective	: OK	
J_{IC} Estimate	: INVALID	

J-R Curve Validity & Data Qualification (E 1152-86)		
J_{max} allowed	: 299.10 kJ/m²	($J_{max}=b_{net}\sigma_f/20$)
Δa (max) allowed	: 2.226 mm	($\Delta a=0.1*b_o$)
Δa (max) allowed	: 6.669 mm	(ω=5)
Data Points	: Zone A = 9	Zone B = 10
Data point spacing	: OK	
J-R Curve Data	: INVALID	

Table C-13. Modified J_{IC} and J-R curve results for specimen 691-02T

Linear Fit	**J = B+M(Δa)**		
Intercept B	: 83.518 kJ/m^2	Slope M	: 288.11 kJ/m^2mm
Fit Coeff. R	: 0.9831	(13 Data Points)	
J_{IC}	: 110.5 kJ/m^2	(631.1 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.094 mm	(0.0037 in)	
T average	: 603.5	(J_{IC} at 0.15)	
Power-Law Fit	**J = C(Δa)^n**		
Coeff. C	: 376.76 kJ/m^2	Exponent n	: 0.7893
Fit Coeff. R	: 0.9835	(13 Data Points)	
J_{IC}(0.20)	: 158.8 kJ/m^2	(906.8 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.335 mm	(0.0132 in)	
T average	: 608.6	(J_{IC} at 0.20)	
J_{IC}(0.15)	: 130.3 kJ/m^2	(744.1 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.261 mm	(0.0103 in)	
T average	: 614.5	(J_{IC} at 0.15)	
K_{jc}	: 348.8 MPa·m$^{0.5}$		

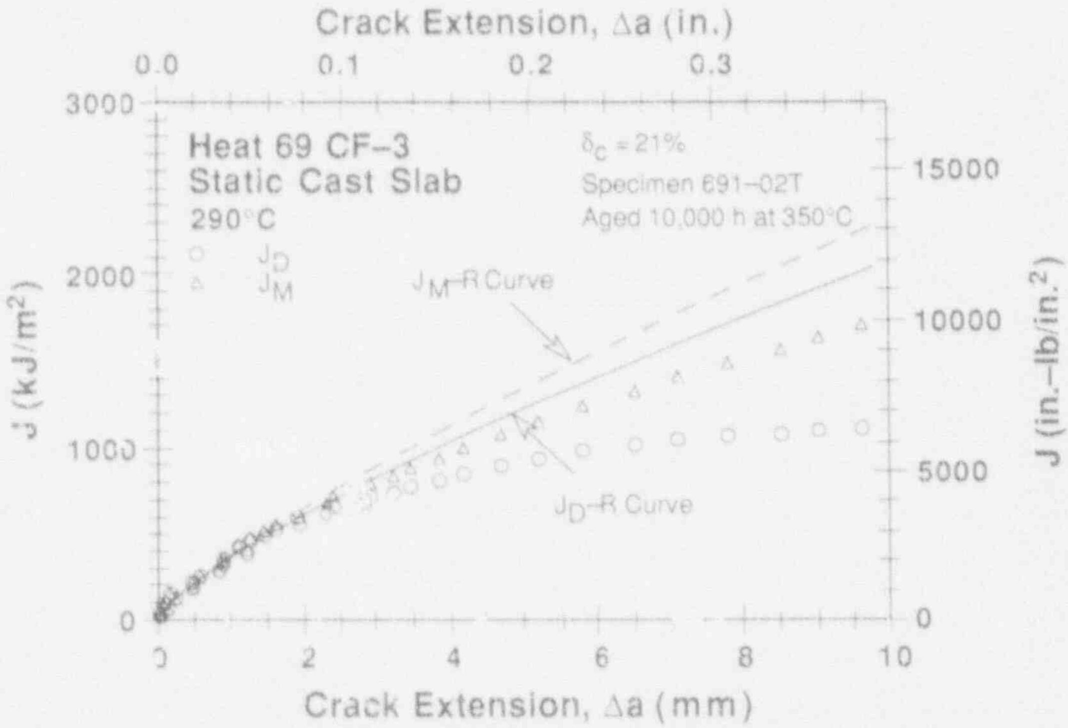

Figure C-11. Deformation and modified J-R curves at 290°C for Heat 69 aged 10,000 h at 350°C.

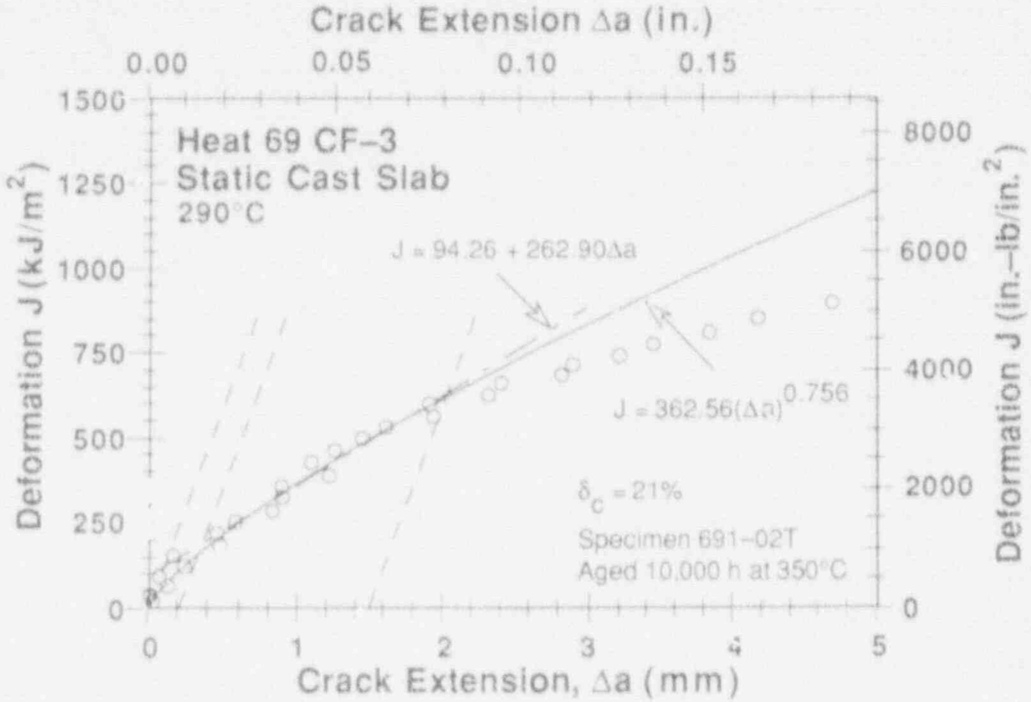

Figure C-12. Deformation J_{IC} at 290°C for Heat 69 aged 10,000 h at 350°C.

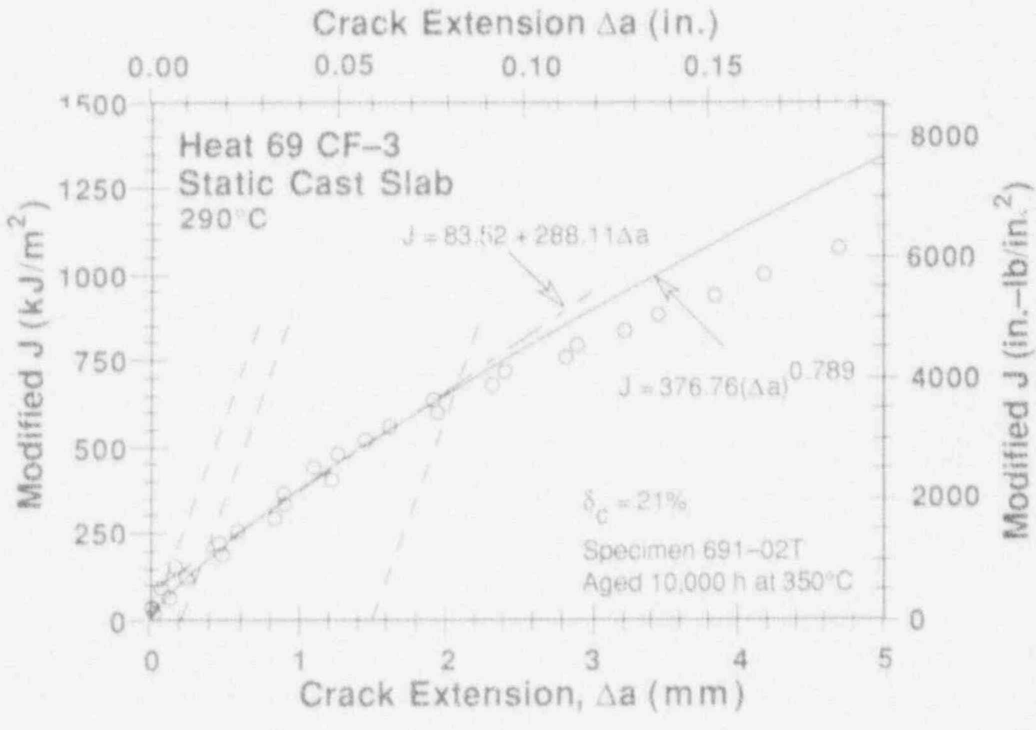

Figure C-13. Modified J_{IC} at 290°C for Heat 69 aged 10,000 h at 350°C.

Table C-14. Test data for specimen 691-03T

Test Number	: 0048	Test Temp.	: 290°C
Material Type	: CF-3	Heat Number	: 69
Aging Temp.	: 350°C	Aging Time	: 30,000 h
Spec. Thickness	: 25.32 mm	Net Thickness	: 20.26 mm
Spec. Width	: 50.80 mm	Flow Stress	: 323.30 MPa

Unload Number	J_d (kJ/m^2)	J_m (kJ/m^2)	Δa (mm)	Load (kN)	Deflection (mm)
1	15.45	15.46	0.0189	16.810	0.302
2	27.56	27.54	-0.0085	19.001	0.440
3	56.35	56.55	0.0776	21.911	0.724
4	87.25	87.53	0.0972	23.842	0.999
5	118.31	119.[illegible]	0.1866	25.367	1.255
6	149.93	150.95	0.2106	26.454	1.504
7	182.80	185.67	0.4000	27.352	1.757
8	224.41	226.52	0.3374	28.406	2.056
9	266.40	271.53	0.5425	29.137	2.359
10	315.67	322.69	0.6497	29.783	2.706
11	363.80	377.04	0.9497	30.117	3.054
12	405.72	425.04	1.2090	30.294	3.365
13	442.90	471.40	1.5620	30.216	3.657
14	484.15	517.82	1.7419	30.220	3.955
15	528.34	565.67	1.8574	29.925	4.257
16	562.29	616.57	2.3507	29.[illegible]92	4.561
17	603.49	661.41	2.4488	29.393	4.858
18	634.17	711.77	2.9424	28.741	5.159
19	679.19	758.74	3.1986	28.162	5.467
20	708.54	813.54	3.5569	27.474	5.811
21	748.10	867.82	3.8516	26.698	6.160
22	777.06	932.20	4.[illegible]	25.987	6.564
23	8[illegible].96	990.50	4.9826	24.820	6.961
24	848.[illegible]	1057.64	5.4585	23.718	7.410
25	882.66	1132.00	6.0787	22.411	7.912
26	901.17	1203.43	6.8493	20.821	8.420
27	922.82	1283.33	7.6423	19.206	9.014
28	933.33	1359.62	8.4852	17.405	9.611
29	945.89	1432.17	9.2098	15.867	10.212
30	965.87	1502.7[illegible]	9.7853	14.736	10.815
31	979.44	1571.51	10.3797	13.556	11.412

Table C-15. Deformation J_{IC} and J-R curve results for specimen 691-03T

Test Number	: 0048	Test Temp.	: 290°C
Material Type	: CF-3	Heat Number	: 69
Aging Temp.	: 350°C	Aging Time	: 30,000 h
Spec. Thickness	: 25.32 mm	Net Thickness	: 20.26 mm
Spec. Width	: 50.80 mm	Flow Stress	: 323.30 MPa
Modulus E	: 181.77 GPa	(Effective)	
Modulus E	: 180.00 GPa	(Nominal)	
Init. Crack	: 28.4406 mm	Init. a/w	: 0.5598 (Measured)
Final Crack	: 39.4719 mm	Final a/w	: 0.7770 (Measured)
Final Crack	: 38.8203 mm	Final a/w	: 0.7641 (Compliance)

Linear Fit	$J = B+M(\Delta a)$		
Intercept B	: 154.075 kJ/m^2	Slope M	: 197.58 kJ/m^2 mm
Fit Coeff. R	: 0.9778	(9 Data Points)	
J_{IC}	: 181.9 kJ/m^2	(1038.5 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.141 mm	(0.0055 in.)	
T average	: 343.6	(J_{IC} at 0.15)	

Power-Law Fit	$J = C(\Delta a)^n$		
Coeff. C	: 365.46 kJ/m^2	Exponent n	: 0.5447
Fit Coeff. R	: 0.9704	(9 Data Points)	
J_{IC}(0.20)	: 210.3 kJ/m^2	(1201.0 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.363 mm	(0.0143 in.)	
T average	: 339.0	(J_{IC} at 0.20)	
J_{IC}(0.15)	: 188.1 kJ/m^2	(1074.2 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.295 mm	(0.0116 in.)	
T average	: 346.0	(J_{IC} at 0.15)	
K_{jc}	: 307.0 MPa-m$^{0.5}$		

J_{IC} Validity & Data Qualification (E 813-85)

J_{max} allowed	: 481.96 kJ/m^2	(J_{max}=$b_o\sigma_f$/15)
Data Limit	: J_{max} Ignored	
Δa (max) allowed	: 1.901 mm	(at 1.5 exclusion line)
Data Limit	: 1.5 Exclusion line	
Data Points	: Zone A = 4	Zone B = 3
Data point spacing	: OK	
b_{net} and b_o size	: OK	
dJ/da at J_{IC}	: OK	
Initial crack shape	: OK	
Final crack shape	: OK	
Crack size estimate	: Inadequate	(by compliance)
E Effective	: OK	
J_{IC} Estimate	: INVALID	

J-R Curve Validity & Data Qualification (E 1152-86)

J_{max} allowed	: 3[illegible]57 kJ/m^2	(J_{max}=$b_{net}\sigma_f$/20)
Δa (max) allowed	: 2.[illegible]36 mm	(Δa=0.1*b_o)
Δa (max) allowed	: 4.991 mm	(ω=5)
Data Points	: Zone A = 9	Zone B = 5
Data point spacing	: Inadequate	
J-R Curve Data	: INVALID	

Table C-16. Modified J_{IC} and J-R curve results for specimen 691-03T

Linear Fit	**$J = B+M(\Delta a)$**		
Intercept B	: 146.805 kJ/m^2	Slope M	: 220.78 kJ/m^2 mm
Fit Coeff. R	: 0.9828	(9 Data Points)	
J_{IC}	: 177.0 kJ/m^2	(1010.9 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.137 mm	(0.0054 in.)	
T average	: 383.9	(J_{IC} at 0.15)	
Power-Law Fit	**$J = C(\Delta a)^n$**		
Coeff. C	: 381.73 kJ/m^2	Exponent n	: 0.5803
Fit Coeff. R	: 0.9748	(9 Data Points)	
$J_{IC}(0.20)$	: 212.5 kJ/m^2	(1213.2 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.364 mm	(0.0143 in.)	
T average	: 375.3	(J_{IC} at 0.20)	
$J_{IC}(0.15)$	: 188.2 kJ/m^2	(1074.5 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.296 mm	(0.0116 in.)	
T average	: 382.5	(J_{IC} at 0.15)	
K_{jc}	: 218.9 MPa-m$^{0.5}$		

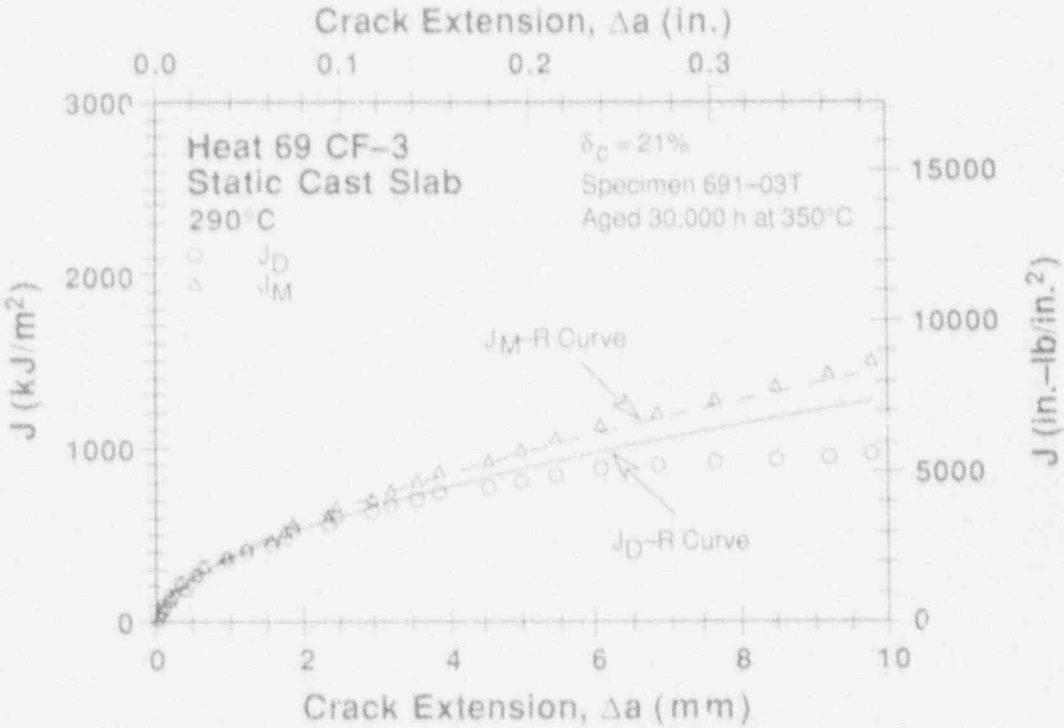

Figure C-14. Deformation and modified J-R curves at 290°C for Heat 69 aged 30,000 h at 350°C.

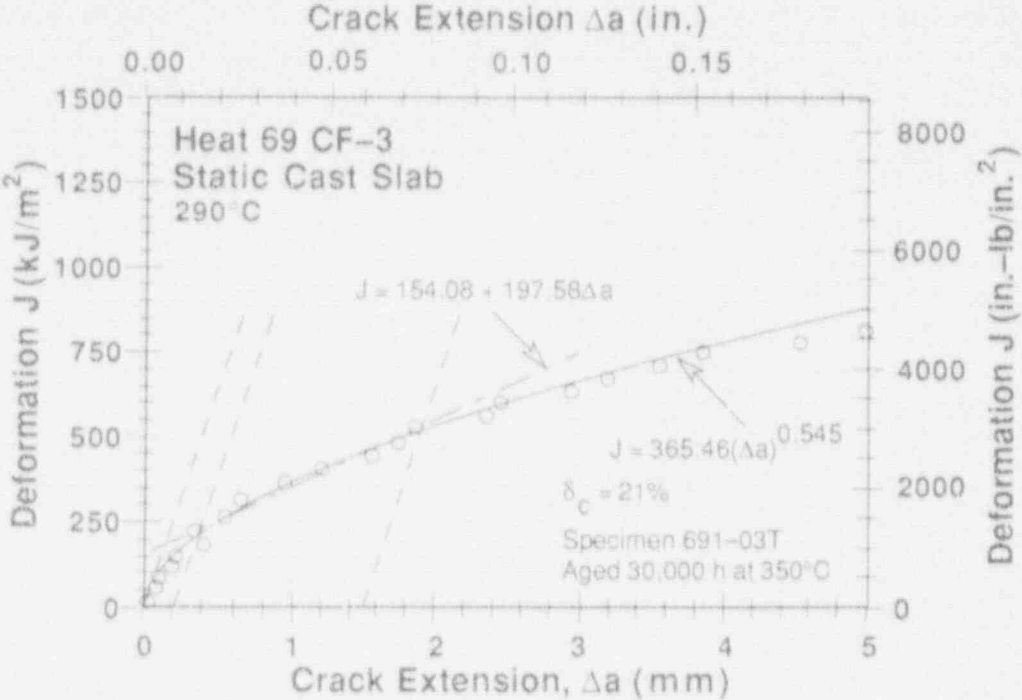

Figure C-15. Deformation J_{IC} at 290°C for Heat 69 aged 30,000 h at 350°C.

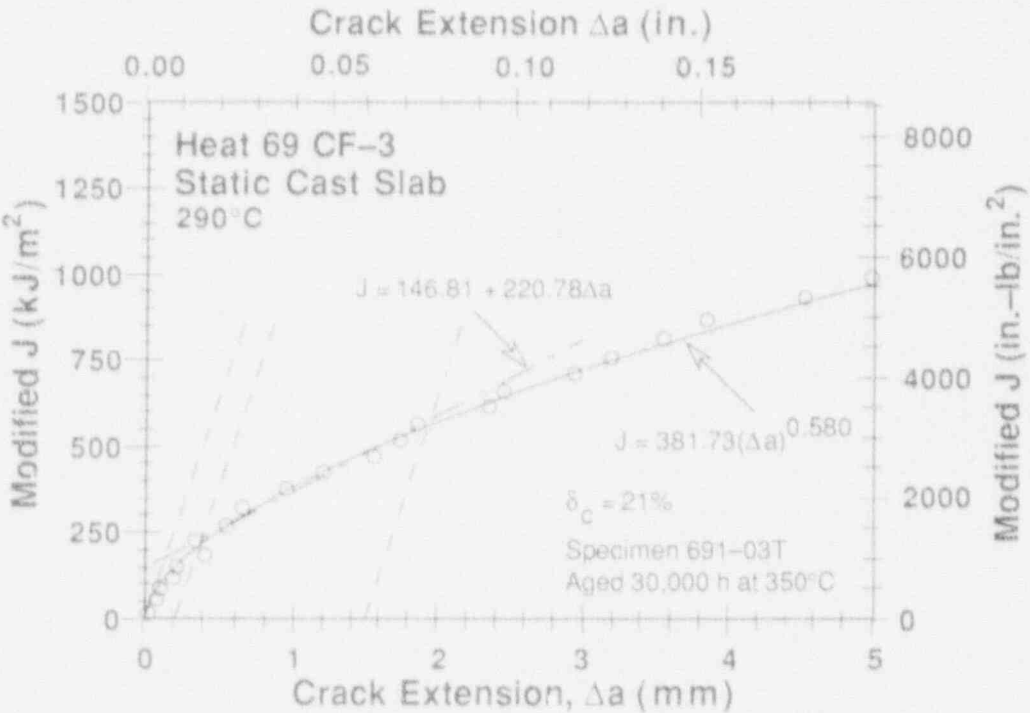

Figure C-16. Modified J_{IC} at 290°C for Heat 69 aged 30,000 h at 350°C.

Table C-17. Test data for specimen 697-01T

Test Number	: 0063	Test Temp.	: 290°C
Material Type	: CF-3	Heat Number	: 69
Aging Temp.	: 400°C	Aging Time	: 10,000 h
Spec. Thickness	: 25.34 mm	Net. Thickness	: 20.30 mm
Spec. Width	: 50.82 mm	Flow Stress	: 336.60 MPa

Unload Number	J_d (kJ/m^2)	J_m (kJ/m^2)	Δa (mm)	Load (kN)	Deflection (mm)
1	20.56	20.66	0.1514	17.672	0.354
2	44.71	44.94	0.2110	20.865	0.606
3	77.72	77.88	0.1933	23.326	0.907
4	115.48	112.11	0.4069	24.916	1.208
5	152.02	155.34	0.4249	26.225	1.509
6	189.67	191.83	0.3124	27.210	1.809
7	230.49	235.59	0.5437	27.869	2.112
8	269.46	278.68	0.8160	28.200	2.412
9	281.96	294.35	1.0152	28.438	2.524
10	322.89	336.05	1.0562	28.513	2.812
11	360.63	382.59	1.4733	28.277	3.112
12	398.69	426.67	1.7273	28.165	3.414
13	428.86	463.48	1.9847	28.005	3.659
14	461.48	500.55	2.1429	27.665	3.909
15	485.88	539.95	2.6403	27.238	4.161
16	514.73	576.43	2.8758	26.515	4.418
17	536.40	613.54	3.3245	25.890	4.662
18	562.29	648.76	3.5792	25.136	4.913
19	587.26	693.21	4.0778	24.576	5.211
20	620.17	742.83	4.4743	23.495	5.564
21	645.97	799.82	5.1626	22.502	5.960
22	672.50	860.59	5.8617	20.739	6.412
23	701.00	927.68	6.5902	19.641	6.925
24	718.01	990.62	7.3908	18.109	7.420
25	755.98	1047.61	7.7114	17.154	7.908
26	758.23	1117.12	8.7457	15.427	8.466
27	763.10	1162.69	9.3437	14.242	8.912
28	776.87	1217.42	9.9126	13.363	9.410

Table C-18. Deformation J_{IC} and J-R curve results for specimen 697-01T

Test Number	: 0063	Test Temp.	: 290°C
Material Type	: CF-3	Heat Number	: 69
Aging Temp.	: 400°C	Aging Time	: 10,000 h
Spec. Thickness	: 25.34 mm	Net. Thickness	: 20.30 mm
Spec. Width	: 50.82 mm	Flow Stress	: 336.60 MPa
Modulus E	: 179.80 GPa	(Effective)	
Modulus E	: 180.00 GPa	(Nominal)	
Init. Crack	: 28.6719 mm	Init. a/w	: 0.5642 (Measured)
Final Crack	: 38.8344 mm	Final a/w	: 0.7642 (Measured)
Final Crack	: 38.5845 mm	Final a/w	: 0.7593 (Compliance)
Linear Fit	**$J = B+M(\Delta a)$**		
Intercept B	: 126.178 kJ/m^2	Slope M	: 162.35 kJ/m^{2}mm
Fit Coeff. R	: 0.9670	(8 Data Points)	
J_{IC}	: 143.5 kJ/m^2	(819.3 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.107 mm	(0.0042 in)	
T average	: 257.6	(J_{IC} at 0.15)	
Power-Law Fit	**$J = C(\Delta a)^n$**		
Coeff. C	: 296.40 kJ/m^2	Exponent n	: 0.5102
Fit Coeff. R	: 0.9408	(8 Data Points)	
J_{IC}(0.20)	: 166.3 kJ/m^2	(952.2 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.324 mm	(0.0128 in)	
T average	: 243.0	(J_{IC} at 0.20)	
J_{IC}(0.15)	: 149.3 kJ/m^2	(852.8 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.261 mm	(0.0103 in)	
T average	: 248.6	(J_{IC} at 0.15)	
K_{Jc}	: 268.1 MPa-m$^{0.5}$		
J_{IC} Validity & Data Qualification (E 813-85)			
J_{max} allowed	: 496.89 kJ/m^2	($J_{max}=b_o\sigma_f/15$)	
Data Limit	: J_{max} Ignored		
Δa (max) allowed	: 1.797 mm	(at 1.5 exclusion line)	
Data Limit	: 1.5 Exclusion line		
Data Points	: Zone A = 3	Zone B = 2	
Data point spacing	: OK		
b_{net} and b_o size	: OK		
dJ/da at J_{IC}	: OK		
Initial crack shape	: OK		
Final crack shape	: OK		
Crack size estimate	: OK	(by compliance)	
E Effective	: OK		
J_{IC} Estimate	: VALID		
J-R Curve Validity & Data Qualification (E 1152-86)			
J_{max} allowed	: 341.68 kJ/m^2	($J_{max}=b_{net}\sigma_f/20$)	
Δa (max) allowed	: 2.214 mm	($\Delta a=0.1*b_o$)	
Δa (max) allowed	: 4.705 mm	($\omega=5$)	
Data Points	: Zone A = 1	Zone B = 12	
Data point spacing	: Inadequate		
J-R Curve Data	: INVALID		

Table C-19. Modified J_{IC} and J-R curve results for specimen 697-01T

Linear Fit	**J = B+M(Δa)**		
Intercept B	: 121.389 kJ/m^2	Slope M	: 180.48 kJ/m^{2}mm
Fit Coeff. R	: 0.9737	(8 Data Points)	
J_{IC}	: 140.2 kJ/m^2	(800.5 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.104 mm	(0.0041 in)	
T average	: 286.4	(J_{IC} at 0.15)	
Power-Law Fit	**J = C(Δa)^n**		
Coeff. C	: 309.87 kJ/m^2	Exponent n	: 0.5414
Fit Coeff. R	: 0.9478	(8 Data Points)	
J_{IC}(0.20)	: 168.7 kJ/m^2	(963.3 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.325 mm	(0.0128 in)	
T average	: 267.9	(J_{IC} at 0.20)	
J_{IC}(0.15)	: 149.8 kJ/m^2	(855.5 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.261 mm	(0.0103 in)	
T average	: 273.6	(J_{IC} at 0.15)	
K_{jc}	: 277.5 MPa-m$^{0.5}$		

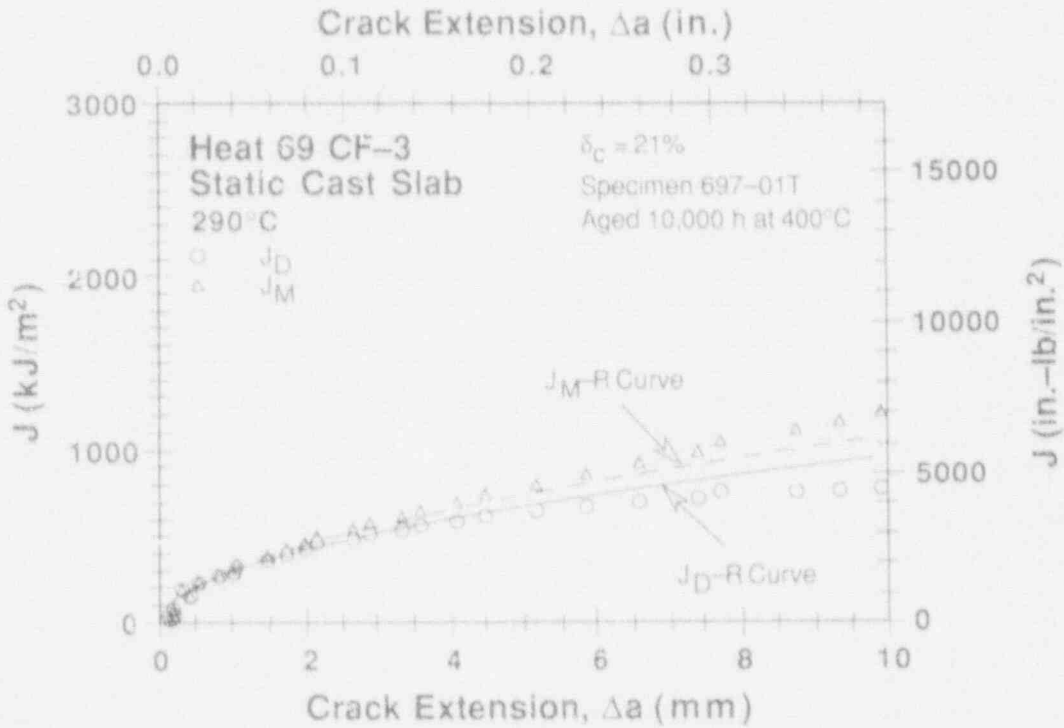

Figure C-17. Deformation and modified J-R curves at 290°C for Heat 69 aged 10,000 h at 400°C.

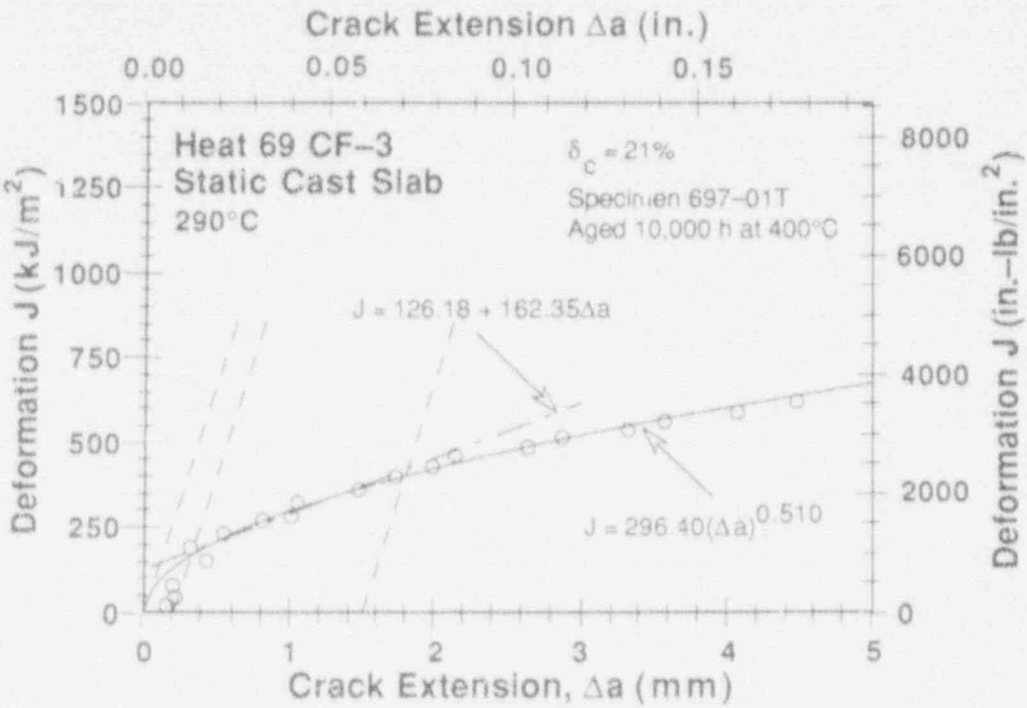

Figure C-18. Deformation J_{IC} at 290°C for Heat 69 aged 10,000 h at 400°C.

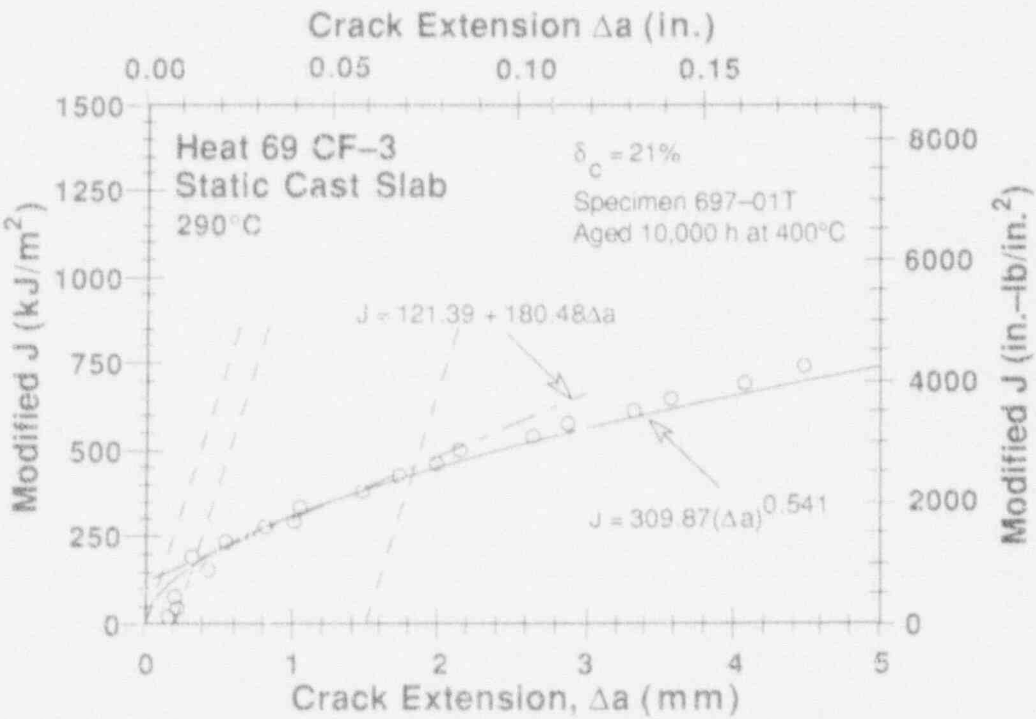

Figure C-19. Modified J_{IC} at 290°C for Heat 69 aged 10,000 h at 400°C.

Table C-20. Test data for specimen P1B-12

Test Number	: 0074	Test Temp.	: 290°C
Material Type	: CF-8	Heat Number	: P1
Aging Temp.	: 320°C	Aging Time	: 30,000 h
Spec. Thickness	: 25.34 mm	Net Thickness	: 20.31 mm
Spec. Width	: 50.83 mm	Flow Stress	: 306.10 MPa

Unload Number	J_d (kJ/m^2)	J_m (kJ/m^2)	Δa (mm)	Load (kN)	Deflection (mm)
1	14.05	14.08	0.0697	15.238	0.306
2	39.73	39.58	-0.0302	18.423	0.608
3	69.19	69.06	-0.0252	20.134	0.909
4	99.98	100.13	0.0288	21.295	1.205
5	137.93	138.71	0.1135	22.385	1.553
6	178.33	179.32	0.1347	23.237	1.906
7	218.94	221.93	0.2965	23.936	2.256
8	264.81	263.35	-0.0005	24.587	2.606
9	305.76	310.78	0.3684	25.198	2.960
10	351.88	353.84	0.2176	25.768	3.309
11	388.96	395.39	0.4145	26.007	3.611
12	427.10	435.12	0.4784	26.414	3.910
13	466.56	476.46	0.5471	26.622	4.211
14	502.30	518.55	0.7598	26.917	4.510
15	538.39	560.42	0.9388	27.057	4.809
16	575.01	603.36	1.1209	27.140	5.110
17	613.39	645.79	1.2295	27.122	5.408
18	655.44	688.36	1.2426	27.118	5.707
19	685.46	734.16	1.6152	27.110	6.010
20	718.53	777.15	1.8369	27.152	6.310
21	755.31	819.71	1.9589	27.035	6.602
22	794.40	865.88	2.1000	26.835	6.911
23	828.73	910.47	2.2942	26.571	7.212
24	856.40	955.19	2.6028	26.378	7.512
25	893.90	997.88	2.6924	26.207	7.810
26	926.60	1051.45	3.0347	26.022	8.160
27	961.71	1103.19	3.2949	25.932	8.511
28	1015.47	1162.21	3.3724	25.806	8.911
29	1074.47	1239.62	3.6258	25.676	9.412
30	1137.93	1314.39	3.7717	25.403	9.909
31	1184.81	1407.53	4.3303	24.452	10.512
32	1227.15	1495.63	4.8510	23.736	11.112
33	1248.44	1581.75	5.5512	21.906	11.710
34	1263.06	1662.16	6.2286	19.805	12.312
35	1271.30	1750.80	7.0170	18.434	13.010
36	1294.64	1837.32	7.6059	17.578	13.709
37	1335.06	1924.00	8.0132	16.394	14.413
38	1366.23	2009.13	8.4647	15.706	15.110
39	1375.61	2091.99	9.0532	14.850	15.808

Table C-21. Deformation J_{IC} and J-R curve results for specimen P1B-12

Test Number	: 0074	Test Temp.	: 290°C
Material Type	: CF-8	Heat Number	: P1
Aging Temp.	: 320°C	Aging Time	: 30,000 h
Spec. Thickness	: 25.34 mm	Net Thickness	: 20.31 mm
Spec. Width	: 50.83 mm	Flow Stress	: 306.10 MPa
Modulus E	: 172.27 GPa	(Effective)	
Modulus E	: 180.00 GPa	(Nominal)	
Init. Crack	: 29.0063 mm	Init. a/w	: 0.5706 (Measured)
Final Crack	: 39.4344 mm	Final a/w	: 0.7758 (Measured)
Final Crack	: 38.0595 mm	Final a/w	: 0.7487 (Compliance)

Linear Fit	**J = B+M(Δa)**		
Intercept B	: 353.900 kJ/m^2	Slope M	: 207.18 kJ/m^2mm
Fit Coeff. R	: 0.9881	(10 Data Points)	
J_{IC}	: 426.0 kJ/m^2	(2432.4 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.348 mm	(0.0137 in)	
T average	: 380.9	(J_{IC} at 0.15)	

Power-Law Fit	**$J = C(\Delta a)^n$**		
Coeff. C	: 571.23 kJ/m^2	Exponent n	: 0.4030
Fit Coeff. R	: 0.9847	(10 Data Points)	
J_{IC}(0.20)	: 456.3 kJ/m^2	(2605.5 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.573 mm	(0.0225 in)	
T average	: 366.1	(J_{IC} at 0.20)	
J_{IC}(0.15)	: 433.4 kJ/m^2	(2474.7 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.504 mm	(0.0198 in)	
T average	: 374.0	(J_{IC} at 0.15)	
K_{jc}	: 365.4 MPa-$m^{0.5}$		

J_{IC} Validity & Data Qualification (E 813-85)		
J_{max} allowed	: 445.41 kJ/m^2	($J_{max}=b_o\sigma_f/15$)
Data Limit	: J_{max} Ignored	
Δa (max) allowed	: 2.133 mm	(at 1.5 exclusion line)
Data Limit	: 1.5 Exclusion line	
Data Points	: Zone A = 3	Zone B = 4
Data point spacing	: OK	
b_{net} or b_o size	: Inadequate	
dJ/da at J_{IC}	: OK	
a_o Measurement	: 9 outside limit	
a_o Measurement	: 1 outside limit	
a_f Measurement	: Near-surface	outside limit
Crack size estimate	: Inadequate	(by compliance)
E Effective	: OK	
J_{IC} Estimate	: INVALID	

J-R Curve Validity & Data Qualification (E 1152-86)		
J_{max} allowed	: 310.84 kJ/m^2	($J_{max}=b_{net}\sigma_f/20$)
Δa (max) allowed	: 2.183 mm	($\Delta a=0.1*b_o$)
Δa (max) allowed	: 3.792 mm	(ω=5)
Data Points	: Zone A = 15	Zone B = 4
Data point spacing	: Inadequate	
J-R Curve Data	: INVALID	

Table C-22. Modified J_{IC} and J-R curve results for specimen P1B-12

Linear Fit	**J = B+M(Δa)**		
Intercept B	: 338.806 kJ/m^2	Slope M	: 247.33 kJ/m^{2}mm
Fit Coeff. R	: 0.9919	(10 Data Points)	
J_{IC}	: 424.6 kJ/m^2	(2424.4 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.347 mm	(0.0137 in)	
T average	: 454.7	(J_{IC} at 0.15)	
Power-Law Fit	**J = C(Δa)^n**		
Coeff. C	: 597.61 kJ/m^2	Exponent n	: 0.4531
Fit Coeff. R	: 0.9870	(10 Data Points)	
J_{IC}(0.20)	: 467.8 kJ/m^2	(2670.0 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.582 mm	(0.0229 in)	
T average	: 429.3	(J_{IC} at 0.20)	
J_{IC}(0.15)	: 440.3 kJ/m^2	(2514.3 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.510 mm	(0.0201 in)	
T average	: 437.9	(J_{IC} at 0.15)	
K_{Jc}	: 383.5 MPa-m$^{0.5}$		

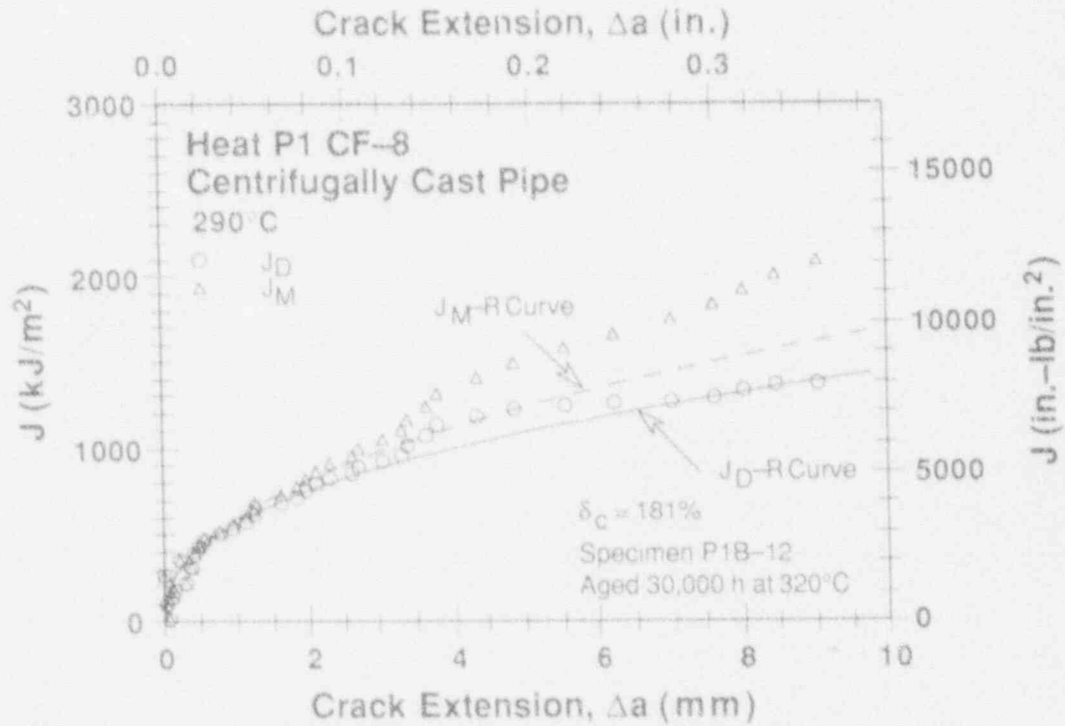

Figure C-20. Deformation and modified J-R curves at 290°C for Heat P1 aged 30,000 h at 320°C.

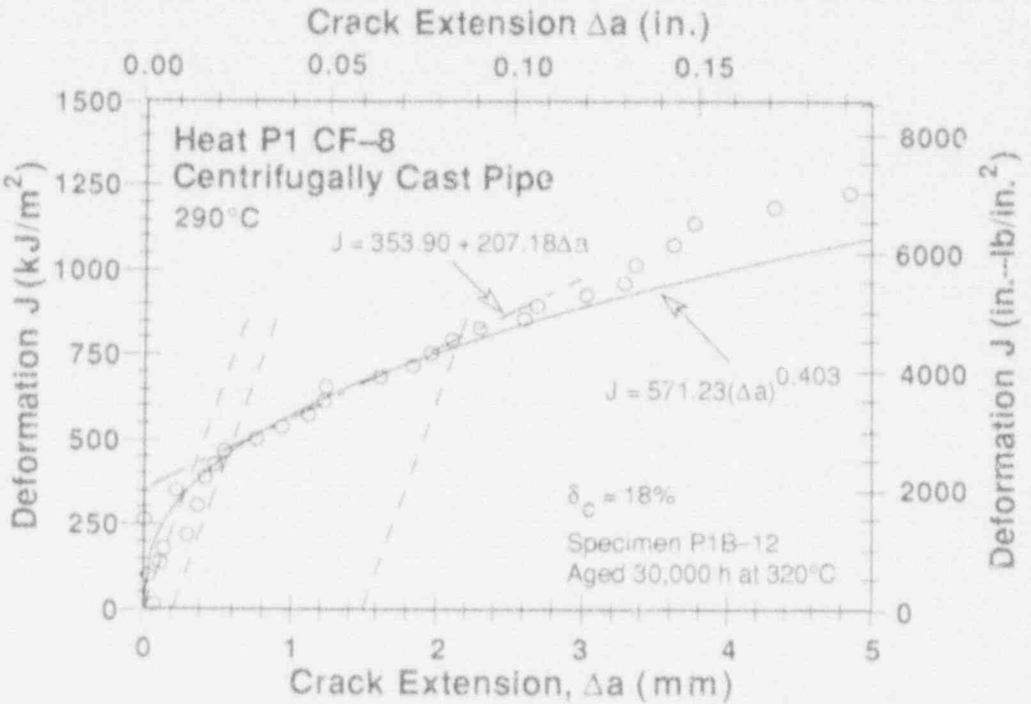

Figure C-21. Deformation J_{IC} at 290°C for Heat P1 aged 30,000 h at 320°C.

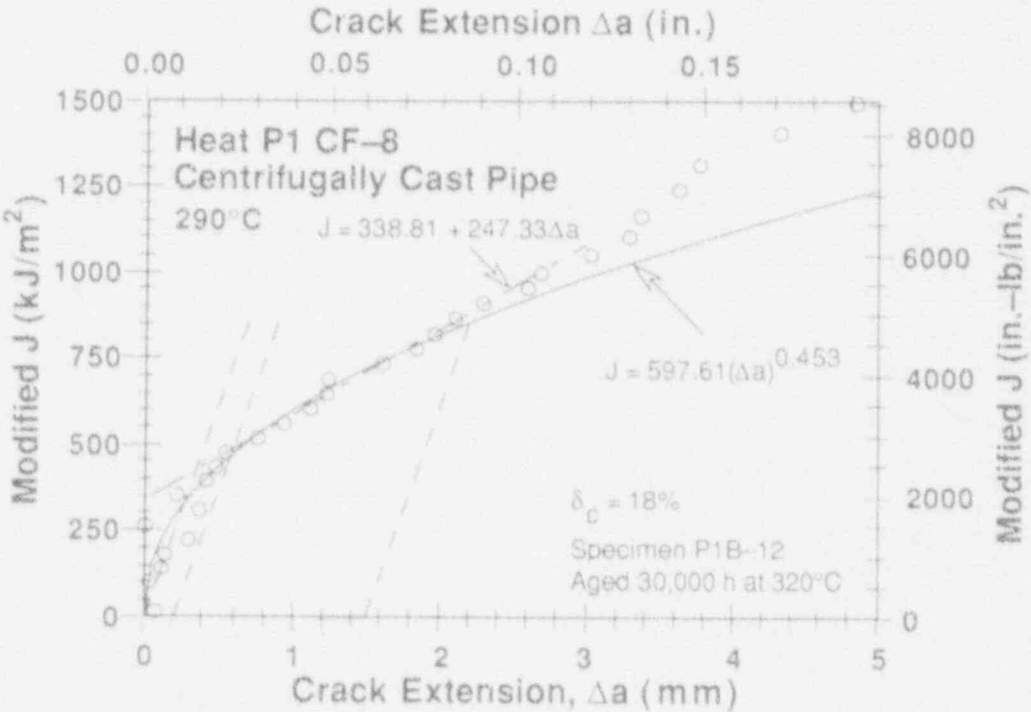

Figure C-22. Modified J_{IC} at 290°C for Heat P1 aged 30,000 h at 320°C.

Table C-23. Test data for specimen P1B-10

Test Number	: 0062	Test Temp.	: 290°C
Material Type	: CF-8	Heat Number	: P1
Aging Temp.	: 350°C	Aging Time	: 30.000 h
Spec. Thickness	: 25.34 mm	Net. Thickness	: 20.31 mm
Spec. Width	: 50.81 mm	Flow Stress	: 351.60 MPa

Unload Number	J_d (kJ/m^2)	J_m (kJ/m^2)	Δa (mm)	Load (kN)	Deflection (mm)
1	21.28	21.32	0.0536	18.000	0.373
2	38.00	38.01	0.0357	20.030	0.555
3	53.37	52.81	-0.1950	21.297	0.707
4	74.89	75.66	0.1683	22.546	0.909
5	96.57	96.89	0.0775	23.513	1.109
6	120.06	120.96	0.1705	24.284	1.310
7	144.09	144.74	0.1375	25.162	1.509
8	170.57	168.64	-0.1492	25.772	1.708
9	194.82	196.23	0.1708	26.386	1.910
10	219.25	221.68	0.2566	26.857	2.112
11	244.83	248.55	0.3532	27.422	2.314
12	271.66	274.53	0.2965	27.835	2.509
13	303.82	310.11	0.4994	28.271	2.759
14	338.00	344.89	0.5314	28.799	3.010
15	377.89	378.93	0.2536	29.060	3.257
16	408.60	419.43	0.6774	29.492	3.516
17	446.41	451.84	0.4632	29.703	3.757
18	475.36	491.62	0.8610	29.646	4.008
19	510.45	527.16	0.8762	29.813	4.259
20	541.24	566.47	1.1471	29.870	4.512
21	578.13	604.27	1.1743	29.889	4.770
22	605.53	641.95	1.4626	29.985	5.008
23	639.16	680.06	1.5810	30.115	5.261
24	664.82	719.91	1.9366	29.754	5.512
25	701.14	756.35	1.9393	29.462	5.761
26	728.92	797.92	2.2498	29.303	6.018
27	768.58	833.47	2.1620	29.019	6.263
28	786.22	875.40	2.6601	28.652	6.517
29	830.33	917.34	2.6180	28.260	6.813
30	850.92	964.92	3.1192	27.858	7.107
31	884.65	1008.43	3.2924	27.527	7.408
32	906.73	1055.90	3.7241	27.348	7.710
33	954.44	1107.43	3.7856	27.204	8.061
34	987.33	1163.68	4.1432	26.692	8.412
35	1022.64	1223.71	4.5028	26.084	8.807
36	1060.31	1300.08	5.0326	24.695	9.311
37	1080.61	1372.29	5.7087	23.510	9.807
38	1140.39	1456.11	6.0005	22.607	10.410
39	1168.44	1542.24	6.6671	21.529	11.006
40	1171.87	1622.99	7.5144	19.704	11.608
41	1202.51	1698.87	7.9838	18.518	12.210
42	1211.98	1775.30	8.6487	17.422	12.808
43	1221.92	1848.19	9.2474	16.551	13.406
44	1248.73	1919.76	9.6529	15.453	14.004
45	1267.98	1992.14	10.1130	14.803	14.605

Table C-24. Deformation J_{IC} and J-R curve results for specimen P1B-10

Test Number	: 0062	Test Temp.	: 290°C
Material Type	: CF-8	Heat Number	: P1
Aging Temp.	: 350°C	Aging Time	: 30,000 h
Spec. Thickness	: 25.34 mm	Net. Thickness	: 20.31 mm
Spec. Width	: 50.81 mm	Flow Stress	: 331.60 MPa
Modulus E	: 175.70 GPa	(Effective)	
Modulus E	: 180.00 GPa	(Nominal)	
Init. Crack	: 28.0031 mm	Init. a/w	: 0.5511 (Measured)
Final Crack	: 39.1750 mm	Final a/w	: 0.7710 (Measured)
Final Crack	: 38.1161 mm	Final a/w	: 0.7502 (Compliance)
Linear Fit	**$J = B+M(\Delta a)$**		
Intercept B	: 216.945 kJ/m^2	Slope M	: 261.34 kJ/m^{2}mm
Fit Coeff. R	: 0.9595	(12 Data Points)	
J_{IC}	: 270.2 kJ/m^2	(1542.8 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.204 mm	(0.0080 in)	
T average	: 417.6	(J_{IC} at 0.15)	
Power-Law Fit	**$J = C(\Delta a)^n$**		
Coeff. C	: 491.48 kJ/m^2	Exponent n	: 0.5951
Fit Coeff. R	: 0.9821	(12 Data Points)	
J_{IC}(0.20)	: 294.0 kJ/m^2	(1678.6 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.422 mm	(0.0166 in)	
T average	: 439.8	(J_{IC} at 0.20)	
J_{IC}(0.15)	: 262.0 kJ/m^2	(1496.3 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.348 mm	(0.0137 in)	
T average	: 447.6	(J_{IC} at 0.15)	
K_{jc}	: 365.0 MPa-m$^{0.5}$		
J_{IC} Validity & Data Qualification (E 813-85)			
J_{max} allowed	: 504.18 kJ/m^2	($J_{max}=b_o\sigma_f/15$)	
Data Limit	: J_{max} Ignored		
Δa (max) allowed	: 2.072 mm	(at 1.5 exclusion line)	
Data Limit	: 1.5 Exclusion line		
Data Points	: Zone A = 5	Zone B = 4	
Data point spacing	: OK		
b_{net} and b_o size	: OK		
dJ/da at J_{IC}	: OK		
Initial crack shape	: OK		
Final crack shape	: OK		
Crack size estimate	: Inadequate	(by compliance)	
E Effective	: OK		
J_{IC} Estimate	: INVALID		
J-R Curve Validity & Data Qualification (E 1152-86)			
J_{max} allowed	: 336.74 kJ/m^2	($J_{max}=b_{net}\sigma_f/20$)	
Δa (max) allowed	: 2.281 mm	($\Delta a=0.1*b_o$)	
Δa (max) allowed	: 5.404 mm	($\omega=5$)	
Data Points	: Zone A = 18	Zone B = 7	
Data point spacing	: Inadequate		
J-R Curve Data	: INVALID		

Table C-25. Modified J_{IC} and J-R curve results for specimen P1B-10

Linear Fit	**$J = B + M(\Delta a)$**		
Intercept B	: 205.777 kJ/m^2	Slope M	: 294.60 kJ/m^{2}mm
Fit Coeff. R	: 0.9698	(12 Data Points)	
J_{IC}	: 264.5 kJ/m^2	(1510.5 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.199 mm	(0.0078 in)	
T average	: 470.7	(J_{IC} at 0.15)	
Power-Law Fit	**$J = C(\Delta a)^n$**		
Coeff. C	: 513.90 kJ/m^2	Exponent n	: 0.6331
Fit Coeff. R	: 0.9867	(12 Data Points)	
J_{IC}(0.20)	: 299.2 kJ/m^2	(1708.5 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.426 mm	(0.0168 in)	
T average	: 487.8	(J_{IC} at 0.20)	
J_{IC}(0.15)	: 263.9 kJ/m^2	(1506.7 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.349 mm	(0.0137 in)	
T average	: 495.7	(J_{IC} at 0.15)	
K_{Jc}	: 381.4 MPa-m$^{0.5}$		

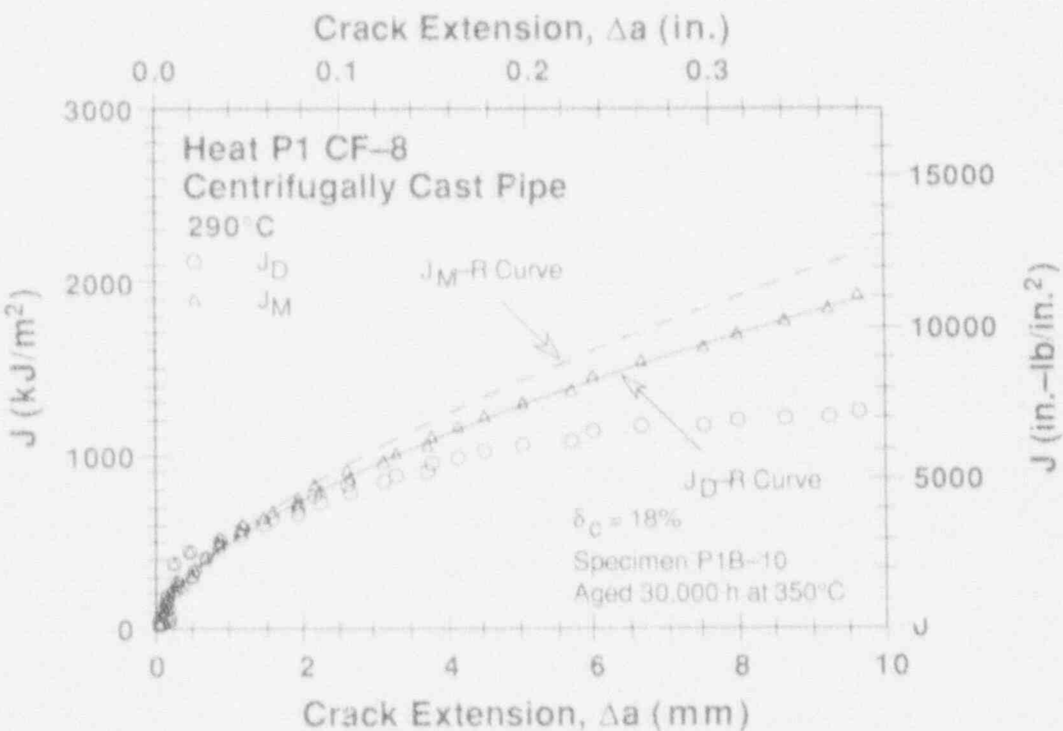

Figure C-23. Deformation and modified J-R curves at 290°C for Heat P1 aged 30,000 h at 350°.

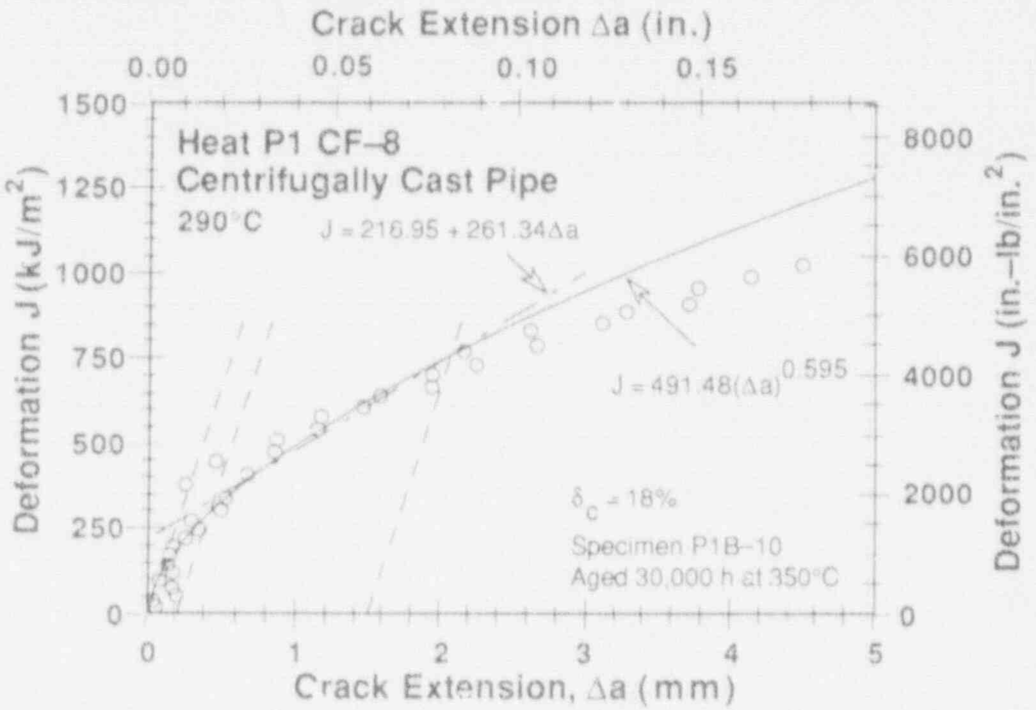

Figure C-24. Deformation J_{IC} at 290°C for Heat P1 aged 30,000 h at 350°C.

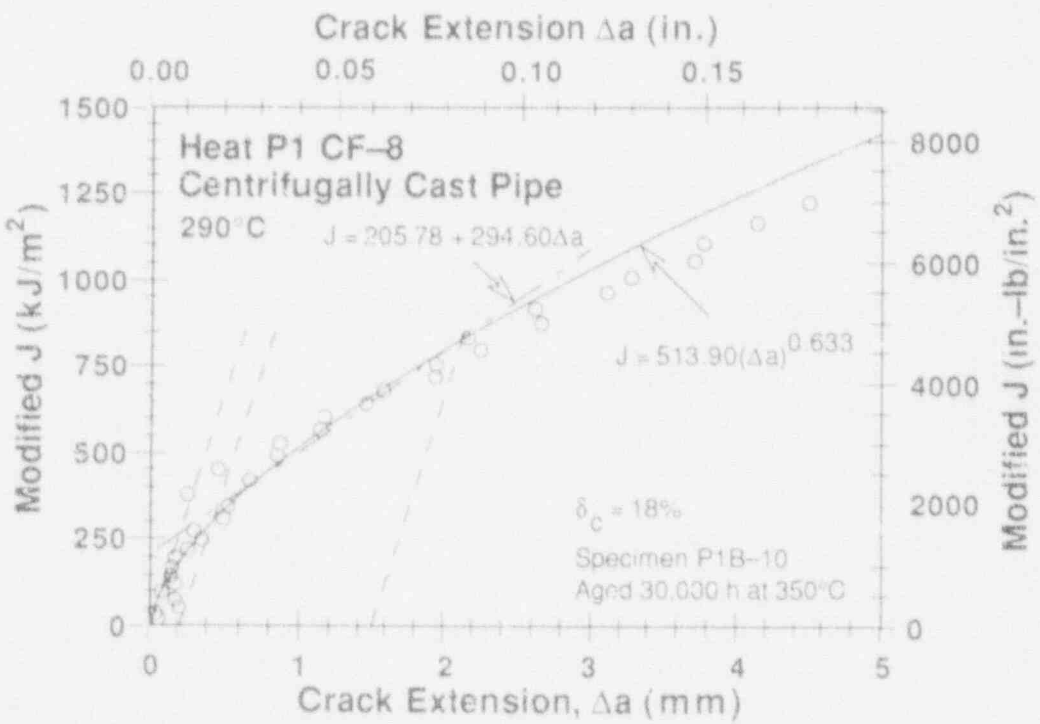

Figure C-25. Modified J_{IC} at 290°C for Heat P1 aged 30,000 h at 350°C

Table C-26. Test data for specimen 683-06B

Test Number	: 0070	Test Temp.	: 290°C
Material Type	: CF-8	Heat Number	: 68
Aging Temp.	: 550°C	Aging Time	: 1 h
Spec. Thickness	: 25.39 mm	Net Thickness	: 20.44 mm
Spec. Width	: 50.83 mm	Flow Stress	: 282.20 MPa

Unload Number	J_d (kJ/m^2)	J_m (kJ/m^2)	Δa (mm)	Load (kN)	Deflection (mm)
1	10.96	10.93	-0.0923	15.474	0.255
2	28.02	28.07	-0.0276	18.302	0.457
3	56.79	56.86	-0.0197	20.329	0.758
4	93.23	93.92	0.1074	21.725	1.110
5	131.56	132.46	0.1376	22.851	1.460
6	175.47	175.72	0.0705	23.736	1.835
7	215.20	214.69	0.0071	24.428	2.161
8	259.90	261.58	0.1566	25.103	2.535
9	301.73	302.13	0.0818	25.680	2.862
10	342.23	348.60	0.3860	26.209	3.210
11	384.75	394.23	0.5258	26.543	3.559
12	430.53	441.17	0.5721	26.924	3.909
13	475.14	490.41	0.7385	27.214	4.263
14	520.66	538.65	0.8267	27.533	4.610
15	562.11	590.15	1.1261	27.674	4.966
16	607.56	638.42	1.2033	27.853	5.309
17	649.63	690.26	1.4515	27.830	5.659
18	692.85	740.88	1.6259	27.891	6.008
19	737.30	793.12	1.7973	28.021	6.360
20	779.07	846.82	2.0247	28.007	6.717
21	836.58	896.22	1.8858	28.068	7.060
22	868.82	951.71	2.3101	27.870	7.407
23	906.70	1004.16	2.5625	27.768	7.762
24	948.04	1056.88	2.7494	27.642	8.109
25	992.75	1118.93	3.0180	27.380	8.510
26	1037.50	1180.77	3.2687	27.257	8.912
27	1106.65	1256.73	3.3620	26.775	9.412
28	1151.02	1335.43	3.8049	26.522	9.911
29	1216.72	1427.36	4.1206	26.297	10.512
30	1276.25	1520.98	4.5048	25.653	11.115
31	1342.97	1628.03	4.9281	24.910	11.810
32	1387.12	1735.07	5.5487	23.913	12.513
33	1450.76	1838.20	5.9146	23.503	13.209
34	1509.52	1945.31	6.3361	22.938	13.910
35	1562.48	2052.19	6.7797	22.196	14.616
36	1630.00	2154.78	7.0520	21.558	15.310

Table C-27. Deformation J_{IC} and J-R curve results for specimen 683-06B

Test Number	: 0070	Test Temp.	: 290°C
Material Type	: CF-8	Heat Number	: 68
Aging Temp.	: 550°C	Aging Time	: 1 h
Spec. Thickness	: 25.39 mm	Net Thickness	: 20.44 mm
Spec. Width	: 50.83 mm	Flow Stress	: 282.20 MPa
Modulus E	: 176.88 GPa	(Effective)	
Modulus E	: 180.00 GPa	(Nominal)	
Init. Crack	: 28.6813 mm	Init. a/w	: 0.5643 (Measured)
Final Crack	: 36.9031 mm	Final a/w	: 0.7260 (Measured)
Final Crack	: 35.7332 mm	Final a/w	: 0.7030 (Compliance)
Linear Fit	**$J = B+M(\Delta a)$**		
Intercept B	: 272.385 kJ/m^2	Slope M	: 267.16 kJ/m^{2}mm
Fit Coeff. R	: 0.9832	(11 Data Points)	
J_{IC}	: 356.8 kJ/m^2	(2037.6 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.316 mm	(0.0124 in)	
T average	: 593.4	(J_{IC} at 0.15)	
Power-Law Fit	**$J = C(\Delta a)^n$**		
Coeff. C	: 553.11 kJ/m^2	Exponent n	: 0.5130
Fit Coeff. R	: 0.9876	(11 Data Points)	
J_{IC}(0.20)	: 413.0 kJ/m^2	(2358.3 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.566 mm	(0.0223 in)	
T average	: 549.9	(J_{IC} at 0.20)	
J_{IC}(0.15)	: 383.5 kJ/m^2	(2189.8 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.490 mm	(0.0193 in)	
T average	: 560.2	(J_{IC} at 0.15)	
K_{jc}	: 384.7 MPa-m$^{0.5}$		
J_{IC} Validity & Data Qualification (E 813-85)			
J_{max} allowed	: 416.69 kJ/m^2	($J_{max}=b_o\sigma_f/15$)	
Data Limit	: J_{max} Ignored		
Δa (max) allowed	: 2.241 mm	(at 1.5 exclusion line)	
Data Limit	: 1.5 Exclusion line		
Data Points	: Zone A = 4	Zone B = 4	
Data point spacing	: OK		
b_{net} or b_o size	: Inadequate		
dJ/da at J_{IC}	: OK		
a_f Measurement	: Near-surface	outside limit	
Initial crack shape	: OK		
Crack size estimate	: Inadequate	(by compliance)	
E Effective	: OK		
J_{IC} Estimate	: INVALID		
J-R Curve Validity & Data Qualification (E 1152-86)			
J_{max} allowed	: 288.44 kJ/m^2	($J_{max}=b_{net}\sigma_f/20$)	
Δa (max) allowed	: 2.215 mm	($\Delta a=0.1*b_o$)	
Δa (max) allowed	: 4.730 mm	(ω=5)	
Data Points	: Zone A = 18	Zone B = 0	
Data point spacing	: Inadequate		
J-R Curve Data	: INVALID		

Table C-28. Modified J_{IC} and J-R curve results for specimen 683-06B

Linear Fit	**$J = B+M(\Delta a)$**		
Intercept B	: 262.843 kJ/m^2	Slope M	: 301.96 kJ/m^2mm
Fit Coeff. R	: 0.9902	(12 Data Points)	
J_{IC}	: 358.8 kJ/m^2	(2049.0 in.-lb/$in.^2$)	
Δa (J_{IC})	: 0.318 mm	(0.0125 in)	
T average	: 670.7	(J_{IC} at 0.15)	
Power-Law Fit	**$J = C(\Delta a)^n$**		
Coeff. C	: 579.91 kJ/m^2	Exponent n	: 0.5622
Fit Coeff. R	: 0.9915	(12 Data Points)	
J_{IC}(0.20)	: 425.8 kJ/m^2	(2431.2 in.-lb/$in.^2$)	
Δa (J_{IC})	: 0.577 mm	(0.0227 in)	
T average	: 631.0	(J_{IC} at 0.20)	
J_{IC}(0.15)	: 391.3 kJ/m^2	(2234.1 in.-lb/$in.^2$)	
Δa (J_{IC})	: 0.497 mm	(0.0196 in)	
T average	: 641.8	(J_{IC} at 0.15)	
K_{Jc}	: 406.0 MPa-$m^{0.5}$		

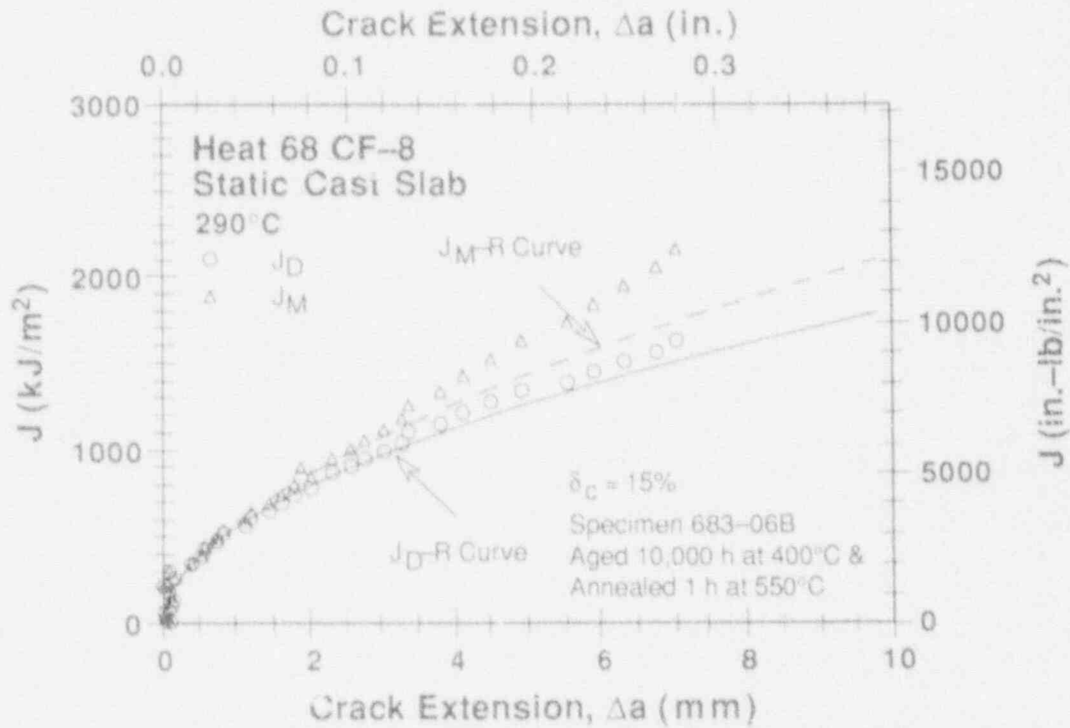

Figure C-26. Deformation and modified J-R curves at 290°C for Heat 68 aged for 10,000 h at 400°C and then recovery annealed.

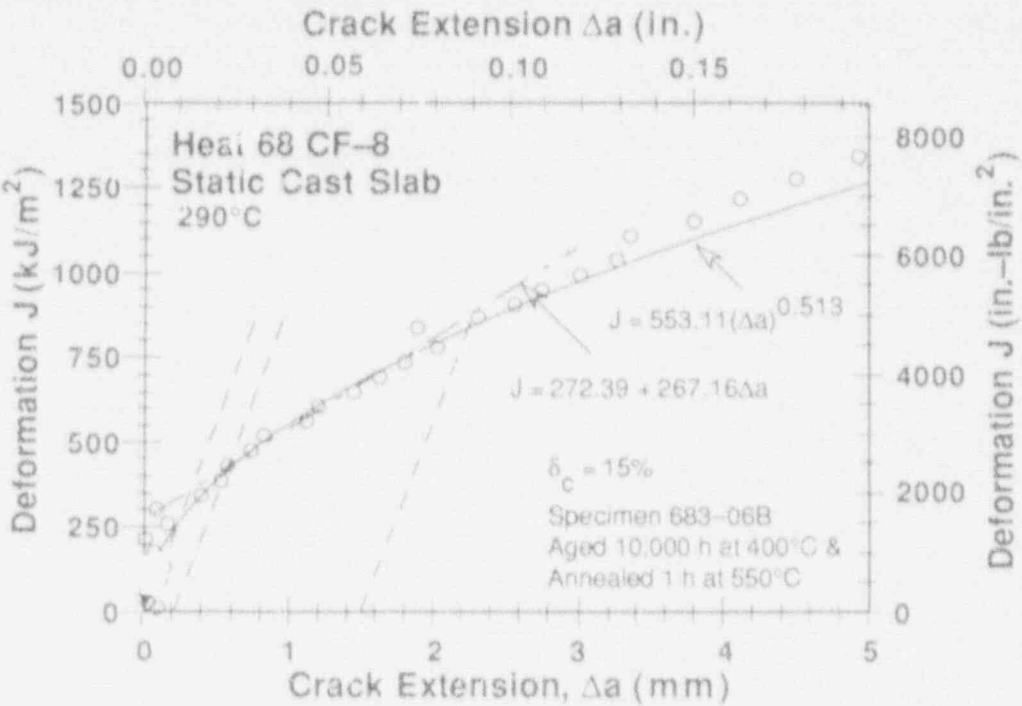

Figure C-27. Deformation J_{IC} at 290°C for Heat 68 aged for 10,000 h at 400°C and then recovery-annealed.

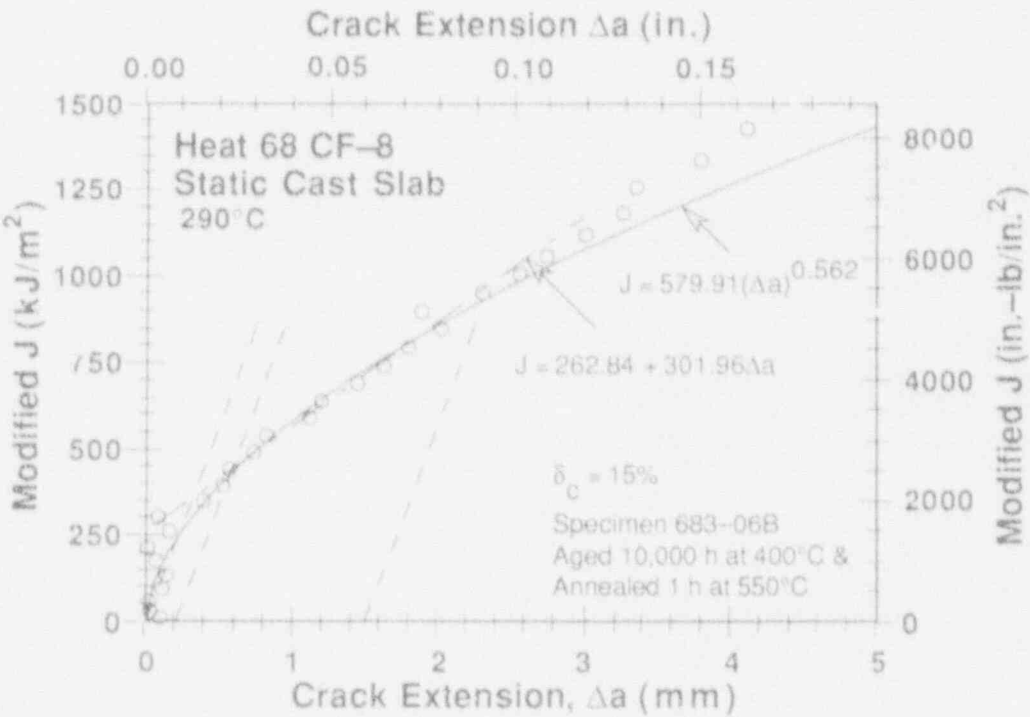

Figure C-28. Modified J_{IC} at 290°C for Heat 68 aged for 10,000 h at 400°C and then recovery-annealed.

Table C-29. Test data for specimen 682-07T

Test Number	: 0077	Test Temp.	: 290°C
Material Type	: CF-8	Heat Number	: 68
Aging Temp.	: 320°C	Aging Time	: 30,000 h
Spec. Thickness	: 25.35 mm	Net Thickness	: 20.27 mm
Spec. Width	: 50.78 mm	Flow Stress	: 309.90 MPa

Unload Number	J_d (kJ/m^2)	J_m (kJ/m^2)	Δa (mm)	Load (kN)	Deflection (mm)
1	15.77	15.85	0.1543	16.552	0.306
2	43.75	44.23	0.3633	19.964	0.607
3	70.03	69.98	0.2[illegible]98	21.596	0.859
4	99.11	98.41	0.0814	22.665	1.110
5	128.74	129.00	0.2213	23.663	1.361
6	160.24	158.17	-0.0468	24.497	1.611
7	190.58	192.11	0.2953	25.207	1.862
8	221.43	223.00	0.2991	25.816	2.110
9	253.14	257.14	0.4686	26.271	2.360
10	285.98	291.09	0.5365	26.703	2.611
11	316.81	326.43	0.7825	27.011	2.858
12	350.89	361.19	0.8163	27.408	3.110
13	385.60	397.35	0.8802	27.669	3.360
14	418.49	434.20	1.0403	27.718	3.609
15	450.82	471.20	1.2139	27.754	3.861
16	485.58	507.91	1.2808	27.848	4.113
17	516.26	545.78	1.5099	27.829	4.361
18	549.32	582.16	1.6089	27.526	4.610
19	575.89	620.95	1.9513	27.528	4.861
20	608.44	657.55	2.0579	27.258	5.115
21	634.17	695.69	2.3675	27.033	5.361
22	663.56	732.52	2.5437	26.644	5.613
23	691.51	771.40	2.7888	26.372	5.870
24	745.71	843.79	3.1599	25.535	6.351
25	779.88	897.71	3.5388	25.143	6.718
26	815.32	955.10	3.9347	24.57[illegible]	7.109
27	865.51	1027.90	4.3114	23.752	7.608
28	909.05	1100.01	4.7546	22.736	8.109
29	927.97	1170.97	5.5174	21.640	8.610
30	972.62	1252.53	6.0197	20.468	9.218
31	1003.33	1332.09	6.6426	19.117	9.812
32	1036.20	1408.72	7.1674	18.232	10.411
33	1058.23	1485.43	7.7867	17.104	11.011
34	1093.33	1558.49	8.1924	16.314	11.613
35	1116.34	1632.4[illegible]	8.7089	15.543	12.211
36	1122.01	1705.08	9.3563	14.372	12.824
37	1131.67	1770.23	9.8692	13.380	13.413
38	1142.46	1835.55	10.3510	12.421	14.008

Table C-30. Deformation J_{IC} and J-R curve results for specimen 682-07T

Test Number	: 0077	Test Temp.	: 290°C
Material Type	: CF-8	Heat Number	: 68
Aging Temp.	: 320°C	Aging Time	: 30,000 h
Spec. Thickness	: 25.35 mm	Net Thickness	: 20.27 mm
Spec. Width	: 50.78 mm	Flow Stress	: 309.90 MPa
Modulus E	: 178.39 GPa	(Effective)	
Modulus E	: 180.00 GPa	(Nominal)	
Init. Crack	: 28.9656 mm	Init. a/w	: 0.5704 (Measured)
Final Crack	: 40.4406 mm	Final a/w	: 0.7964 (Measured)
Final Crack	: 39.3166 mm	Final a/w	: 0.7742 (Compliance)
Linear Fit	**$J = B+M(\Delta a)$**		
Intercept B	: 164.144 kJ/m^2	Slope M	: 230.22 kJ/m^{2}mm
Fit Coeff. R	: 0.9825	(11 Data Points)	
J_{IC}	: 201.6 kJ/m^2	(1151.1 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.163 mm	(0.0064 in)	
T average	: 427.6	(J_{IC} at 0.15)	
Power-Law Fit	**$J = C(\Delta a)^n$**		
Coeff. C	: 401.94 kJ/m^2	Exponent n	: 0.6013
Fit Coeff. R	: 0.9898	(11 Data Points)	
J_{IC}(0.20)	: 225.3 kJ/m^2	(1286.3 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.382 mm	(0.0150 in)	
T average	: 432.0	(J_{IC} at 0.20)	
J_{IC}(0.15)	: 199.0 kJ/m^2	(1136.1 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.311 mm	(0.0122 in)	
T average	: 439.7	(J_{IC} at 0.15)	
K_{Jc}	: 329.3 MPa-m$^{0.5}$		
J_{IC} Validity & Data Qualification (E 813-85)			
J_{max} allowed	: 450.73 kJ/m^2	($J_{max}=b_o\sigma_f/15$)	
Data Limit	: J_{max} Ignored		
Δa (max) allowed	: 1.990 mm	(at 1.5 exclusion line)	
Data Limit	: 1.5 Exclusion line		
Data Points	: Zone A = 2	Zone B = 3	
Data point spacing	: OK		
b_{net} and b_o size	: OK		
dJ/da at J_{IC}	: OK		
a_f Measurement	: Near-surface	outside limit	
Initial crack shape	: OK		
Crack size estimate	: Inadequate	(by compliance)	
E Effective	: OK		
J_{IC} Estimate	: INVALID		
J-R Curve Validity & Data Qualification (E 1152-86)			
J_{max} allowed	: 314.07 kJ/m^2	($J_{max}=b_{net}\sigma_f/20$)	
Δa (max) allowed	: 2.182 mm	($\Delta a=0.1*b_o$)	
Δa (max) allowed	: 5.451 mm	($\omega=5$)	
Data Points	: Zone A = 8	Zone B = 11	
Data point spacing	: OK		
J-R Curve Data	: INVALID		

Table C-31. Modified J_{IC} and J-R curve results for specimen 682-07T

Linear Fit	**$J = B+M(\Delta a)$**		
Intercept B	: 152.808 kJ/m²	Slope M	: 257.63 kJ/m²mm
Fit Coeff. R	: 0.9875	(11 Data Points)	
J_{IC}	: 192.9 kJ/m²	(1101.5 in.-lb/in.²)	
Δa (J_{IC})	: 0.156 mm	(0.0061 in)	
T average	: 478.5	(J_{IC} at 0.15)	
Power-Law Fit	**$J = C(\Delta a)^n$**		
Coeff. C	: 418.12 kJ/m²	Exponent n	: 0.6403
Fit Coeff. R	: 0.9917	(11 Data Points)	
J_{IC}(0.20)	: 225.9 kJ/m²	(1289.8 in.-lb/in.²)	
Δa (J_{IC})	: 0.382 mm	(0.0150 in)	
T average	: 477.2	(J_{IC} at 0.20)	
J_{IC}(0.15)	: 199.7 kJ/m²	(1140.0 in.-lb/in.²)	
Δa (J_{IC})	: 0.315 mm	(0.0124 in)	
T average	: 484.3	(J_{IC} at 0.15)	
K_{jc}	: 342.6 MPa-m$^{0.5}$		

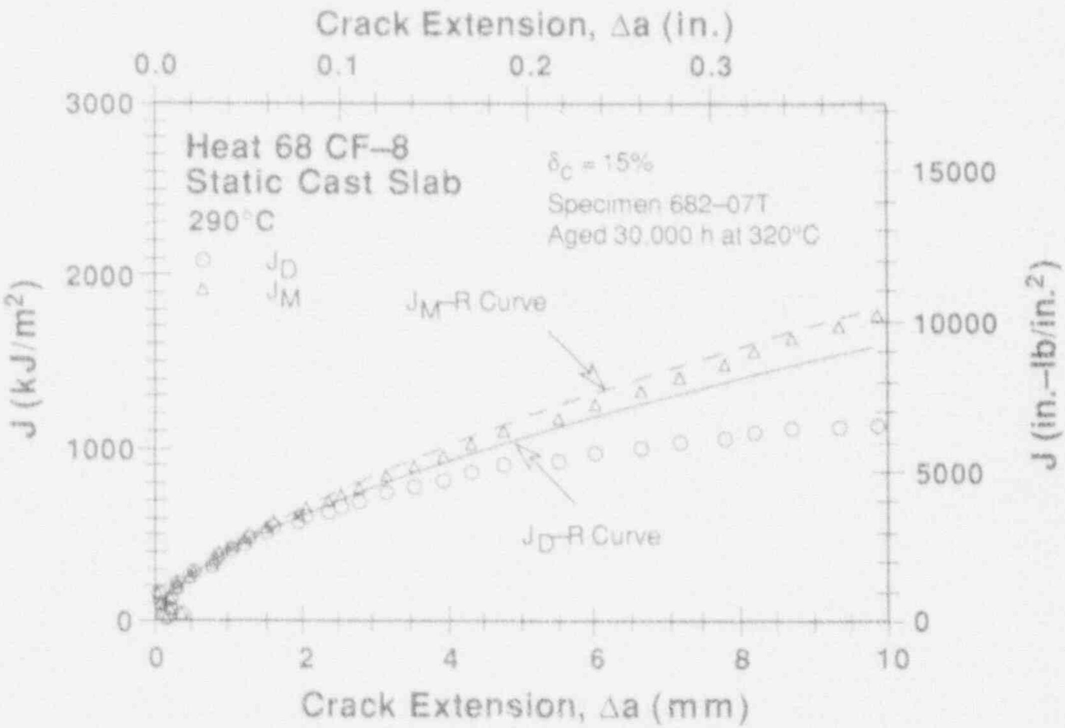

Figure C-29. Deformation and modified J-R curves at 290°C for Heat 68 aged for 30,000 h at 320°C.

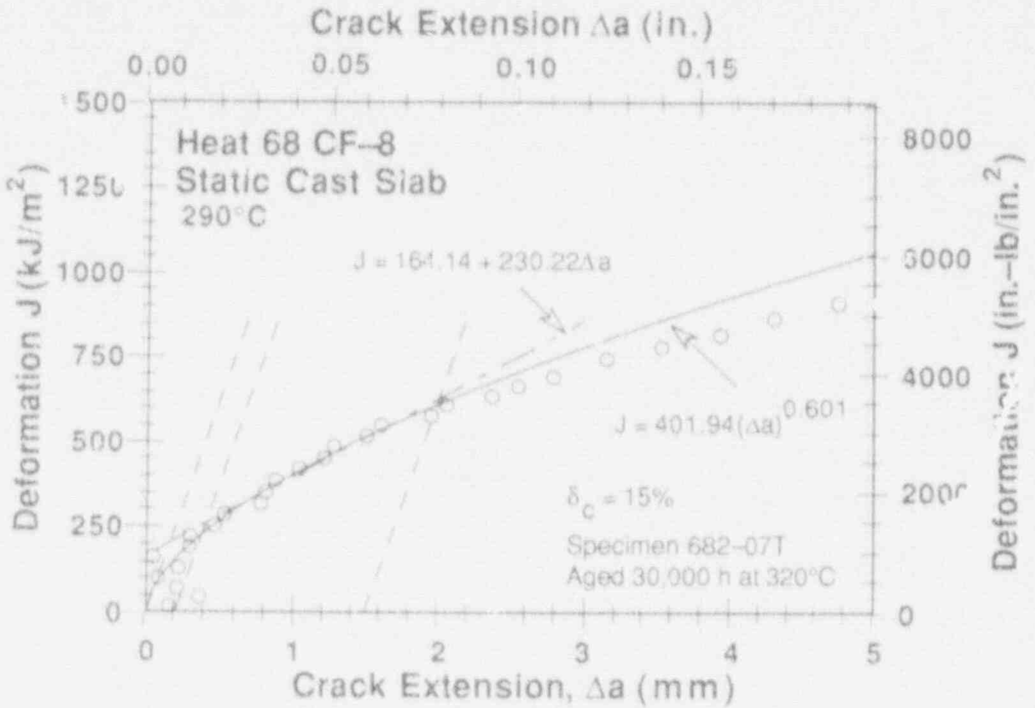

Figure C-30. Deformation J_{IC} at 290°C for Heat 68 aged for 30,000 h at 320°C.

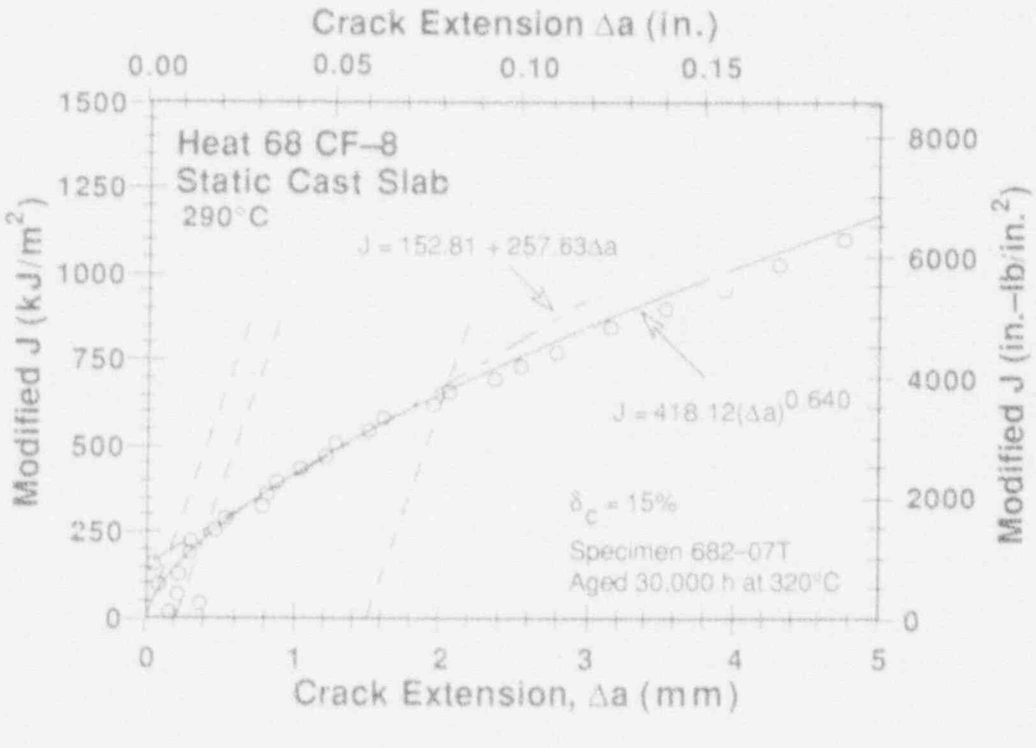

Figure C-31. Modified J_{IC} at 290°C for Heat 68 aged for 30,000 h at 320°C.

Table C-32. Test data for specimen 682-03T

Test Number	: 0075	Test Temp.	: 290°C
Material Type	: CF-8	Heat Number	: 68
Aging Temp.	: 350°C	Aging Time	: 10,000 h
Spec. Thickness	: 25.34 mm	Net Thickness	: 20.30 mm
Spec. Width	: 50.84 mm	Flow Stress	: 320.20 MPa

Unload Number	J_d (kJ/m^2)	J_m (kJ/m^2)	Δa (mm)	Load (kN)	Deflection (mm)
1	16.49	16.65	0.3275	17.305	0.304
2	40.16	40.22	0.2701	20.762	0.558
3	67.44	67.14	0.1575	22.567	0.807
4	96.85	97.30	0.3104	24.005	1.058
5	128.08	126.56	0.0160	25.089	1.307
6	159.90	161.20	0.3450	26.014	1.561
7	193.14	191.93	0.1051	26.797	1.809
8	226.02	227.95	0.3569	27.472	2.059
9	262.24	260.81	0.1260	27.989	2.310
10	293.71	290.37	0.5547	28.350	2.562
11	326.09	333.19	0.5243	28.768	2.810
12	363.03	371.00	0.6630	29.267	3.061
13	399.93	408.25	0.6783	29.533	3.313
14	432.54	447.09	0.9260	29.824	3.561
15	466.08	485.20	1.0937	30.073	3.811
16	503.40	524.52	1.1610	29.984	4.066
17	533.17	564.31	1.4762	30.190	4.311
18	570.20	601.98	1.4950	30.242	4.559
19	602.75	643.45	1.7394	30.169	4.810
20	638.38	683.04	1.8415	29.982	5.063
21	669.03	723.99	2.0917	29.929	5.311
22	697.93	763.58	2.3384	29.945	5.556
23	730.79	804.28	2.5099	29.705	5.809
24	763.21	844.94	2.6808	29.427	6.058
25	806.92	898.18	2.8661	29.319	6.382
26	844.47	950.94	3.1452	28.827	6.702
27	897.80	1017.16	3.3652	28.367	7.110
28	943.56	1082.23	3.6743	27.859	7.508
29	985.98	1164.22	4.2649	26.892	8.010
30	1036.82	1242.78	4.6510	26.067	8.517
31	1094.63	1336.65	5.1161	25.135	9.111
32	1141.27	1429.70	5.6746	24.040	9.710
33	1178.77	1520.07	6.2722	22.775	10.310
34	1200.94	1608.13	6.9776	21.609	10.912
35	1239.76	1692.36	7.4361	20.492	11.509
36	1259.98	1778.35	8.0668	19.300	12.111
37	1276.93	1859.99	8.6579	18.264	12.710
38	1312.07	1940.11	9.0479	17.369	13.310
39	1322.30	2021.67	9.6385	16.280	13.916
40	1335.18	2096.01	10.1257	15.165	14.508

Table C-33. Deformation J_{IC} and J-R curve results for specimen 682-03T

Test Number	: 0075	Test Temp.	: 290°C
Material Type	: CF-8	Heat Number	: 68
Aging Temp.	: 350°C	Aging Time	: 10,000 h
Spec. Thickness	: 25.34 mm	Net Thickness	: 20.30 mm
Spec. Width	: 50.84 mm	Flow Stress	: 320.20 MPa
Modulus E	: 187.02 GPa	(Effective)	
Modulus E	: 180.00 GPa	(Nominal)	
Init. Crack	: 28.6094 mm	Init. a/w	: 0.5628 (Measured)
Final Crack	: 39.3031 mm	Final a/w	: 0.7731 (Measured)
Final Crack	: 38.7351 mm	Final a/w	: 0.7619 (Compliance)
Linear Fit	**$J = B+M(\Delta a)$**		
Intercept B	: 207.622 kJ/m^2	Slope M	: 234.30 kJ/m^2mm
Fit Coeff. R	: 0.9829	(11 Data Points)	
J_{IC}	: 254.1 kJ/m^2	(1451.0 $in.-lb/in.^2$)	
Δa (J_{IC})	: 0.198 mm	(0.0078 in)	
T average	: 427.4	(J_{IC} at 0.15)	
Power-Law Fit	**$J = C(\Delta a)^n$**		
Coeff. C	: 451.45 kJ/m^2	Exponent n	: 0.5437
Fit Coeff. R	: 0.9807	(11 Data Points)	
$J_{IC}(0.20)$	: 281.6 kJ/m^2	(1608.2 $in.-lb/in.^2$)	
Δa (J_{IC})	: 0.420 mm	(0.0165 in)	
T average	: 422.8	(J_{IC} at 0.20)	
$J_{IC}(0.15)$	: 254.6 kJ/m^2	(1453.9 $in.-lb/in.^2$)	
Δa (J_{IC})	: 0.349 mm	(0.0137 in)	
T average	: 431.2	(J_{IC} at 0.15)	
K_{Jc}	: 351.6 $MPa\text{-}m^{0.5}$		
J_{IC} Validity & Data Qualification (E 813-85)			
J_{max} allowed	: 474.51 kJ/m^2	($J_{max}=b_o\sigma_f/15$)	
Data Limit	: J_{max} Ignored		
Δa (max) allowed	: 2.016 mm	(at 1.5 exclusion line)	
Data Limit	: 1.5 Exclusion line		
Data Points	: Zone A = 4	Zone B = 4	
Data point spacing	: OK		
b_{net} and b_o size	: OK		
dJ/da at J_{IC}	: OK		
Initial crack shape	: OK		
Crack size estimate	: Inadequate	(by compliance)	
E Effective	: OK		
J_{IC} Estimate	: INVALID		
J-R Curve Validity & Data Qualification (E 1152-86)			
J_{max} allowed	: 325.00 kJ/m^2	($J_{max}=b_{net}\sigma_f/20$)	
Δa (max) allowed	: 2.223 mm	($\Delta a=0.1*b_o$)	
Δa (max) allowed	: 4.986 mm	($\omega=5$)	
Data Points	: Zone A = 12	Zone B = 9	
Data point spacing	: OK		
J-R Curve Data	: INVALID		

Table C-34. Modified J_{IC} and J-R curve results for specimen 682-03T

Linear Fit	**$J = B+M(\Delta a)$**		
Intercept B	: 195.74(kJ/m²	Slope M	: 263.99 kJ/m²mm
Fit Coeff. R	: 0.987:	(1: Data Points)	
J_{IC}	: 246.6 kJ/m²	(1407.9 in.-lb/in.²)	
Δa (J_{IC})	: 0.193 mm	(0.0076 in)	
T average	: 481.5	(J_{IC} at 0.15)	
Power-Law Fit	**$J = C(\Delta a)^n$**		
Coeff. C	: 469.52 kJ/m²	Exponent n	: 0.5850
Fit Coeff. R	: 0.9842	(11 Data Points)	
J_{IC}(0.20)	: 283.0 kJ/m²	(1616.2 in.-lb/in.²)	
Δa (J_{IC})	: 0.421 mm	(0.0166 in)	
T average	: 471.8	(J_{IC} at 0.20)	
J_{IC}(0.15)	: 253.0 kJ/m²	(1444.8 in.-lb/in.²)	
Δa (J_{IC})	: 0.348 mm	(0.0137 in)	
T average	: 480.4	(J_{IC} at 0.15)	
K_{Jc}	: 366.0 MPa-m$^{0.5}$		

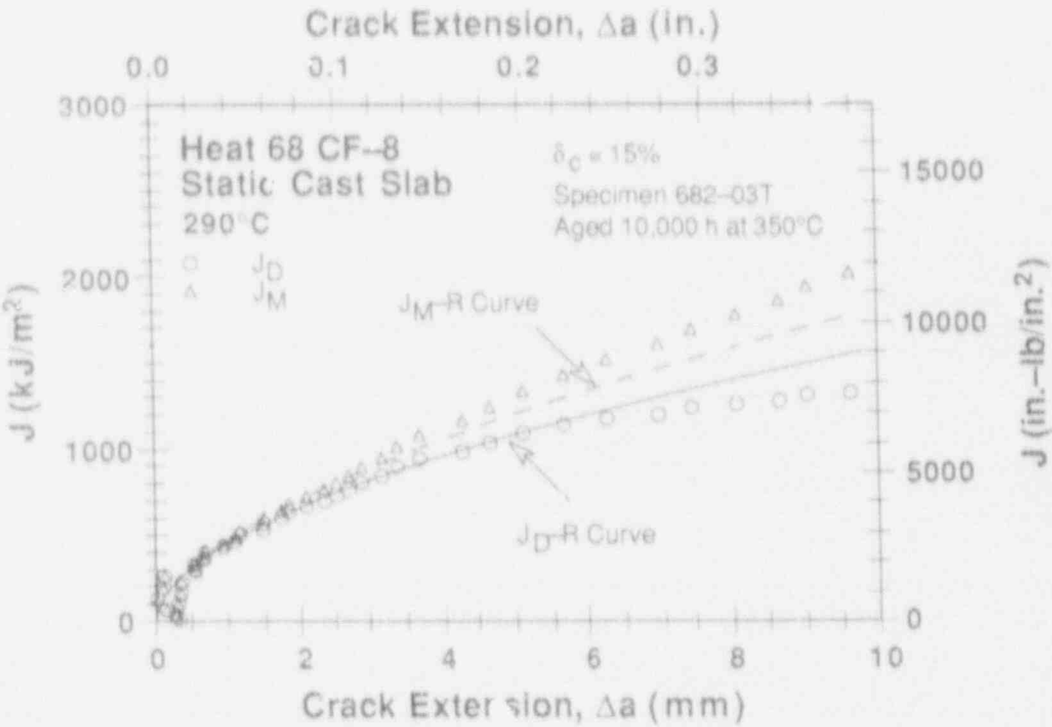

Figure C-32. Deformation and modified J-R curves at 290°C for Heat 68 aged for 10,000 h at 350°C.

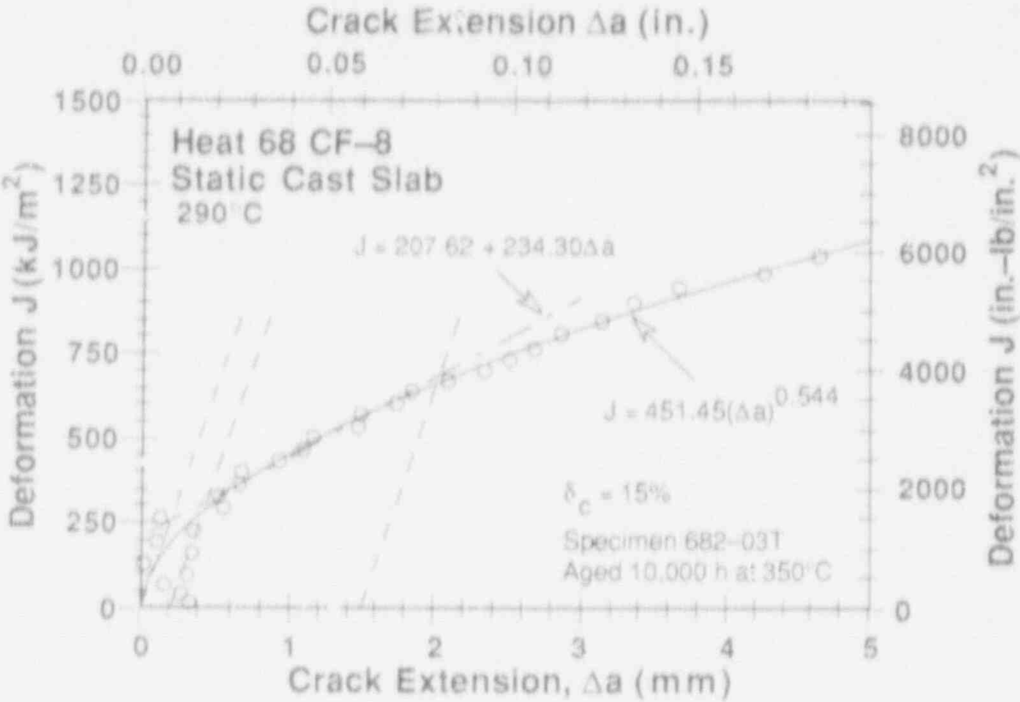

Figure C-33. Deformation J_{IC} at 290°C for Heat 68 aged for 10,000 h at 350°C.

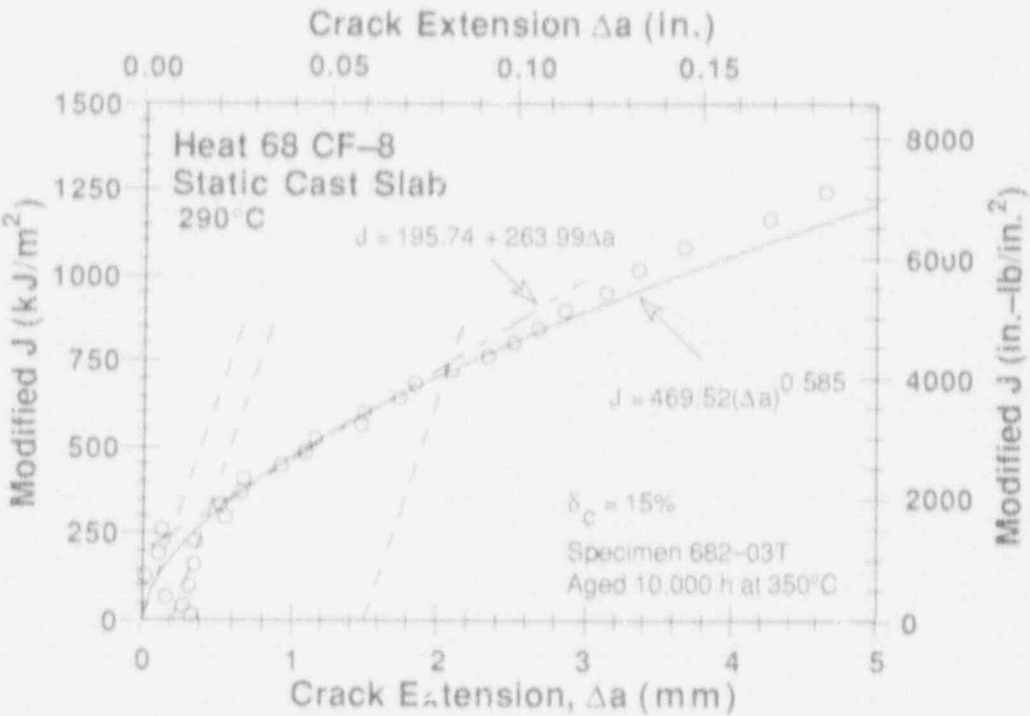

Figure C-34. Modified J_{IC} at 290°C for Heat 68 aged for 10,000 h at 350°C.

Table C-35. Test data for specimen 682-05T

Test Number	: 0060	Test Temp.	: 290°C
Material Type	: CF-8	Heat Number	: 68
Aging Temp.	: 350°C	Aging Time	: 30,000 h
Spec. Thickness	: 25.36 mm	Net Thickness	: 20.28 mm
Spec. Width	: 50.81 mm	Flow Stress	: 328.10 MPa

Unload Number	J_d (kJ/m^2)	J_m (kJ/m^2)	Δa (mm)	Load (kN)	Deflection (mm)
1	21.50	21.35	-0.1867	17.132	0.390
2	36.78	36.88	-0.0318	18.904	0.555
3	51.09	51.19	-0.0298	20.040	0.704
4	72.31	71.62	~0.2513	21.293	0.905
5	94.63	95.29	0.0282	22.287	1.107
6	116.57	117.49	0.0684	23.115	1.307
7	139.92	141.74	0.1895	23.867	1.507
8	164.63	165.53	0.0647	24.545	1.707
9	191.23	191.29	0.0027	25.001	1.909
10	214.85	217.49	0.2189	25.415	2.105
11	241.56	242.47	0.0903	25.921	2.306
12	265.72	270.76	0.3655	26.343	2.506
13	290.87	296.44	0.3976	26.516	2.704
14	316.45	325.42	0.5841	26.738	2.910
15	344.35	351.95	0.5156	26.911	3.109
16	371.41	380.64	0.5911	27.140	3.309
17	395.17	408.82	0.8246	27.238	3.510
18	423.93	436.44	0.7389	27.269	3.709
19	445.40	467.20	1.0890	27.284	3.909
20	473.42	493.97	1.0447	27.343	4.110
21	492.92	525.34	1.4424	27.179	4.312
22	519.22	551.70	1.4442	27.111	4.509
23	540.86	582.60	1.7229	26.919	4.711
24	562.09	611.38	1.9395	26.737	4.912
25	587.98	639.64	2.0043	26.592	5.112
26	610.95	674.90	2.3228	26.364	5.543
27	641.26	704.18	2.2924	26.102	5.558
28	663.08	744.85	2.7385	25.714	5.820
29	686.87	777.19	2.9297	25.232	6.056
30	708.66	814.37	3.2592	25.020	6.308
31	741.91	856.55	3.4799	24.509	6.607
32	766.25	900.87	3.8249	24.150	6.906
33	796.80	950.87	4.1793	23.312	7.259
34	822.83	1008.10	4.7158	22.485	7.661
35	852.96	1068.88	5.2115	21.395	8.107
36	879.16	1136.49	5.8412	20.265	8.606
37	908.91	1201.75	6.3493	19.303	9.111
38	935.58	1266.02	6.8579	18.575	9.610
39	969.23	1329.99	7.2453	18.086	10.111
40	1005.48	1393.53	7.5743	17.194	10.611
41	1027.83	1469.42	8.1830	16.080	11.298
42	1042.43	1540.35	8.7908	15.124	11.809
43	1067.95	1609.64	9.2381	14.292	12.412
44	1082.31	1678.26	9.7656	13.397	13.009
45	1094.06	1744.16	10.2673	12.399	13.612

Table C-36. Deformation J_{IC} and J-R curve results for specimen 682-05T

Test Number	: 0060	Test Temp.	: 290°C
Material Type	: CF-8	Heat Number	: 68
Aging Temp.	: 350°C	Aging Time	: 30,000 h
Spec. Thickness	: 25.36 mm	Net Thickness	: 20.28 mm
Spec. Width	: 50.81 mm	Flow Stress	: 328.10 MPa
Modulus E	: 172.86 GPa	(Effective)	
Modulus E	: 180.00 GPa	(Nominal)	
Init. Crack	: 29.0531 mm	Init. a/w	: 0.5718 (Measured)
Final Crack	: 40.2969 mm	Final a/w	: 0.7930 (Measured)
Final Crack	: 39.3204 mm	Final a/w	: 0.7738 (Compliance)

Linear Fit	**$J = B+M(\Delta a)$**		
Intercept B	: 234.095 kJ/m^2	Slope M	: 192.42 kJ/m^2mm
Fit Coeff. R	: 0.9537	(12 Data Points)	
J_{IC}	: 274.3 kJ/m^2	(1566.4 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.209 mm	(0.0082 in)	
T average	: 309.0	(J_{IC} at 0.15)	

Power-Law Fit	**$J = C(\Delta a)^n$**		
Coeff. C	: 438.62 kJ/m^2	Exponent n	: 0.4370
Fit Coeff. R	: 0.9702	(12 Data Points)	
$J_{IC}(0.20)$	: 303.8 kJ/m^2	(1734.7 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.431 mm	(0.0170 in)	
T average	: 290.8	(J_{IC} at 0.20)	
$J_{IC}(0.15)$	: 282.5 kJ/m^2	(1612.9 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.365 mm	(0.0144 in)	
T average	: 297.6	(J_{IC} at 0.15)	
K_{Jc}	: 318.5 MPa-m$^{0.5}$		

J_{IC} Validity & Data Qualification (E 813-85)

J_{max} allowed	: 475.96 kJ/m^2	($J_{max}=b_o\sigma_f/15$)
Data Limit	: J_{max} Ignored	
Δa (max) allowed	: 1.947 mm	(at 1.5 exclusion line)
Data Limit	: 1.5 Exclusion line	
Data Points	: Zone A = 6	Zone B = 3
Data point spacing	: OK	
b_{net} or b_o size	: Inadequate	
dJ/da at J_{IC}	: OK	
Initial crack shape	: OK	
Final crack shape	: OK	
Crack size estimate	: Inadequate	(by compliance)
E Effective	: OK	
J_{IC} Estimate	: INVALID	

J-R Curve Validity & Data Qualification (E 1152-86)

J_{max} allowed	: 332.64 kJ/m^2	($J_{max}=b_{net}\sigma_f/20$)
Δa (max) allowed	: 2.176 mm	($\Delta a=0.1*b_o$)
Δa (max) allowed	: 4.084 mm	($\omega=5$)
Data Points	: Zone A = 15	Zone B = 6
Data point spacing	: Inadequate	
J-R Curve Data	: INVALID	

Table C-37. Modified J_{IC} and J-R curve results for specimen 682-05T

Linear Fit	**$J = B+M(\Delta a)$**		
Intercept B	: 236.571 kJ/m^2	Slope M	: 206.94 kJ/m^{2}mm
Fit Coeff. R	: 0.9694	(13 Data Points)	
J_{IC}	: 280.9 kJ/m^2	(1603.8 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.214 mm	(0.0084 in)	
T average	: 332.3	(J_{IC} at 0.15)	
Power-Law Fit	**$J = C(\Delta a)^n$**		
Coeff. C	: 458.28 kJ/m^2	Exponent n	: 0.4[illegible]61
Fit Coeff. R	: 0.9808	(13 Data Points)	
J_{IC}(0.20)	: 311.8 kJ/m^2	(1780.2 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.438 mm	(0.0172 in)	
T average	: 322.0	(J_{IC} at 0.20)	
J_{IC}(0.15)	: 288.2 kJ/m^2	(1645.4 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.370 mm	(0.0145 in)	
T average	: 329.2	(J_{IC} at 0.15)	
K_{JC}	: 330.0 MPa-m$^{0.5}$		

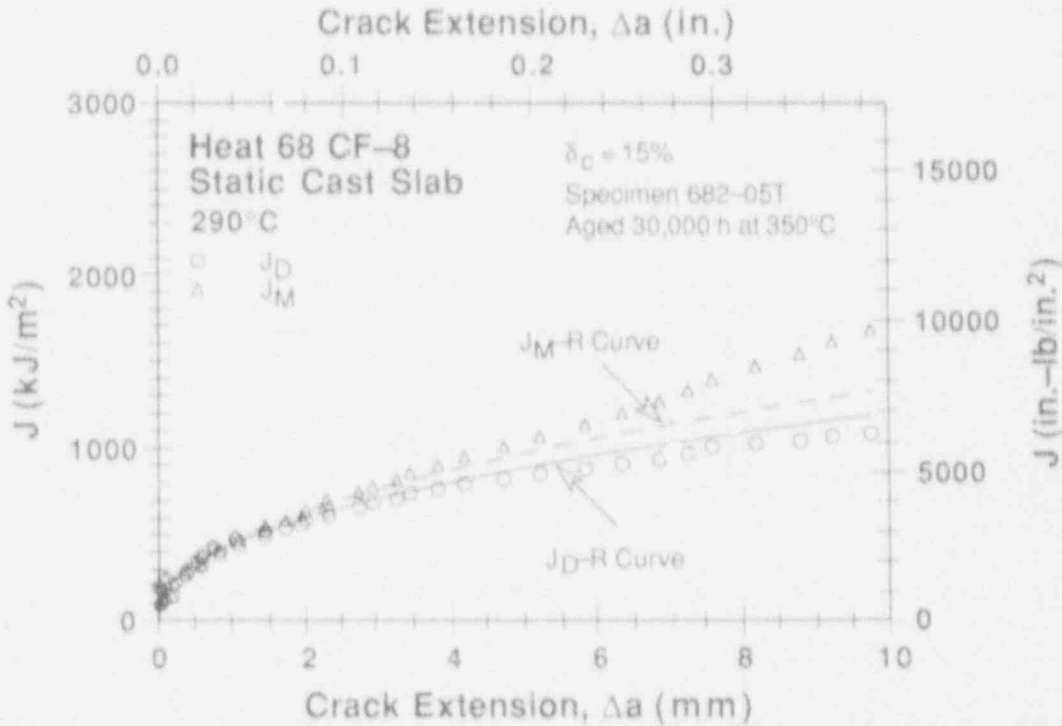

Figure C-35. Deformation and modified J-R curves at 290°C for Heat 68 aged for 30,000 h at 350°C.

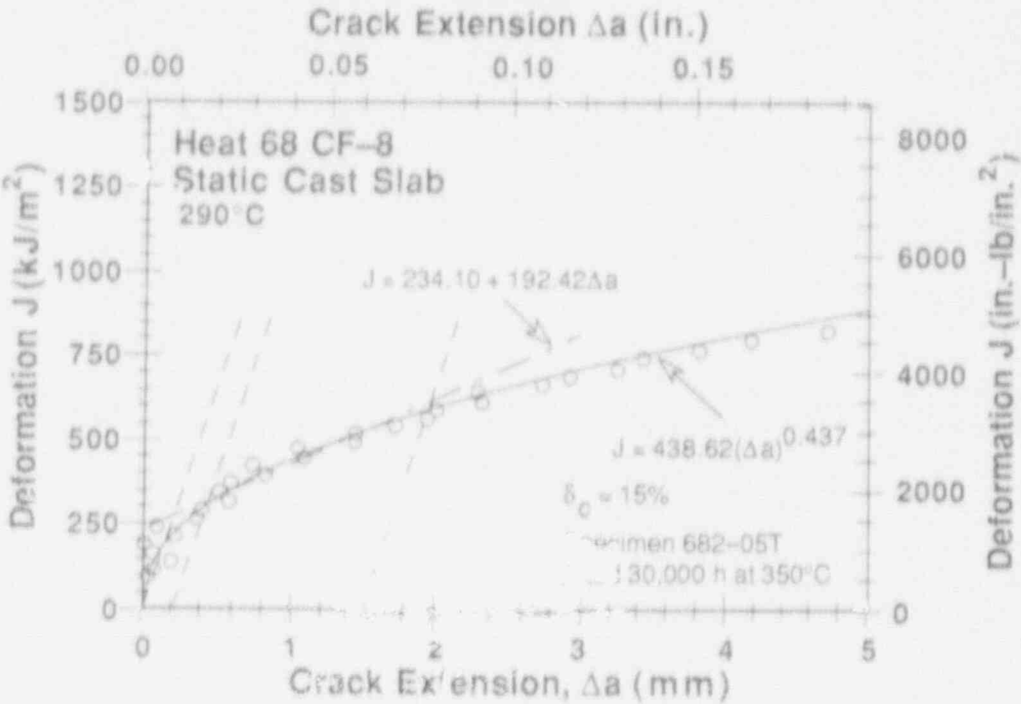

Figure C-36. Deformation J_{IC} at 290°C for Heat 68 aged for 30,000 h at 350°C.

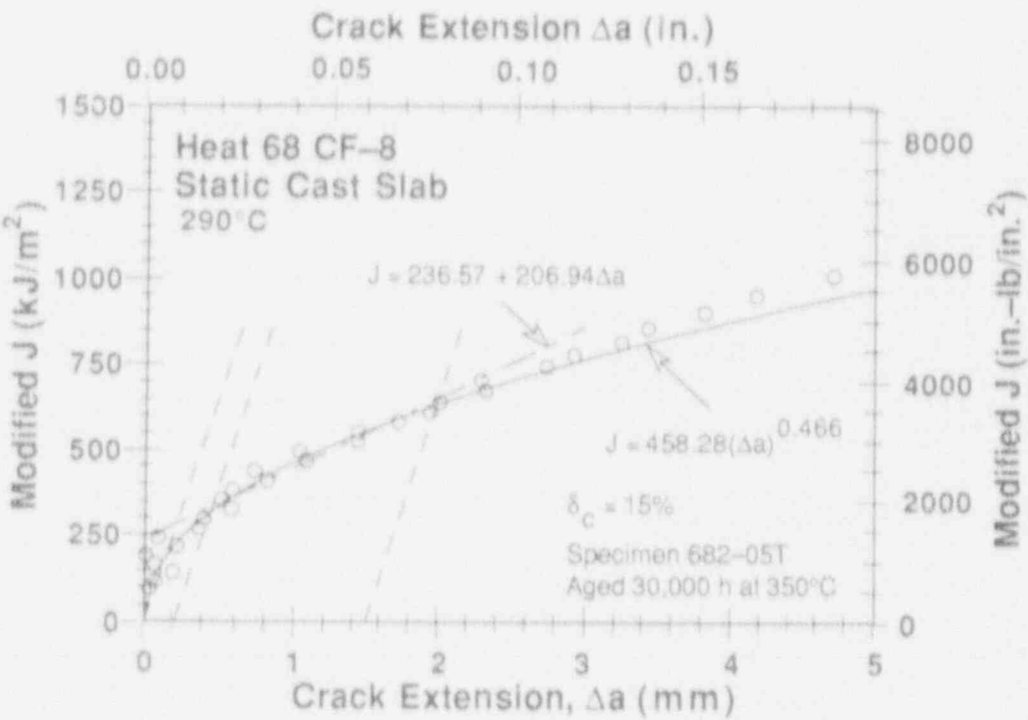

Figure C-37. Modified J_{IC} at 290°C for Heat 68 aged for 30,000 h at 350°C.

Table C-38. Test data for specimen 681-02T

Test Number	: 0061	Test Temp.	: 290°C
Material Type	: CF-8	Heat Number	: 68
Aging Temp.	: 400°C	Aging Time	: 10,000 h
Spec. Thickness	: 25.36 mm	Net Thickness	: 20.31 mm
Spec. Width	: 50.78 mm	Flow Stress	: 332.70 MPa

Unload Number	J_d (kJ/m^2)	J_m (kJ/m^2)	Δa (mm)	Load (kN)	Deflection (mm)
1	16.55	16.55	0.0127	16.930	0.315
2	29.16	28.07	-0.1633	19.025	0.457
3	49.58	49.86	0.0512	21.021	0.656
4	70.75	71.15	0.0858	22.586	0.854
5	93.91	94.87	0.2068	23.795	1.055
6	118.63	118.42	0.0149	24.711	1.256
7	144.93	144.46	-0.0206	25.501	1.456
8	170.77	172.05	0.1707	26.153	1.660
9	195.77	197.82	0.2432	26.763	1.857
10	222.55	225.87	0.3465	27.245	2.060
11	248.42	253.88	0.5016	27.642	2.258
12	275.02	282.46	0.6286	27.920	2.459
13	303.54	310.84	0.6203	28.282	2.658
14	335.53	339.83	0.4633	28.609	2.860
15	360.48	371.55	0.7884	28.593	3.059
16	388.14	400.95	0.8655	28.644	3.266
17	412.41	430.75	1.0933	28.531	3.460
18	437.56	459.46	1.2307	28.481	3.656
19	461.73	490.91	1.4940	28.536	3.860
20	489.70	520.22	1.5390	28.432	4.062
21	520.39	549.52	1.4950	28.376	4.257
22	541.97	582.90	1.8503	28.103	4.461
23	575.33	621.81	2.0063	27.784	4.725
24	597.68	657.86	2.3713	27.377	4.956
25	622.53	694.97	2.6800	27.061	5.206
26	651.53	732.72	2.8896	26.529	5.460
27	679.36	778.20	3.2864	25.932	5.757
28	713.02	830.18	3.6721	25.424	6.107
29	747.68	889.28	4.1513	24.351	6.506
30	781.15	947.27	4.6020	23.729	6.907
31	830.28	1019.34	4.9904	22.939	7.409
32	870.91	1091.73	5.4908	22.208	7.909
33	916.81	1161.52	5.8411	21.249	8.411
34	935.85	1231.87	6.5511	19.854	8.912
35	957.09	1295.35	7.1055	18.847	9.409
36	979.22	1360.35	7.6386	17.743	9.912
37	985.97	1422.75	8.2997	16.631	10.410
38	1011.99	1481.03	8.6638	15.579	10.910
39	1027.93	1544.15	9.1707	14.574	11.434
40	1034.28	1597.54	9.6567	13.778	11.907
41	1045.41	1653.27	10.0983	12.890	12.411
42	1051.54	1707.01	10.5514	12.085	12.910

Table C-39. Deformation J_{IC} and J-R curve results for specimen 681-02T

Test Number	: 0061	Test Temp.	: 290°C
Material Type	: CF-8	Heat Number	: 68
Aging Temp.	: 400°C	Aging Time	: 10,000 h
Spec. Thickness	: 25.36 mm	Net Thickness	: 20.31 mm
Spec. Width	: 50.78 mm	Flow Stress	: 332.70 MPa
Modulus E	: 176.25 GPa	(Effective)	
Modulus E	: 180.00 GPa	(Nominal)	
Init. Crack	: 28.8875 mm	Init. a/w	: 0.5689 (Measured)
Final Crack	: 40.2625 mm	Final a/w	: 0.7928 (Measured)
Final Crack	: 39.4389 mm	Final a/w	: 0.7766 (Compliance)
Linear Fit	**$J = B+M(\Delta a)$**		
Intercept B	: 181.449 kJ/m^2	Slope M	: 204.28 kJ/m^2mm
Fit Coeff. R	: 0.9596	(13 Data Points)	
J_{IC}	: 214.4 kJ/m^2	(1224.0 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.161 mm	(0.0063 in)	
T average	: 325.3	(J_{IC} at 0.15)	
Power-Law Fit	**$J = C(\Delta a)^n$**		
Coeff. C	: 396.19 kJ/m^2	Exponent n	: 0.5102
Fit Coeff. R	: 0.9514	(13 Data Points)	
$J_{IC}(0.20)$	: 242.5 kJ/m^2	(1385.0 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.382 mm	(0.0150 in)	
T average	: 312.3	(J_{IC} at 0.20)	
$J_{IC}(0.15)$	: 219.8 kJ/m^2	(1255.1 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.315 mm	(0.0124 in)	
T average	: 319.1	(J_{IC} at 0.15)	
K_{JC}	: 311.9 MPa-m$^{0.5}$		
J_{IC} Validity & Data Qualification (E 813-85)			
J_{max} allowed	: 485.62 kJ/m^2	($J_{max}=b_o\sigma_f/15$)	
Data Limit	: J_{max} Ignored		
Δa (max) allowed	: 1.915 mm	(at 1.5 exclusion line)	
Data Limit	: 1.5 Exclusion line		
Data Points	: Zone A = 5	Zone B = 4	
Data point spacing	: OK		
b_{net} and b_o size	: OK		
dJ/da at J_{IC}	: OK		
a_f Measurement	: Near-surface	outside limit	
Initial crack shape	: OK		
Crack size estimate	: Inadequate	(by compliance)	
E Effective	: OK		
J_{IC} Estimate	: INVALID		
J-R Curve Validity & Data Qualification (E 1152-86)			
J_{max} allowed	: 337.91 kJ/m^2	($J_{max}=b_{net}\sigma_f/20$)	
Δa (max) allowed	: 2.189 mm	($\Delta a=0.1*b_o$)	
Δa (max) allowed	: 4.702 mm	($\omega=5$)	
Data Points	: Zone A = 13	Zone B = 8	
Data point spacing	: OK		
J-R Curve Data	: INVALID		

Table C-40. Modified J_{IC} and J-R curve results for specimen 681-02T

Linear Fit	**J = B+M(Δa)**		
Intercept B	: 173.779 kJ/m^2	Slope M	: 229.16 kJ/m^{2}mm
Fit Coeff. R	: 0.9684	(13 Data Points)	
J_{IC}	: 209.9 kJ/m^2	(1198.7 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.158 mm	(0.0062 in)	
T average	: 364.9	(J_{IC} at 0.15)	
Power-Law Fit	**J = C(Δa)^n**		
Coeff. C	: 413.74 kJ/m^2	Exponent n	: 0.5455
Fit Coeff. R	: 0.9588	(13 Data Points)	
J_{IC}(0.20)	: 245.7 kJ/m^2	(1402.8 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.385 mm	(0.0151 in)	
T average	: 346.9	(J_{IC} at 0.20)	
J_{IC}(0.15)	: 220.6 kJ/m^2	(1259.7 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.316 mm	(0.0124 in)	
T average	: 353.9	(J_{IC} at 0.15)	
K_{Jc}	: 323.9 MPa-m$^{0.5}$		

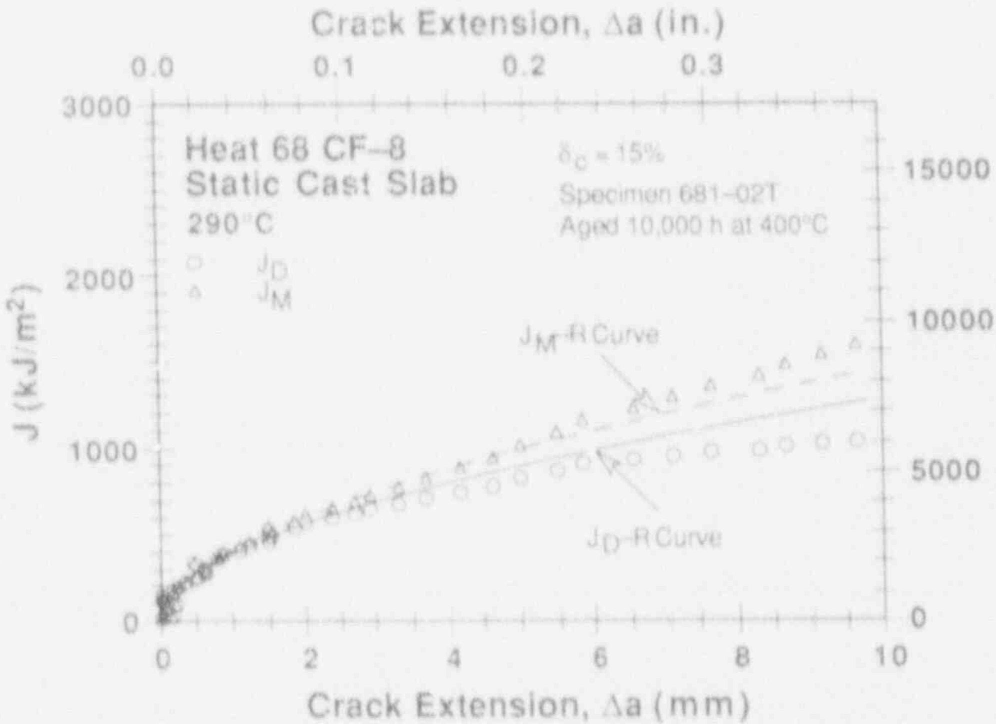

Figure C-38. Deformation and modified J-R curves at 290°C for Heat 68 aged for 10,000 h at 400°C.

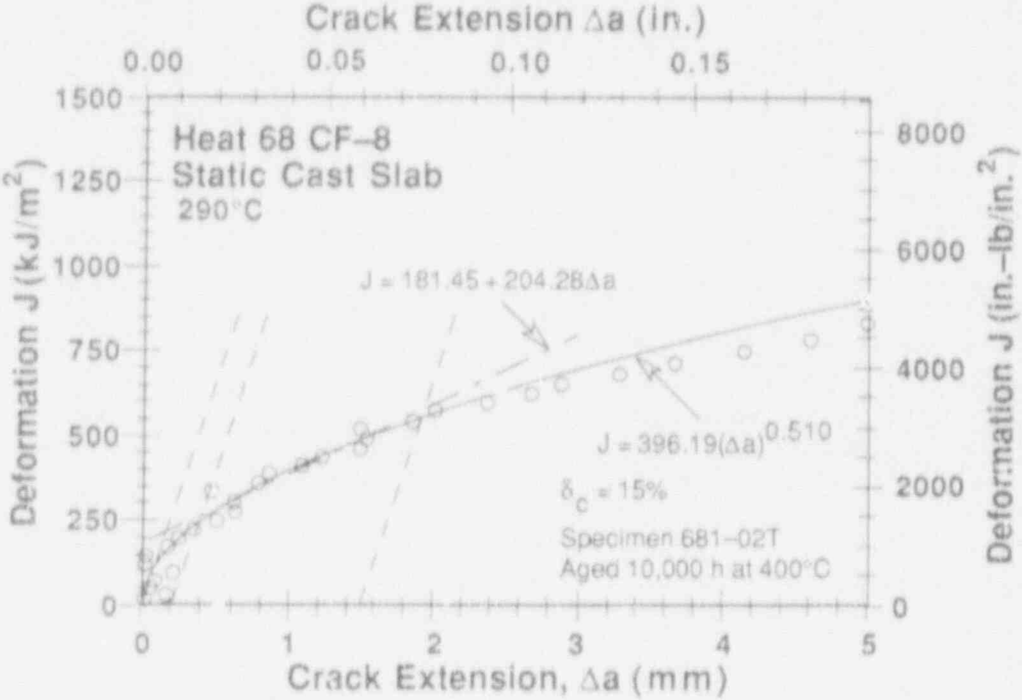

Figure C-39. Deformation J_{IC} at 290°C for Heat 68 aged for 10,000 h at 400°C.

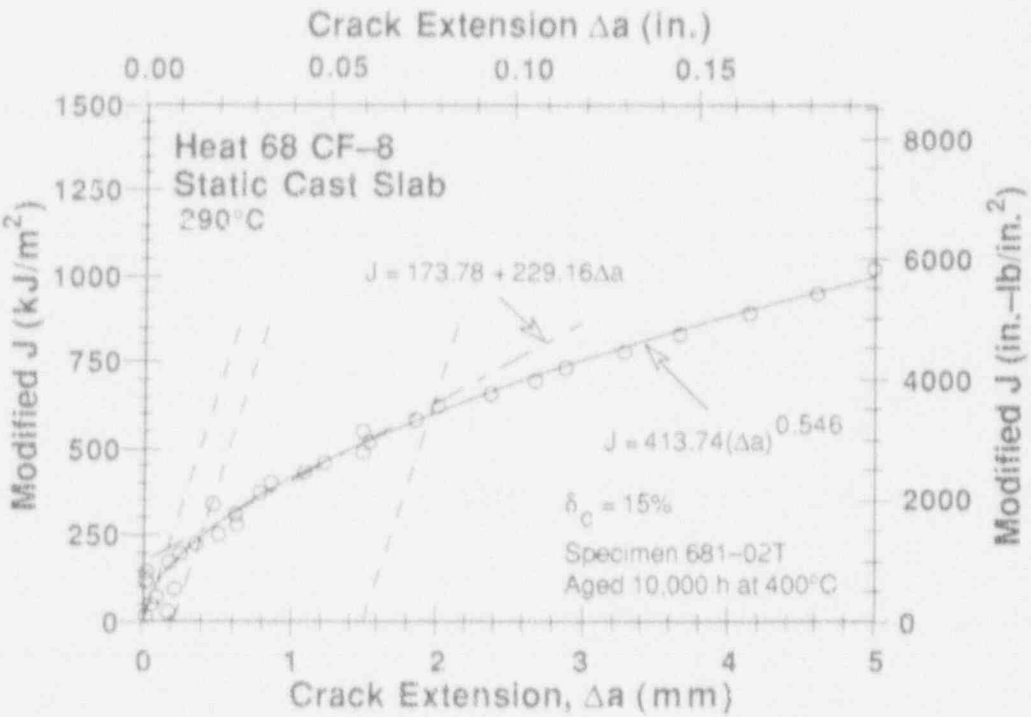

Figure C-40. Modified J_{IC} at 290°C for Heat 68 aged for 10,000 h at 400°C.

Table C-41. Test data for specimen 741-05T

Test Number	: 0071	Test Temp.	: 290°C
Material Type	: CF-8M	Heat Number	: 74
Aging Temp.	: 400°C	Aging Time	: 3,000 h
Spec. Thickness	: 25.33 mm	Net Thickness	: 20.32 mm
Spec. Width	: 50.81 mm	Flow Stress	: 325.70 MPa

Unload Number	J_d (kJ/m^2)	J_m (kJ/m^2)	Δa (mm)	Load (kN)	Deflection (mm)
1	14.89	14.97	0.1981	15.840	0.304
2	36.65	36.14	-0.1835	19.055	0.554
3	62.91	63.45	0.1671	20.957	0.804
4	84.58	84.63	0.0503	22.189	1.008
5	109.11	107.38	-0.2650	23.178	1.209
6	133.05	133.67	0.0684	24.061	1.410
7	157.67	156.34	-0.1621	24.771	1.609
8	183.63	183.66	-0.0266	25.314	1.811
9	197.10	198.50	0.0999	25.717	1.926
10	234.50	239.61	0.3824	26.636	2.229
11	260.19	262.55	0.1949	26.766	2.412
12	294.27	299.04	0.3380	27.092	2.662
13	325.54	334.11	0.5402	27.453	2.908
14	352.18	362.17	0.6098	27.453	3.109
15	377.87	392.05	0.7988	27.793	3.311
16	408.22	419.29	0.6691	27.879	3.509
17	429.15	451.87	1.1239	27.998	3.710
18	453.40	477.95	1.0081	27.958	3.909
19	481.75	510.30	1.3172	28.032	4.108
20	511.26	538.54	1.2759	27.995	4.311
21	530.84	570.97	1.6697	27.944	4.509
22	558.64	599.11	1.6796	27.802	4.711
23	579.12	631.56	2.0100	27.751	4.911
24	607.68	660.55	2.0215	27.536	5.115
25	630.43	691.66	2.2311	27.496	5.309
26	650.41	722.67	2.4956	27.064	5.510
27	674.49	752.07	2.6180	26.874	5.710
28	704.61	799.73	2.9979	26.606	6.009
29	737.62	844.68	3.2419	26.026	6.310
30	768.60	890.41	3.5268	25.415	6.610
31	796.37	935.43	3.8438	24.874	6.910
32	831.31	996.06	4.2865	24.170	7.311
33	862.04	1055.14	4.7479	23.715	7.711
34	890.86	1114.03	5.2101	22.697	8.112
35	912.71	1171.06	5.7240	21.595	8.510
36	937.87	1226.29	6.1422	20.974	8.908
37	984.69	1296.26	6.4432	20.087	9.410
38	1010.83	1366.22	6.9812	18.998	9.907
39	1018.75	1444.55	7.7981	17.165	10.505
40	1053.59	1516.19	8.2003	16.317	11.106
41	1071.01	1592.32	8.8075	15.367	11.708
42	1095.20	1663.91	9.2719	14.555	12.310
43	1116.69	1733.93	9.7231	13.649	12.905
44	1134.80	1804.02	10.1830	12.992	13.512

Table C-42. Deformation J_{IC} and J-R curve results for specimen 741-05T

Test Number	: 0071	Test Temp.	: 290°C
Material Type	: CF-8M	Heat Number	: 74
Aging Temp.	: 400°C	Aging Time	: 3,000 h
Spec. Thickness	: 25.33 mm	Net Thickness	: 20.32 mm
Spec. Width	: 50.81 mm	Flow Stress	: 325.70 MPa
Modulus E	: 173.59 GPa	(Effective)	
Modulus E	: 180.00 GPa	(Nominal)	
Init. Crack	: 29.3063 mm	Init. a/w	: 0.5768 (Measured)
Final Crack	: 40.1938 mm	Final a/w	: 0.7911 (Measured)
Final Crack	: 39.4892 mm	Final a/w	: 0.7772 (Compliance)

Linear Fit	**$J = B+M(\Delta a)$**		
Intercept B	: 251.968 kJ/m^2	Slope M	: 179.02 kJ/m^2mm
Fit Coeff. R	: 0.9544	(10 Data Points)	
J_{IC}	: 292.1 kJ/m^2	(1668.0 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.224 mm	(0.0088 in)	
T average	: 292.9	(J_{IC} at 0.15)	

Power-Law Fit	**$J = C(\Delta a)^n$**		
Coeff. C	: 438.16 kJ/m^2	Exponent n	: 0.4212
Fit Coeff. R	: 0.9565	(10 Data Points)	
$J_{IC}(0.20)$	: 309.3 kJ/m^2	(1766.2 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.437 mm	(0.0172 in)	
T average	: 284.5	(J_{IC} at 0.20)	
$J_{IC}(0.15)$	: 288.8 kJ/m^2	(1649.1 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.372 mm	(0.0146 in)	
T average	: 291.3	(J_{IC} at 0.15)	
K_{Jc}	: 317.3 MPa-$m^{0.5}$		

J_{IC} Validity & Data Qualification (E 813-85)		
J_{max} allowed	: 466.87 kJ/m^2	($J_{max}=b_o\sigma_f/15$)
Data Limit	: J_{max} Ignored	
Δa (max) allowed	: 1.945 mm	(at 1.5 exclusion line)
Data Limit	: 1.5 Exclusion line	
Data Points	: Zone A = 3	Zone B = 2
Data point spacing	: OK	
b_{net} or b_o size	: Inadequate	
dJ/da at J_{IC}	: OK	
Initial crack shape	: OK	
Final crack shape	: OK	
Crack size estimate	: Inadequate	(by compliance)
E Effective	: OK	
J_{IC} Estimate	: INVALID	

J-R Curve Validity & Data Qualification (E 1152-86)		
J_{max} allowed	: 330.94 kJ/m^2	($J_{max}=b_{net}\sigma_f/20$)
Δa (max) allowed	: 2.150 mm	($\Delta a=0.1*b_o$)
Δa (max) allowed	: 3.947 mm	($\omega=5$)
Data Points	: Zone A = 11	Zone B = 9
Data point spacing	: OK	
J-R Curve Data	: INVALID	

Table C-43. Modified J_{IC} and J-R curve results for specimen 741-05T

Linear Fit	**J = B+M(Δa)**		
Intercept B	: 244.099 kJ/m^2	Slope M	: 207.19 kJ/m^{2}mm
Fit Coeff. R	: 0.9661	(10 Data Points)	
J_{IC}	: 290.3 kJ/m^2	(1657.5 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.223 mm	(0.0088 in)	
T average	: 339.0	(J_{IC} at 0.15)	
Power-Law Fit	**J = C(Δa)^n**		
Coeff. C	: 459.05 kJ/m^2	Exponent n	: 0.4624
Fit Coeff. R	: 0.9662	(10 Data Points)	
J_{IC}(0.20)	: 314.5 kJ/m^2	(1795.9 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.441 mm	(0.0174 in)	
T average	: 325.3	(J_{IC} at 0.20)	
J_{IC}(0.15)	: 291.1 kJ/m^2	(1662.3 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.373 mm	(0.0147 in)	
T average	: 332.6	(J_{IC} at 0.15)	
K_{JC}	: 330.7 MPa-m$^{0.5}$		

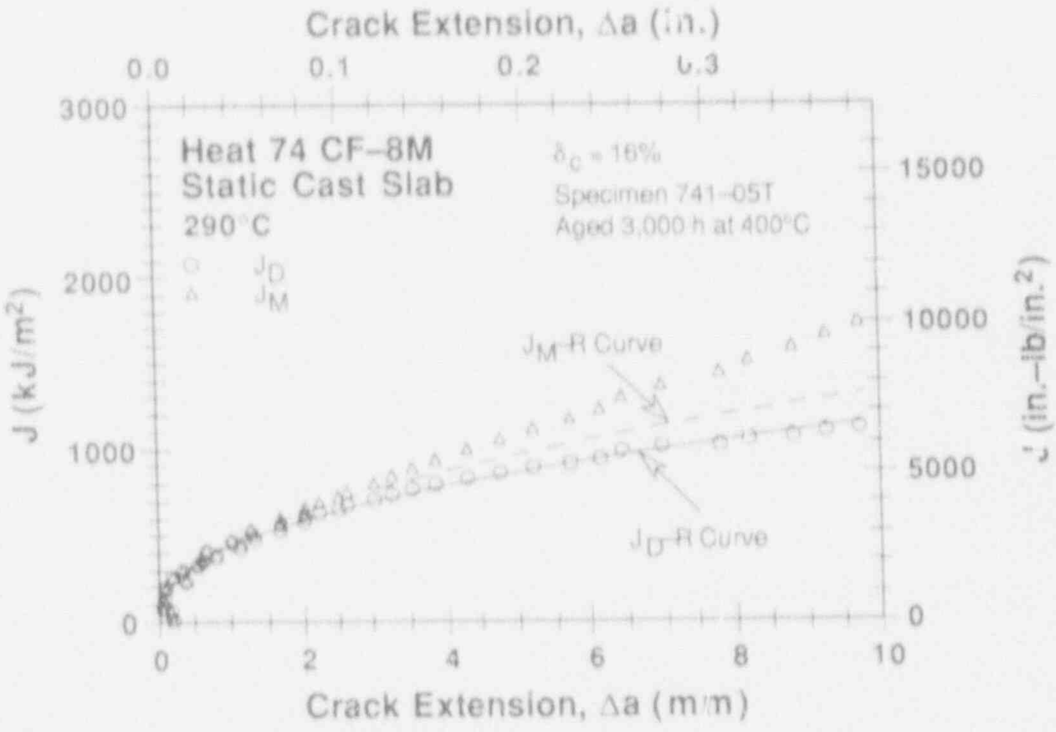

Figure C-41. Deformation and modified J-R curves at 290°C for Heat 74 aged 3,000 h at 400°C.

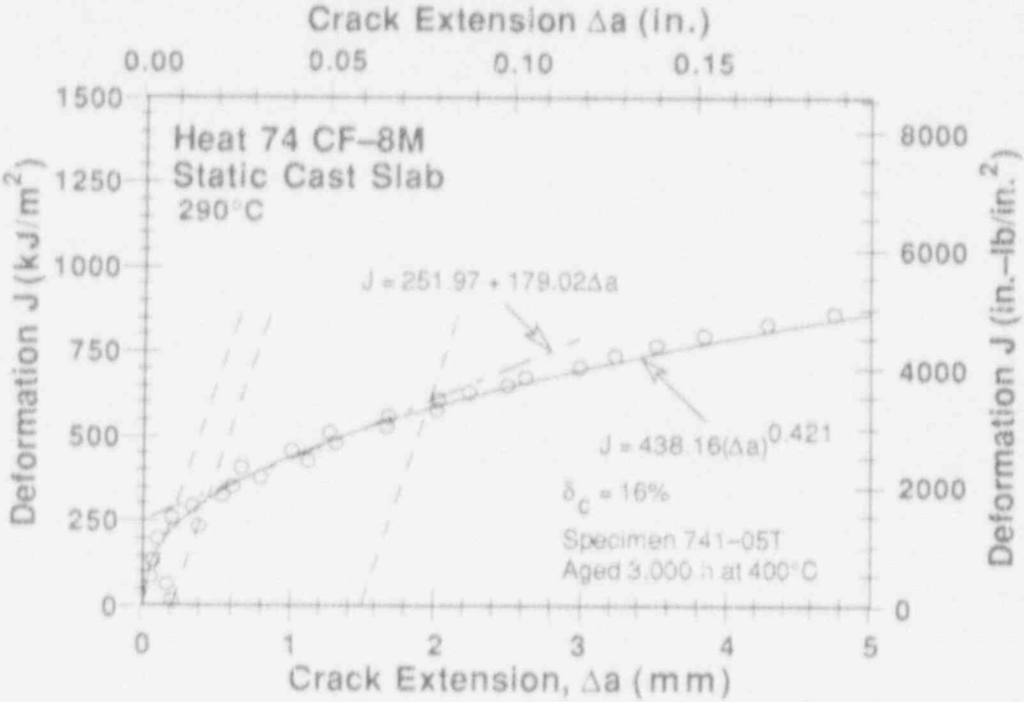

Figure C-42. Deformation J_{IC} at 290°C for Heat 74 aged 3,000 h at 400°C.

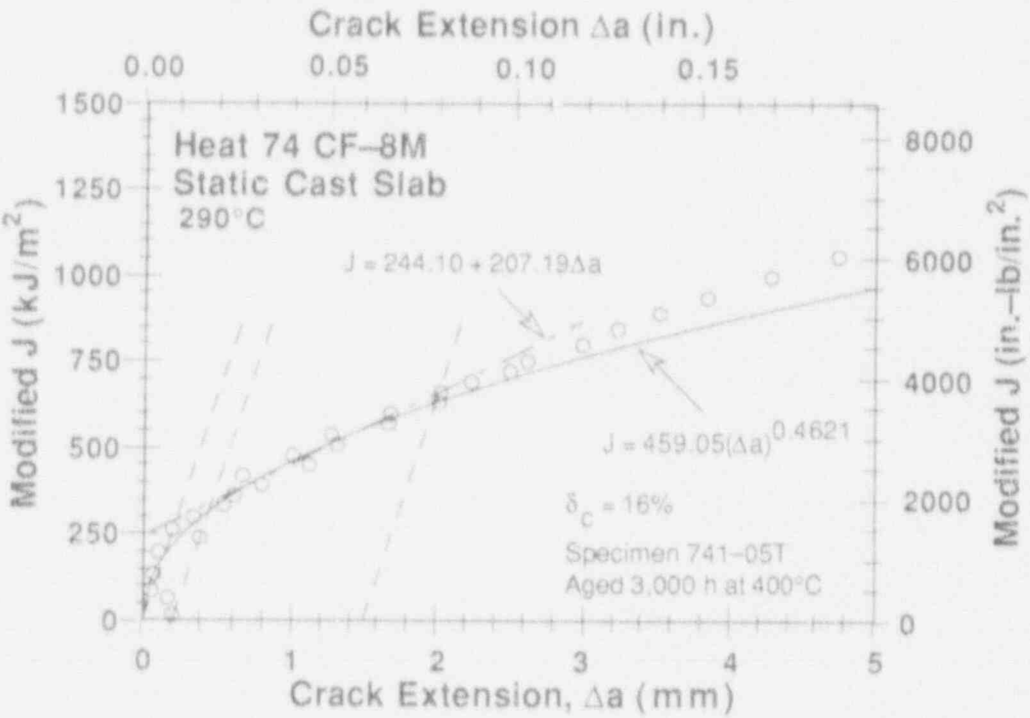

Figure C-43. Modified J_{IC} at 290°C for Heat 74 aged 3,000 h at 400°C.

Table C-44. Test data for specimen 741-02T

Test Number	: 0050	Test Temp.	: 290°C
Material Type	: CF-8M	Heat Number	: 74
Aging Temp.	: 400°C	Aging Time	: 10,000 h
Spec. Thickness	: 25.37 mm	Net Thickness	: 20.33 mm
Spec. Width	: 50.75 mm	Flow Stress	: 335.50 MPa

Unload Number	J_d (kJ/m^2)	J_m (kJ/m^2)	Δa (mm)	Load (kN)	Deflection (mm)
1	10.99	10.97	-0.0933	16.063	0.240
2	18.46	18.57	0.1272	17.938	0.326
3	29.92	29.91	0.0302	19.901	0.453
4	47.97	48.23	0.1562	21.940	0.625
5	67.93	67.69	-0.0021	23.399	0.805
6	92.24	92.88	0.1940	25.015	1.006
7	117.43	116.74	-0.0307	26.089	1.206
8	150.33	152.04	0.2763	27.389	1.457
9	183.82	184.64	0.1858	28.390	1.704
10	218.64	222.17	0.4154	29.178	1.956
11	253.35	259.11	0.5754	29.623	2.208
12	283.33	296.86	0.7486	30.132	2.457
13	324.63	335.53	0.8780	30.308	2.710
14	361.46	374.37	0.9756	30.384	2.961
15	393.97	413.36	1.2606	30.351	3.204
16	429.11	452.40	1.4160	30.207	3.458
17	460.50	492.43	1.7320	29.805	3.707
18	492.86	531.23	1.9493	29.420	3.959
19	524.74	571.00	2.1966	29.146	4.212
20	562.57	610.09	2.5271	28.653	4.460
21	576.91	648.97	2.9280	27.871	4.710
22	609.10	689.87	3.1527	27.413	4.984
23	629.13	727.79	3.5926	27.158	5.223
24	662.29	770.13	3.8042	26.657	5.509
25	696.25	825.74	4.2696	25.992	5.860
26	726.13	878.32	4.7270	24.983	6.210
27	758.14	937.62	5.2393	23.334	6.613
28	776.15	994.32	5.9259	22.160	7.010
29	797.57	1048.58	6.4771	21.016	7.412
30	828.96	1116.11	7.0425	19.704	7.910
31	850.60	1182.29	7.6977	18.637	8.411
32	876.71	1245.45	8.2107	17.695	8.911
33	899.54	1308.81	8.7401	16.598	9.413
34	918.36	1369.85	9.2618	15.470	9.914
35	922.63	1427.93	9.8960	14.106	10.416
36	939.16	1481.45	10.3119	13.360	10.909

Table C-45. Deformation J_{IC} and J-R curve results for specimen 741-02T

Test Number	: 0050	Test Temp.	: 290°C
Material Type	: CF-8M	Heat Number	: 74
Aging Temp.	: 400°C	Aging Time	: 10,000 h
Spec. Thickness	: 25.37 mm	Net Thickness	: 20.33 mm
Spec. Width	: 50.75 mm	Flow Stress	: 335.50 MPa
Modulus E	: 180.45 GPa	(Effective)	
Modulus E	: 180.00 GPa	(Nominal)	
Init. Crack	: 28.4375 mm	Init. a/w	: 0.5603 (Measured)
Final Crack	: 39.3563 mm	Final a/w	: 0.7754 (Measured)
Final Crack	: 38.7494 mm	Final a/w	: 0.7635 (Compliance)
Linear Fit	**$J = B+M(\Delta a)$**		
Intercept B	: 151.434 kJ/m²	Slope M	: 189.78 kJ/m² mm
Fit Coeff. R	: 0.9866	(8 Data Points)	
J_{IC}	: 176.4 kJ/m²	(1007.1 in.-lb/in.²)	
Δa (J_{IC})	: 0.131 mm	(0.0052 in)	
T average	: 304.2	(J_{IC} at 0.15)	
Power-Law Fit	**$J = C(\Delta a)^n$**		
Coeff. C	: 348.86 kJ/m²	Exponent n	: 0.5460
Fit Coeff. R	: 0.9950	(8 Data Points)	
J_{IC}(0.20)	: 195.3 kJ/m²	(1115.0 in.-lb/in.²)	
Δa (J_{IC})	: 0.346 mm	(0.0136 in)	
T average	: 302.6	(J_{IC} at 0.20)	
J_{IC}(0.15)	: 174.0 kJ/m²	(993.4 in.-lb/in.²)	
Δa (J_{IC})	: 0.280 mm	(0.0110 in)	
T average	: 308.9	(J_{IC} at 0.15)	
K_{Jc}	: 297.5 MPa-m$^{0.5}$		
J_{IC} Validity & Data Qualification (E 813-85)			
J_{max} allowed	: 499.15 kJ/m²	($J_{max}=b_o\sigma_f/15$)	
Data Limit	: J_{max} ignored		
Δa (max) allowed	: 1.865 mm	(at 1.5 exclusion line)	
Data Limit	: 1.5 Exclusion line		
Data Points	: Zone A = 2	Zone B = 2	
Data point spacing	: OK		
b_{net} and b_o size	: OK		
dJ/da at J_{IC}	: OK		
a_f Measurement	: Near-surface	(outside limit)	
Initial crack shape	: OK		
Crack size estimate	: Inadequate	(by compliance)	
E Effective	: OK		
J_{IC} Estimate	: INVALID		
J-R Curve Validity & Data Qualification (E 1152-86)			
J_{max} allowed	: 341.04 kJ/m²	($J_{max}=b_{net}\sigma_f/20$)	
Δa (max) allowed	: 2.232 mm	($\Delta a=0.1*b_o$)	
Δa (max) allowed	: 4.997 mm	($\omega=5$)	
Data Points	: Zone A = 5	Zone B = 11	
Data point spacing	: OK		
J-R Curve Data	: INVALID		

Table C-46. Modified J_{IC} and J-R curve results for specimen 741-02T

Linear Fit	$J = B+M(\Delta a)$		
Intercept B	: 144.332 kJ/m²	Slope M	: 211.41 kJ/m² mm]
Fit Coeff. R	: 0.9905	(8 Data Points)	
J_{IC}	: 171.3 kJ/m²	(978.3 in.-lb/in.²)	
Δa (J_{IC})	: 0.128 mm	(0.0050 in)	
T average	: 338.9	(J_{IC} at 0.15)	
Power-Law Fit	$J = C(\Delta a)^n$		
Coeff. C	: 363.52 kJ/m²	Exponent N	: 0.5804
Fit Coeff. R	: 0.9960	(8 Data Points)	
J_{IC} (0.20)	: 196.5 kJ/m²	(1121.8 in.-lb/in.²)	
Δa (J_{IC})	: 0.346 mm	(0.0136 in)	
T average	: 333.5	(J_{IC} at 0.20)	
J_{IC} (0.15)	: 173.3 kJ/m²	(989.7 in.-lb/in.²)	
Δa (J_{IC})	: 0.279 mm	(0.0110 in)	
T average	: 339.9	(J_{IC} at 0.15)	
K_{JC}	: 308.2 MPa-m$^{0.5}$		

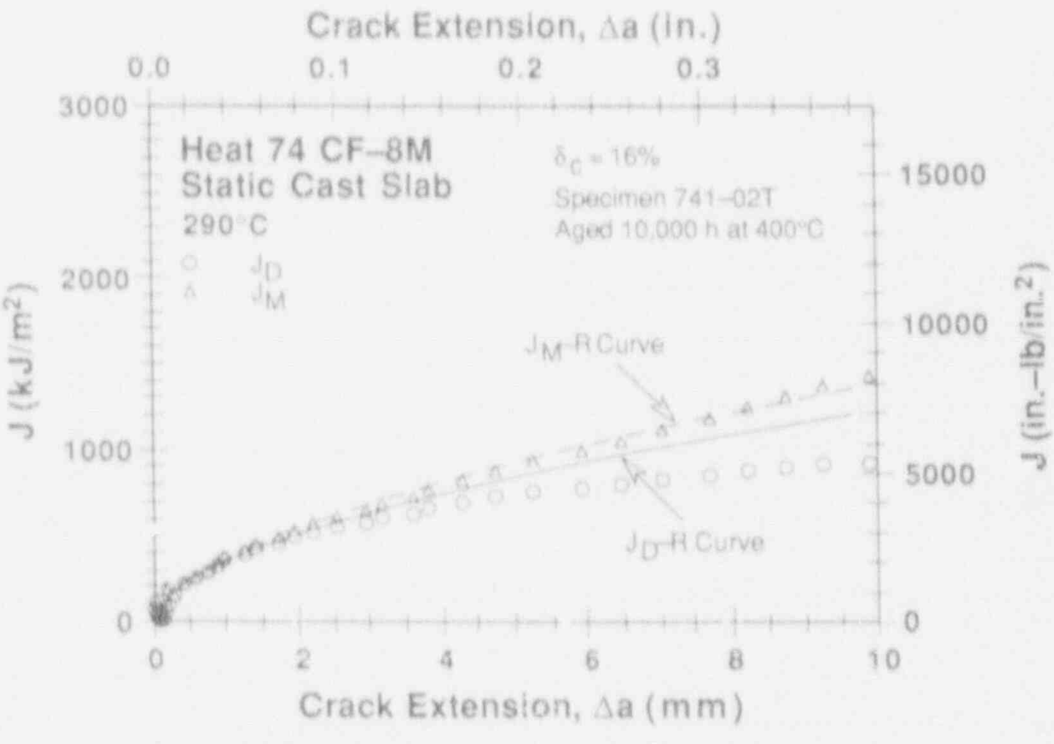

Figure C-44. Deformation and modified J-R curves at 290°C for Heat 74 aged 10,000 h at 400°C.

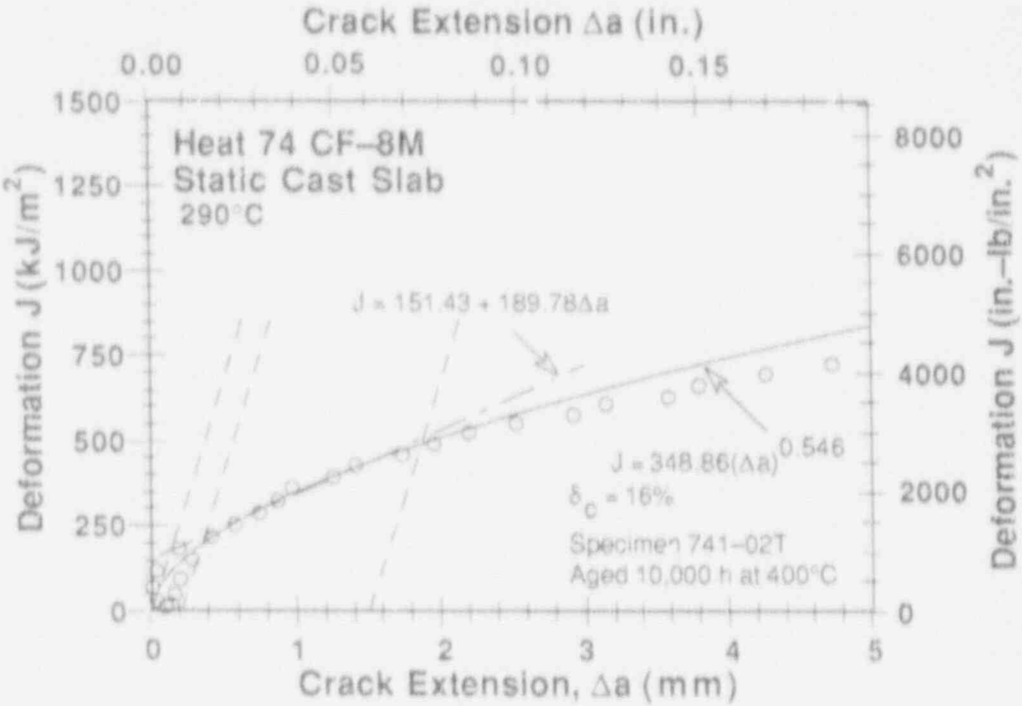

Figure C–45. Deformation J_{IC} at 290°C for Heat 74 aged 10,000 h at 400°C.

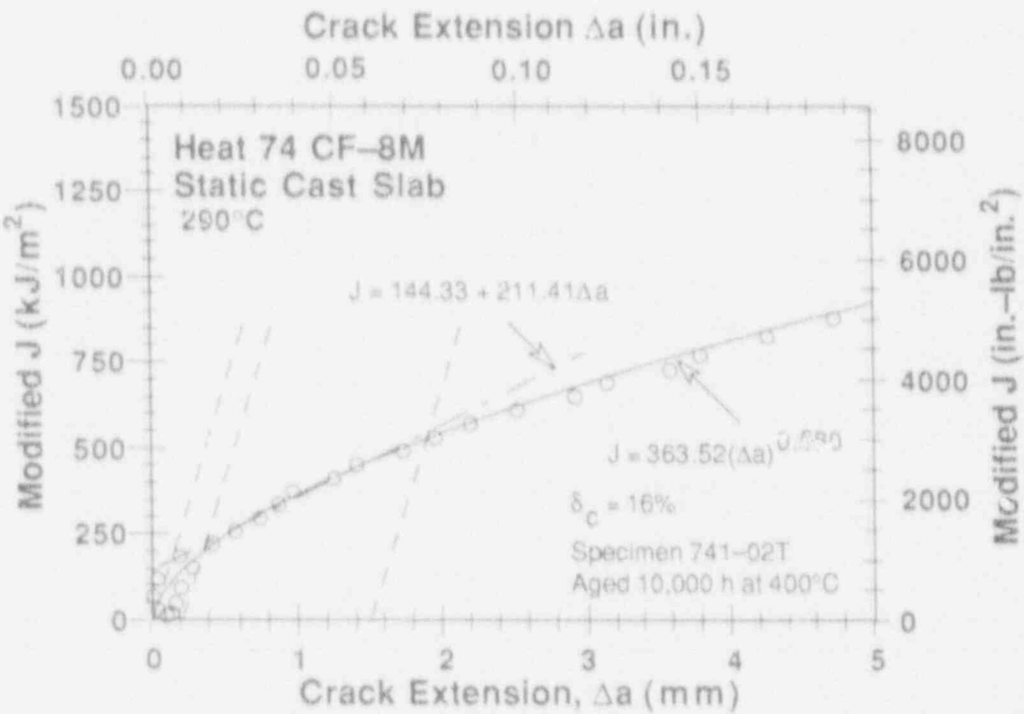

Figure C–46. Modified J_{IC} at 290°C for Heat 74 aged 10,000 h at 400°C.

Table C-47. Test data for specimen 741-04T

Test Number	: 0049	Test Temp.	: 290°C
Material Type	: CF-8M	Heat Number	: 74
Aging Temp.	: 450°C	Aging Time	: 3,000 h
Spec. Thickness	: 25.33 mm	Net Thickness	: 20.33 mm
Spec. Width	: 50.83 mm	Flow Stress	: 332.10 MPa

Unload Number	J_d (kJ/m^2)	J_m (kJ/m^2)	Δa (mm)	Load (kN)	Deflection (mm)
1	18.78	18.85	0.1174	16.104	0.375
2	31.41	31.56	0.1742	17.932	0.522
3	52.92	52.59	-0.0197	19.873	0.745
4	81.01	81.81	0.2614	21.674	1.006
5	103.32	104.00	0.2389	22.758	1.210
6	126.14	128.28	0.4566	23.515	1.405
7	150.33	152.30	0.4362	24.219	1.607
8	174.62	178.83	0.6675	24.747	1.806
9	200.13	204.11	0.6476	25.096	2.009
10	224.03	232.15	0.9728	25.326	2.208
11	248.83	257.83	1.0336	25.443	2.409
12	271.93	285.75	1.3364	25.148	2.607
13	295.64	312.49	1.4975	25.084	2.810
14	319.75	339.75	1.6509	24.945	3.008
15	341.84	367.25	1.9295	24.615	3.209
16	362.87	394.04	2.1857	24.106	3.409
17	390.78	434.02	2.6735	23.588	3.700
18	406.86	452.80	2.7777	23.158	3.859
19	429.85	487.59	3.1982	22.494	4.109
20	453.58	518.43	3.4354	21.894	4.355
21	480.05	563.31	3.9996	21.042	4.692
22	506.00	601.23	4.3381	20.258	5.005
23	533.91	652.50	4.9528	19.467	5.406
24	557.36	700.44	5.5495	18.586	5.803
25	585.38	747.14	5.9721	17.669	6.203
26	603.13	807.42	6.8590	15.878	6.706
27	617.66	859.43	7.5903	14.396	7.206
28	620.53	909.25	8.4533	12.968	7.704
29	626.17	955.90	9.1649	11.664	8.207
30	629.55	1000.94	9.8494	10.609	8.709
31	633.64	1043.40	10.4480	9.706	9.207

Table C-48. Deformation J_{IC} and J-R curve results for specimen 741-04T

Test Number	: 0049	Test Temp.	: 290°C
Material Type	: CF-8M	Heat Number	: 74
Aging Temp.	: 450°C	Aging Time	: 3,000 h
Spec. Thickness	: 25.33 mm	Net Thickness	: 20.33 mm
Spec. Width	: 50.83 mm	Flow Stress	: 332.10 MPa
Modulus E	: 169.48 GPa	(Effective)	
Modulus E	: 180.00 GPa	(Nominal)	
Init. Crack	: 29.3219 mm	Init. a/w	: 0.5769 (Measured)
Final Crack	: 40.6281 mm	Final a/w	: 0.7993 (Measured)
Final Crack	: 39.7699 mm	Final a/w	: 0.7824 (Compliance)
Linear Fit	**J = B+M(Δa)**		
Intercept B	: 67.901 kJ/m²	Slope M	: 157.51 kJ/m² mm
Fit Coeff. R	: 0.9794	(11 Data Points)	
J_{IC}	: 77.0 kJ/m²	(439.9 in.-lb/in.²)	
Δa (J_{IC})	: 0.058 mm	(0.0023 in)	
T average	: 242.1	(J_{IC} at 0.15)	
Power-Law Fit	**$J = C(\Delta a)^n$**		
Coeff. C	: 232.90 kJ/m²	Exponent n	: 0.6511
Fit Coeff. R	: 0.9772	(11 Data Points)	
J_{IC}(0.20)	: 100.7 kJ/m²	(574.8 in.-lb/in.²)	
Δa (J_{IC})	: 0.276 mm	(0.0109 in)	
T average	: 238.8	(J_{IC} at 0.20)	
J_{IC}(0.15)	: 85.4 kJ/m²	(487.8 in.-lb/in.²)	
Δa (J_{IC})	: 0.214 mm	(0.0084 in)	
T average	: 242.8	(J_{IC} at 0.15)	
K_{Jc}	: 238.5 MPa-m$^{0.5}$		
J_{IC} Validity & Data Qualification (E 813-85)			
J_{max} allowed	: 476.19 kJ/m²	($J_{max}=b_o\sigma_f/15$)	
Data Limit	: J_{max} Ignored		
Δa (max) allowed	: 1.753 mm	(at 1.5 exclusion line)	
Data Limit	: 1.5 Exclusion line		
Data Points	: Zone A = 5	Zone B = 3	
Data point spacing	: OK		
b_{net} and b_o size	: OK		
dJ/da at J_{IC}	: OK		
Initial crack shape	: OK		
Final crack shape	: OK		
Crack size estimate	: Inadequate	(by compliance)	
E Effective	: OK		
J_{IC} Estimate	: INVALID		
J-R Curve Validity & Data Qualification (E 1152-86)			
J_{max} allowed	: 337.58 kJ/m²	($J_{max}=b_{net}\sigma_f/20$)	
Δa (max) allowed	: 2.151 mm	($\Delta a=0.1*b_o$)	
Δa (max) allowed	: 5.857 mm	($\omega=5$)	
Data Points	: Zone A = 0	Zone B = 14	
Data point spacing	: Inadequate		
J-R Curve Data	: INVALID		

Table C-49. Modified J_{IC} and J-R curve results for specimen 741-04T

Linear Fit	**J = B+M(Δa)**		
Intercept B	: 64.1 kJ/m²	Slope M	: 170.84 kJ/m² mm
Fit Coeff. R	: 0.98..	(11 Data Points)	
J_{IC}	: 73.6 kJ/m²	(420.1 in.-lb/in.²)	
Δa (J_{IC})	: 0.055 mm	(0.0022 in)	
T average	: 262.5	(J_{IC} at 0.15)	
Power-Law Fit	**J = C(Δa)ⁿ**		
Coeff. C	: 242.22 kJ/m²	Exponent n	: 0.6777
Fit Coeff. R	: 0.9798	(11 Data Points)	
J_{IC} (0.20)	: 101.3 kJ/m²	(578.4 in.-lb/in.²)	
Δa (J_{IC})	: 0.276 mm	(0.0109 in)	
T average	: 257.3	(J_{IC} at 0.20)	
J_{IC}(0.15)	: 85.2 kJ/m²	(486.7 in.-lb/in.²)	
Δa (J_{IC})	: 0.214 mm	(0.0084 in)	
T average	: 261.2	(J_{IC} at 0.15)	
K_{jc}	: 245.8 MPa-m$^{0.5}$		

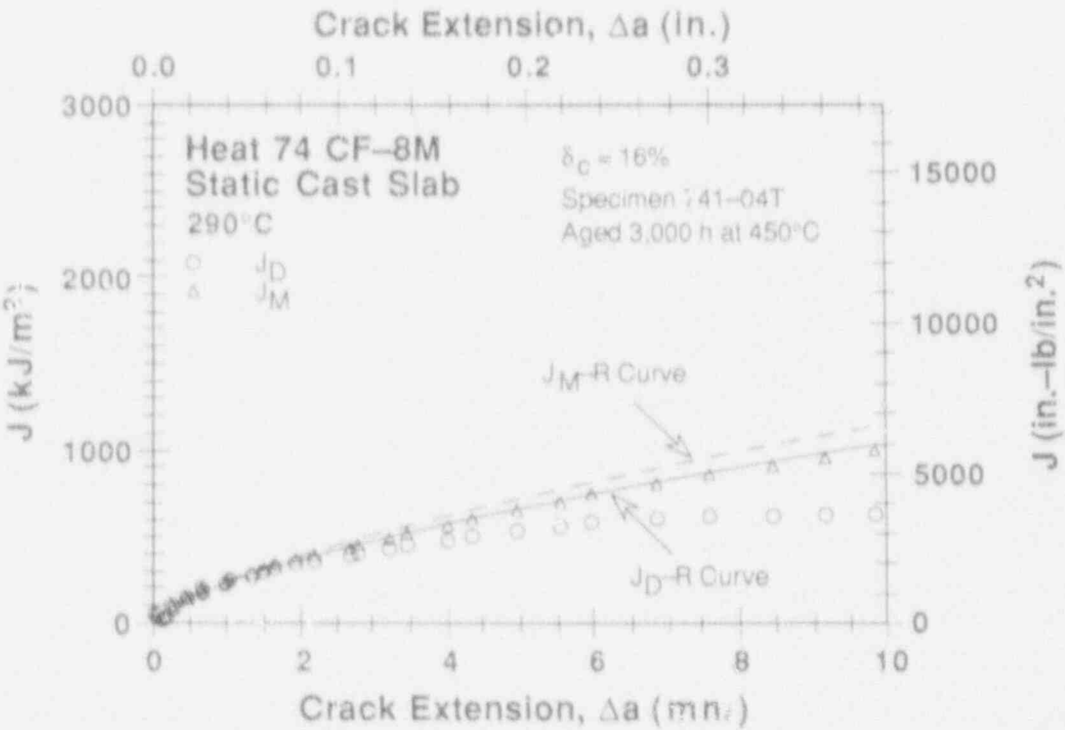

Figure C-47. Deformation and modified J-R curves at 290°C for Heat 74 aged 3,000 h at 450°C.

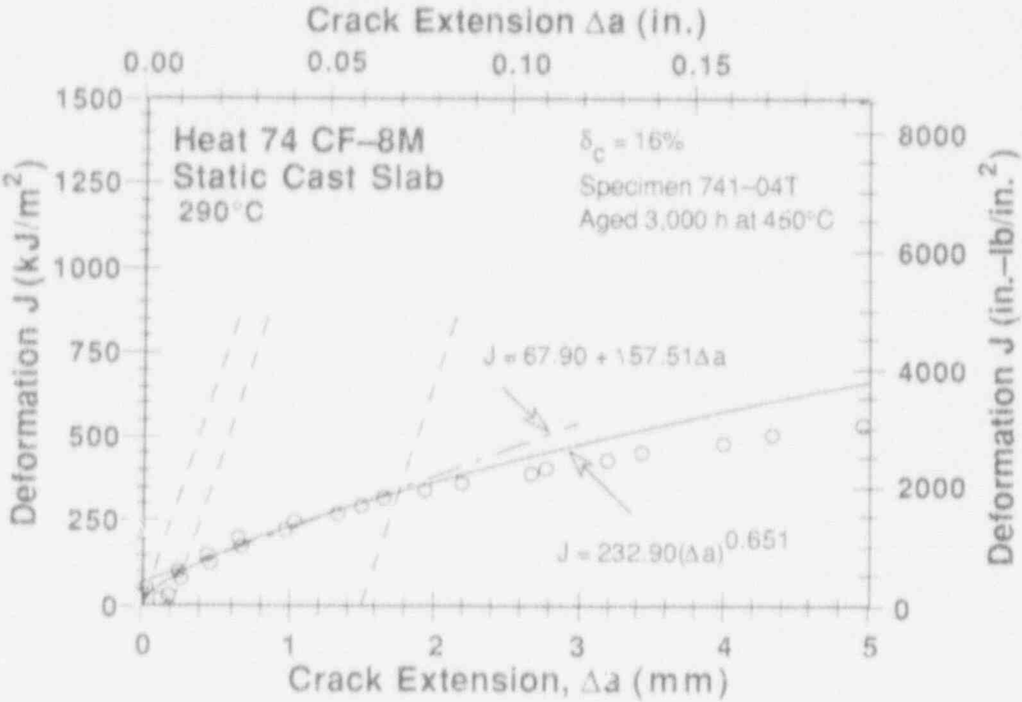

Figure C-48. Deformation J_{IC} at 290°C for Heat 74 aged 3,000 h at 450°C.

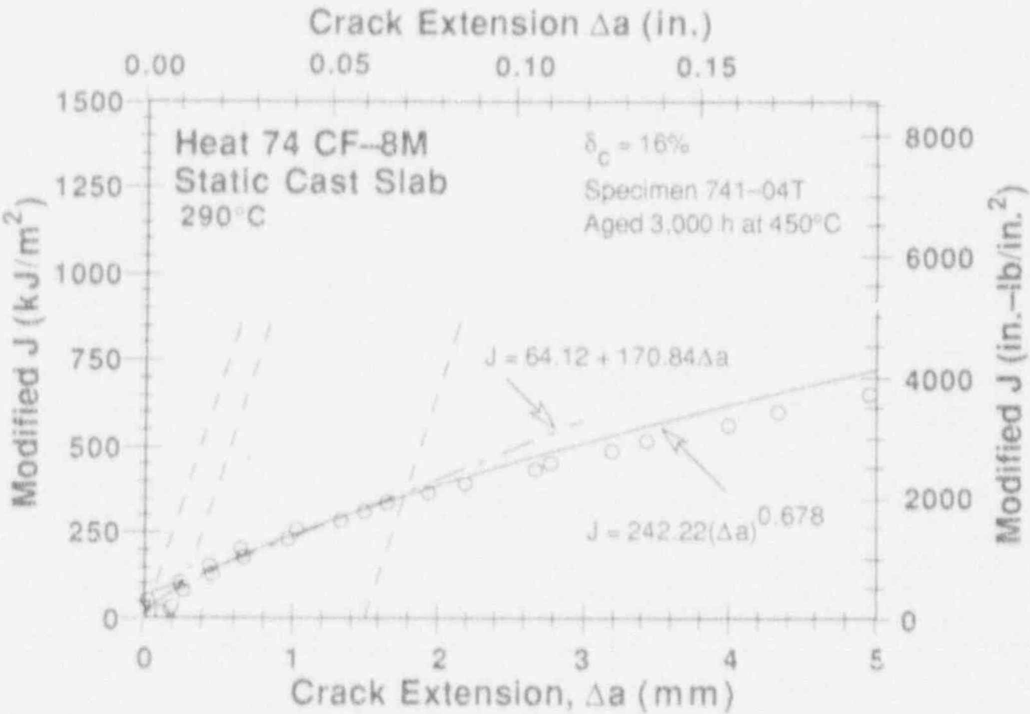

Figure C-49. Modified J_{IC} at 290°C for Heat 74 aged 3,000 h at 450°C.

Table C-50. Test data for specimen 753-05B

Test Number	: 0059	Test Temp.	: 290°C
Material Type	: CF-8M	Heat Number	: 75
Aging Temp.	: 550°C	Aging Time	: 1 h
Spec. Thickness	: 25.34 mm	Net Thickness	: 20.34 mm
Spec. Width	: 50.78 mm	Flow Stress	: 333.50 MPa

Unload Number	J_d (kJ/m^2)	J_m (kJ/m^2)	Δa (mm)	Load (kN)	Deflection (mm)
1	14.66	14.67	0.0153	18.000	0.280
2	31.69	31.66	-0.0196	21.478	0.454
3	54.48	54.70	0.0895	23.841	0.653
4	79.23	79.17	0.0136	25.272	0.857
5	112.12	112.48	0.0890	26.699	1.108
6	146.29	146.67	0.0907	27.777	1.360
7	180.75	182.70	0.2543	28.701	1.608
8	217.02	219.15	0.2702	29.530	1.860
9	254.24	256.70	0.2941	30.206	2.108
10	292.31	295.54	0.3410	30.820	2.357
11	329.43	335.36	0.4871	31.409	2.606
12	368.56	375.09	0.5159	31.762	2.856
13	407.62	416.56	0.6194	32.212	3.106
14	446.53	459.18	0.7635	32.539	3.360
15	485.18	501.09	0.8791	32.742	3.610
16	523.20	544.68	1.0606	32.962	3.862
17	561.87	586.59	1.1580	33.048	4.109
18	601.43	630.54	1.2805	32.976	4.361
19	637.45	674.78	1.4953	33.250	4.610
20	677.97	717.85	1.5574	33.333	4.860
21	715.31	764.84	1.7785	33.293	5.116
22	753.10	807.62	1.8867	33.314	5.360
23	808.22	872.37	2.0791	33.274	5.713
24	849.64	915.56	2.1124	32.780	5.960
25	882.62	962.79	2.3691	32.684	6.213
26	921.23	1006.03	2.4485	32.574	6.462
27	954.16	1055.15	2.7140	32.221	6.725
28	991.13	1104.53	2.9077	31.380	7.006
29	1023.80	1163.57	3.2996	30.769	7.333
30	1063.31	1209.13	3.3857	30.369	7.608
31	1090.38	1266.12	3.7939	29.754	7.919
32	1128.59	1332.91	4.1642	29.116	8.308
33	1184.79	1419.48	4.5322	28.144	8.808
34	1222.94	1506.12	5.0865	26.897	9.311
35	1254.13	1587.40	5.6299	25.424	9.809
36	1285.68	1668.05	6.1367	24.783	10.312
37	1335.82	1746.48	6.4133	23.941	10.810
38	1369.37	1828.17	6.8610	22.737	11.312
39	1387.15	1905.30	7.3900	21.493	11.813
40	1414.59	1978.58	7.7817	20.757	12.311
41	1442.[illegible]	2053.32	8.1691	19.958	12.811
42	1452.91	2126.65	8.6608	18.421	13.311
43	1421.31	2192.61	9.4082	16.390	13.812
44	1425.50	2266.57	9.9233	15.653	14.412
45	1449.54	2342.68	10.2916	15.157	15.008

Table C-51. Deformation J_{IC} and J-R curve results for specimen 753-05B

Test Number	: 0059	Test Temp.	: 290°C
Material Type	: CF-8M	Heat Number	: 75
Aging Temp.	: 550°C	Aging Time	: 1 h
Spec. Thickness	: 25.34 mm	Net Thickness	: 20.34 mm
Spec. Width	: 50.78 mm	Flow Stress	: 333.50 MPa
Modulus E	: 185.61 GPa	(Effective)	
Modulus E	: 180.00 GPa	(Nominal)	
Init. Crack	: 28.8406 mm	Init. a/w	: 0.5679 (Measured)
Final Crack	: 40.1438 mm	Final a/w	: 0.7905 (Measured)
Final Crack	: 39.1322 mm	Final a/w	: 0.7706 (Compliance)

Linear Fit	**$J = B+M(\Delta a)$**		
Intercept B	: 219.619 kJ/m^2	Slope M	: 287.94 kJ/m^{2}mm
Fit Coeff. R	: 0.9939	(11 Data Points)	
J_{IC}	: 280.1 kJ/m^2	(1599.3 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.210 mm	(0.0083 in)	
T average	: 480.5	(J_{IC} at 0.15)	

Power-Law Fit	**$J = C(\Delta a)^n$**		
Coeff. C	: 518.46 kJ/m^2	Exponent n	: 0.5622
Fit Coeff. R	: 0.9956	(11 Data Points)	
J_{IC}(0.20)	: 329.8 kJ/m^2	(1883.2 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.447 mm	(0.0176 in)	
T average	: 451.8	(J_{IC} at 0.20)	
J_{IC}(0.15)	: 298.0 kJ/m^2	(1701.5 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.373 mm	(0.0147 in)	
T average	: 460.3	(J_{IC} at 0.15)	
K_{Jc}	: 381.5 MPa-m$^{0.5}$		

J_{IC} Validity & Data Qualification (E 813-85)		
J_{max} allowed	: 487.83 kJ/m^2	($J_{max}=b_o\sigma_f/15$)
Δa (max) allowed	: 1.866 mm	(at J_{max})
Data Limit	: J_{max}	
Data Points	: Zone A [illegible]	Zone B = 3
Data point spacing	: OK	
b_{net} or b_o size	: Inadequate	
dJ/da at J_{IC}	: OK	
a_f Measurement	: Near-surface	outside limit
Initial crack shape	: OK	
Crack [illegible] estimate	: Inadequate	(by compliance)
E Effective	: OK	
J_{IC} Estimate	: INVALID	

J-R Curve Validity & Data Qualification (E 1152-36)		
J_{max} allowed	: 339.22 kJ/m^2	($J_{max}=b_{net}\sigma_f/20$)
Δa (max) allowed	: 2.194 mm	($\Delta a=0.1*b_o$)
Δa (max) allowed	: 5.133 mm	($\omega=5$)
Data Points	: Zone A = 17	Zone B = 6
Data point spacing	: Inadequate	
J-R Curve Data	: INVALID	

Table C-52. Modified J_{IC} and J-R curve results for specimen 753-05B

Linear Fit	**J = B+M(Δa)**		
Intercept B	: 207.666 kJ/m²	Slope M	: 321.01 kJ/m²mm
Fit Coeff. R	: 0.9957	(11 Data Points)	
J_{IC}	: 273.5 kJ/m²	(1561.6 in.-lb/in.²)	
Δa (J_{IC})	: 0.205 mm	(0.0081 in)	
T average	: 535.7	(J_{IC} at 0.15)	
Power-Law Fit	**J = C(Δa)ⁿ**		
Coeff. C	: 539.77 kJ/m²	Exponent n	: 0.5993
Fit Coeff. R	: 0.9964	(11 Data Points)	
J_{IC}(0.20)	: 335.0 kJ/m²	(1912.9 in.-lb/in.²)	
Δa (J_{IC})	: 0.451 mm	(0.0178 in)	
T average	: 500.2	(J_{IC} at 0.20)	
J_{IC}(0.15)	: 299.7 kJ/m²	(1711.4 in.-lb/in.²)	
Δa (J_{IC})	: 0.375 mm	(0.0148 in)	
T average	: 508.8	(J_{IC} at 0.15)	
K_{Jc}	: 397.5 MPa-m$^{0.5}$		

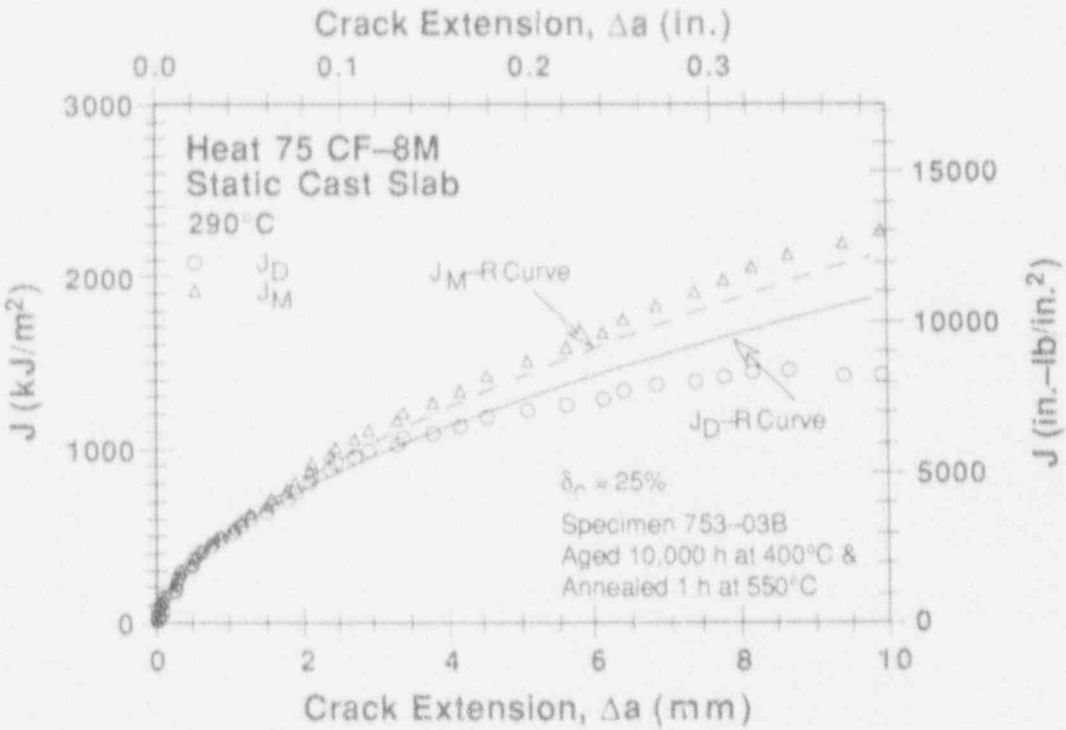

Figure C-50. Deformation and modified J-R curves at 290°C for Heat 75 aged 10,000 h at 400°C and annealed 1 h at 550°C.

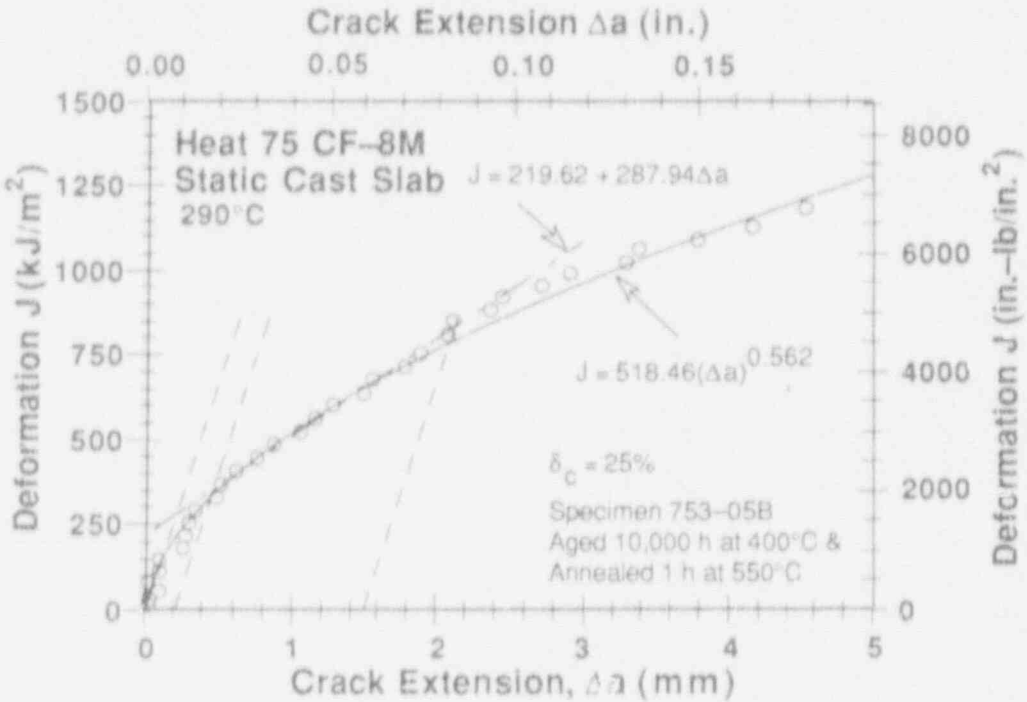

Figure C–51. Deformation J_{IC} at 290°C for Heat 75 aged 10,000 h at 400°C and annealed 1 h at 550°C.

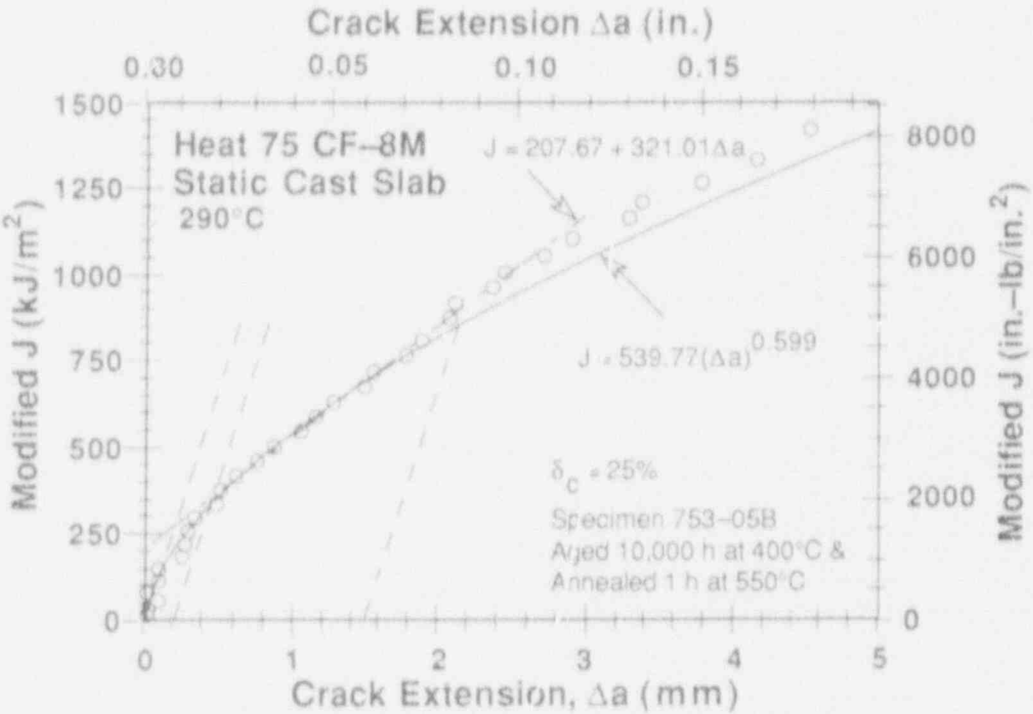

Figure C–52. Modified J_{IC} at 290°C for Heat 75 aged 10,000 h at 400°C and annealed 1 h at 550°C.

Table C-53. Test data for specimen 752-07T

Test Number	: 0051		Test Temp.	: 290°C	
Material Type	: CF-8M		Heat Number	: 75	
Aging Temp.	: 320°C		Aging Time	: 30,000 h	
Spec. Thickness	: 25.38 mm		Net Thickness	: 20.34 mm	
Spec. Width	: 50.83 mm		Flow Stress	: 389.00 MPa	

Unload Number	J_d (kJ/m^2)	J_m (kJ/m^2)	Δa (mm)	Load (kN)	Deflection (mm)
1	11.46	11.49	0.1279	17.109	0.241
2	19.28	19.20	-0.0882	20.045	0.331
3	41.93	41.65	-0.2084	23.879	0.537
4	71.17	71.63	0.0269	26.701	0.767
5	102.90	104.39	0.2408	28.603	1.006
6	138.94	139.18	0.0585	30.300	1.255
7	177.60	179.98	0.2941	31.382	1.505
8	216.19	219.07	0.3375	32.377	1.755
9	256.01	261.18	0.5049	32.990	2.006
10	297.24	302.44	0.5061	33.420	2.257
11	334.70	348.12	0.9469	33.459	2.508
12	373.23	390.74	1.1409	33.449	2.764
13	410.95	433.03	1.3344	33.598	3.006
14	443.79	480.09	1.8806	33.156	3.261
15	482.28	519.49	1.9124	32.884	3.509
16	518.27	566.23	2.2560	32.240	3.759
17	553.66	608.17	2.4493	31.610	4.007
18	582.84	653.78	2.9008	30.749	4.261
19	614.80	693.79	3.10[illegible]0	29.472	4.511
20	635.88	737.85	3.6634	28.524	4.763
21	662.16	775.04	3.9134	27.483	5.010
22	675.96	826.15	4.7220	26.203	5.311
23	703.02	878.20	5.2302	25.263	5.662
24	744.09	939.51	5.6111	24.593	6.060
25	779.77	1011.33	6.2393	23.475	6.511
26	822.96	1084.99	6.7259	21.726	7.011
27	838.95	1160.46	7.6155	20.397	7.519
28	859.94	1225.83	8.2391	19.019	8.009
29	894.42	1297.64	8.7267	17.699	8.541
30	908.91	1360.54	9.3257	16.581	9.012
31	928.16	1423.63	9.8385	15.571	9.512
32	936.12	1485.36	10.4356	14.292	10.008

Table C-54. Deformation J_{IC} and J-R curve results for specimen 752-07T

Test Number	: 0051	Test Temp.	: 290°C
Material Type	: CF-8M	Heat Number	: 75
Aging Temp.	: 320°C	Aging Time	: 30,000 h
Spec. Thickness	: 25.38 mm	Net Thickness	: 20.34 mm
Spec. Width	: 50.83 mm	Flow Stress	: 389.00 MPa
Modulus E	: 182.48 GPa	(Effective)	
Modulus E	: 180.00 GPa	(Nominal)	
Init. Crack	: 28.6969 mm	Init. a/w	: 0.5646 (Measured)
Final Crack	: 39.7750 mm	Final a/w	: 0.7826 (Measured)
Final Crack	: 39.1325 mm	Final a/w	: 0.7699 (Compliance)
Linear Fit	**$J = B+M(\Delta a)$**		
Intercept B	: 153.189 kJ/m^2	Slope M	: 196.18 kJ/m^2 mm
Fit Coeff. R	: 0.9620	(7 Data Points)	
J_{IC}	: 175.3 kJ/m^2	(1000.9 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.113 mm	(0.0044 in)	
T average	: 236.6	(J_{IC} at 0.15)	
Power-Law Fit	**$J = C(\Delta a)^n$**		
Coeff. C	: 357.96 kJ/m^2	Exponent n	: 0.4876
Fit Coeff. R	: 0.9674	(7 Data Points)	
J_{IC} (0.20)	: 210.0 kJ/m^2	(1199.1 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.335 mm	(0.0132 in)	
T average	: 212.1	(J_{IC} at 0.20)	
J_{IC} (0.15)	: 189.7 kJ/m^2	(1083.1 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.272 mm	(0.0107 in)	
T average	: 217.1	(J_{IC} at 0.15)	
K_{Jc}	: 295.2 MPa-m$^{0.5}$		
J_{IC} Validity & Data Qualification (E 813-85)			
J_{max} allowed	: 573.86 kJ/m^2	($J_{max}=b_o\sigma_f/15$)	
Data Limit	: J_{max} Ignored		
Δa (max) allowed	: 1.807 mm	(at 1.5 exclusion line)	
Data Limit	: 1.5 Exclusion line		
Data Points	: Zone A = 4	Zone B = 1	
Data point spacing	: OK		
b_{net} and b_o size	: OK		
dJ/da at J_{IC}	: OK		
a_o Measurement	: 1 outside limit		
a_f Measurement	: Near-surface	(outside limit)	
Crack size estimate	: Inadequate	(by compliance)	
E Effective	: OK		
J_{IC} Estimate	: INVALID		
J-R Curve Validity & Data Qualification (E 1152-86)			
J_{max} allowed	: 395.52 kJ/m^2	($J_{max}=b_{net}\sigma_f/20$)	
Δa (max) allowed	: 2.213 mm	($\Delta a=0.1*b_o$)	
Δa (max) allowed	: 4.516 mm	($\omega=5$)	
Data Points	: Zone A = 5	Zone B = 8	
Data point spacing	: OK		
J-R Curve Data	: INVALID		

Table C-55. Modified J_{IC} and J-R curve results for specimen 752-07T

Linear Fit	**J = B+M(Δa)**		
Intercept B	: 149.312 kJ/m²	Slope M	: 215.09 kJ/m² mm
Fit Coeff. R	: 0.9689	(7 Data Points)	
J_{IC}	: 173.3 kJ/m²	(989.4 in.-lb/in.²)	
Δa (J_{IC})	: 0.111 mm	(0.0044 in)	
T average	: 259.4	(J_{IC} at 0.15)	
Power-Law Fit	**J = C(Δa)^n**		
Coeff. C	: 373.14 kJ/m²	Exponent n	: 0.5147
Fit Coeff. R	: 0.9726	(7 Data Points)	
J_{IC} (0.20)	: 213.2 kJ/m²	(1217.3 in.-lb/in.²)	
Δa (J_{IC})	: 0.337 mm	(0.0133 in)	
T average	: 232.0	(J_{IC} at 0.20)	
J_{IC} (0.15)	: 191.3 kJ/m²	(1092.1 in.-lb/in.²)	
Δa (J_{IC})	: 0.273 mm	(0.0107 in)	
T average	: 237.2	(J_{IC} at 0.15)	
K_{Jc}	: 304.7 MPa-m^0.5		

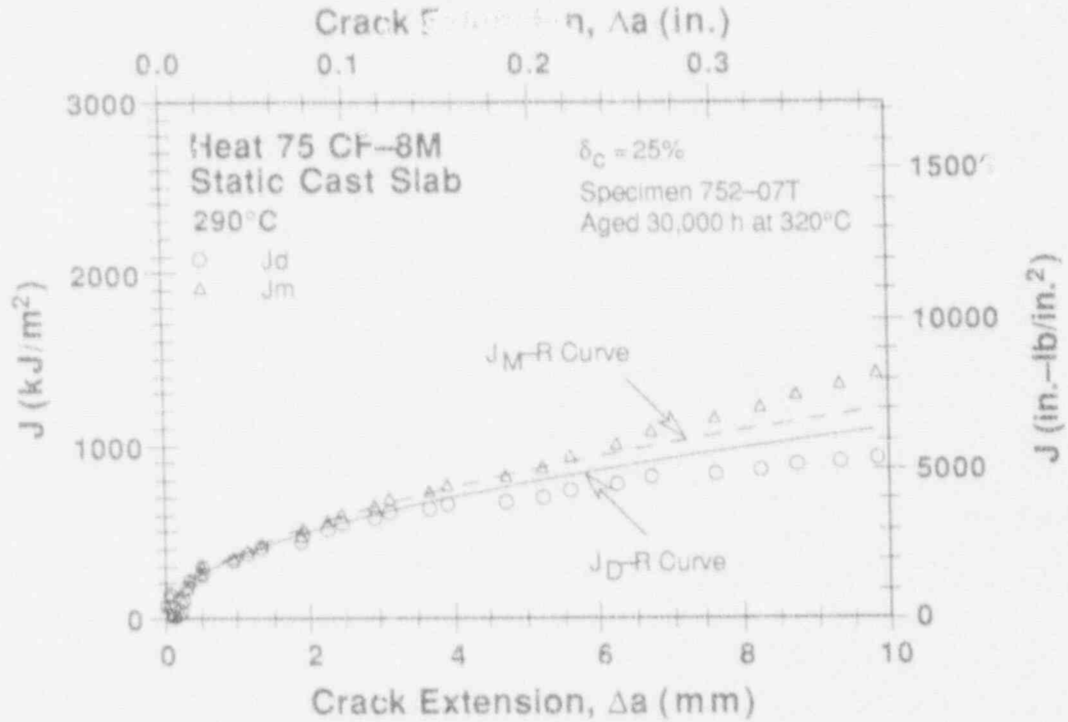

Figure C-55. Deformation and modified J-R curves at 290°C for Heat 75 aged 30,000 h at 320°C.

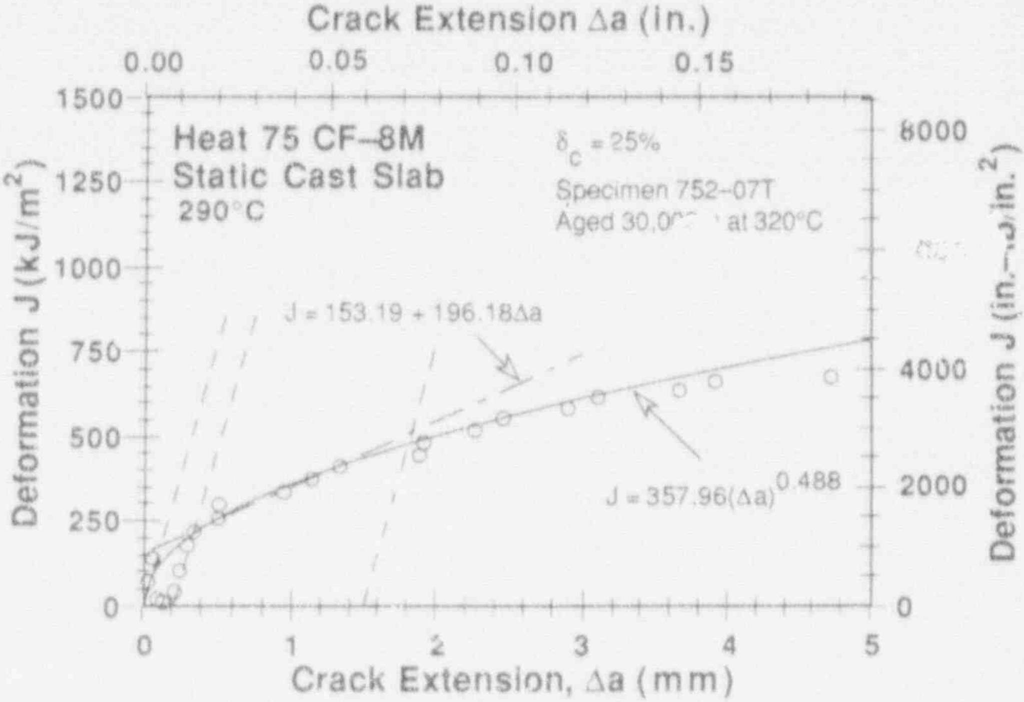

Figure C-54. Deformation J_{IC} at 290°C for Heat 75 aged 30,000 h at 320°C.

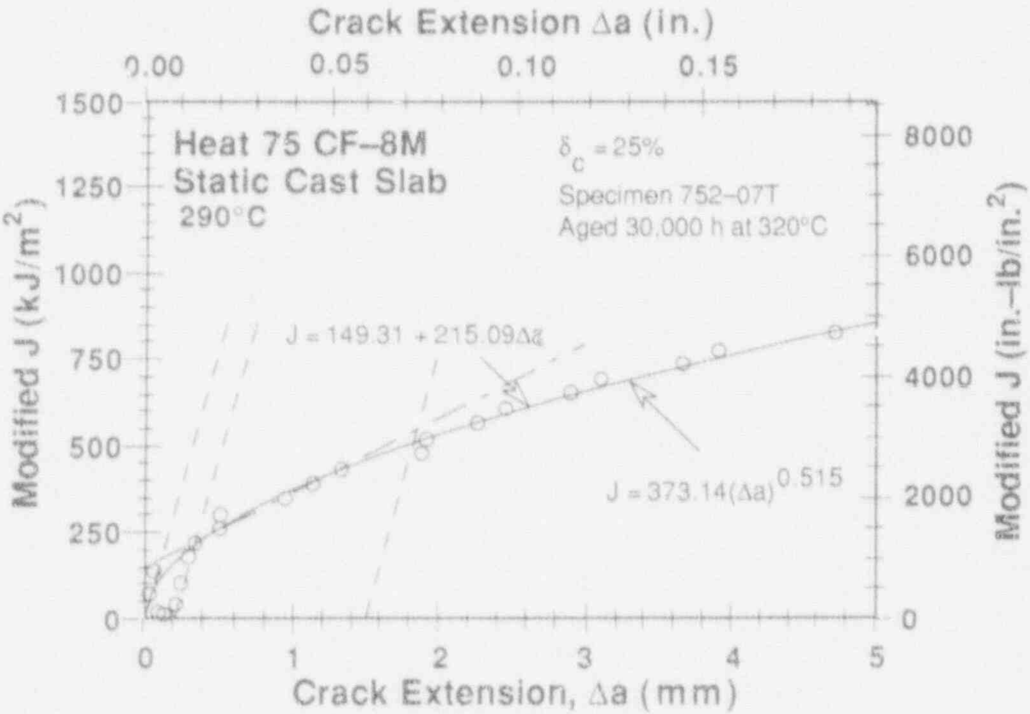

Figure C-55. Modified J_{IC} at 290°C for Heat 75 aged 30,000 h at 320°C.

Table C-56. Test data for specimen 752-03T

Test Number	: 0056	Test Temp.	: 290°C
Material Type	: CF-8M	Heat Number	: 75
Aging Temp.	: 350°C	Aging Time	: 10,000 h
Spec. Thickness	: 25.34 mm	Net Thickness	: 20.31 mm
Spec. Width	: 50.77 mm	Flow Stress	: 409.90 MPa

Unload Number	J_d (kJ/m^2)	J_m (kJ/m^2)	Δa (mm)	Load (kN)	Deflection (mm)
1	11.30	11.34	0.2290	18.067	0.223
2	23.59	23.58	0.1486	22.416	0.353
3	41.47	[illegible]39	0.1058	25.616	0.505
4	60.97	[illegible].67	0.0141	27.752	0.655
5	89.36	9[illegible].11	0.2821	30.234	0.854
6	[illegible]8.69	119.27	0.2494	31.937	1.055
7	150.94	152.67	0.4082	33.436	1.258
8	183.27	185.03	0.4117	34.545	1.457
9	216.75	221.01	0.6389	35.402	1.658
10	249.94	255.55	0.7422	35.938	1.858
11	282.53	293.03	1.0697	36.392	2.058
12	315.98	327.97	1.1566	36.514	2.258
13	350.53	366.00	1.3387	36.698	2.458
14	381.70	404.36	1.[illegible]726	36.397	2.658
15	417.43	440.04	1.6748	36.131	2.863
16	444.08	481.29	2.2453	35.456	3.062
17	472.44	513.71	2.3928	34.992	3.258
18	499.26	553.77	2.8392	34.426	3.463
19	533.72	597.65	3.1312	32.608	3.710
20	574.59	652.91	3.5372	33.089	4.006
21	618.89	717.92	4.0646	31.474	4.358
22	653.16	780.44	4.7246	29.791	4.709
23	693.02	848.27	5.3203	27.647	5.112
24	725.01	912.58	5.9577	26.247	5.507
25	768.54	978.48	6.3638	24.999	5.926
26	777.88	1039.63	7.2507	22.605	6.307
27	790.64	1094.50	7.9333	20.939	6.707
28	797.29	1150.37	8.6911	19.272	7.111
29	804.03	1202.06	9.3486	17.415	7.513
30	811.74	1265.42	10.1171	16.107	8.010

Table C-57. Deformation J_{IC} and J-R curve results for specimen 752-03T

Test Number	: 0056	Test Temp.	: 290°C
Material Type	: CF-8M	Heat Number	: 75
Aging Temp.	: 350°C	Aging Time	: 10,000 h
Spec. Thickness	: 25.34 mm	Net Thickness	: 20.31 mm
Spec. Width	: 50.77 mm	Flow Stress	: 409.90 MPa
Modulus E	: 186.26 GPa	(Effective)	
Modulus E	: 180.00 GPa	(Nominal)	
Init. Crack	: 27.9844 mm	Init. a/w	: 0.5512 (Measured)
Final Crack	: 38.6594 mm	Final a/w	: 0.7615 (Measured)
Final Crack	: 38.1014 mm	Final a/w	: 0.7505 (Compliance)
Linear Fit	**$J = B+M(\Delta a)$**		
Intercept B	: 89.444 kJ/m^2	Slope M	: 189.41 kJ/m^{2}mm
Fit Coeff. R	: 0.9879	(10 Data Points)	
J_{IC}	: 101.1 kJ/m^2	(577.5 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.062 mm	(0.0024 in)	
T average	: 210.0	(J_{IC} at 0.15)	
Power-Law Fit	**$J = C(\Delta a)^n$**		
Coeff. C	: 288.18 kJ/m^2	Exponent n	: 0.6266
Fit Coeff. R	: 0.9909	(10 Data Points)	
J_{IC}(0.20)	: 129.5 kJ/m^2	(739.5 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.279 mm	(0.0110 in)	
T average	: 205.5	(J_{IC} at 0.20)	
J_{IC}(0.15)	: 110.8 kJ/m^2	(632.9 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.218 mm	(0.0086 in)	
T average	: 209.2	(J_{IC} at 0.15)	
K_{Jc}	: 276.1 MPa-m$^{0.5}$		
J_{IC} Validity & Data Qualification (E 813-85)			
J_{max} allowed	: 622.57 kJ/m^2	($J_{max}=b_o\sigma_f/15$)	
Data Limit	: J_{max} Ignored		
Δa (max) allowed	: 1.750 mm	(at 1.5 exclusion line)	
Data Limit	: 1.5 Exclusion line		
Data Points	: Zone A = 3	Zone B = 3	
Data point spacing	: OK		
b_{net} and b_o size	: OK		
dJ/da at J_{IC}	: OK		
Initial crack shape	: OK		
Final crack shape	: OK		
Crack size estimate	: Inadequate	(by compliance)	
E Effective	: OK		
J_{IC} Estimate	: INVALID		
J-R Curve Validity & Data Qualification (E 1152-86)			
J_{max} allowed	: 416.25 kJ/m^2	($J_{max}=b_{net}\sigma_f/20$)	
Δa (max) allowed	: 2.278 mm	($\Delta a=0.1^*b_o$)	
Δa (max) allowed	: 5.653 mm	($\omega=5$)	
Data Points	: Zone A = 1	Zone B = 15	
Data point spacing	: Inadequate		
J-R Curve Data	: INVALID		

Table C-58. Modified J_{IC} and J-R curve results for specimen 752-03T

Linear Fit	**J = B+M(Δa)**		
Intercept B	: 84.358 kJ/m^2	Slope M	: 205.21 kJ/m^{2}mm
Fit Coeff. R	: 0.9903	(10 Data Points)	
J_{IC}	: 96.4 kJ/m^2	(550.6 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.059 mm	(0.0023 in)	
T average	: 227.5	(J_{IC} at 0.15)	
Power-Law Fit	**J = C(Δa)^n**		
Coeff. C	: 298.74 kJ/m^2	Exponent n	: 0.6540
Fit Coeff. R	: 0.9920	(10 Data Points)	
J_{IC}(0.20)	: 129.7 kJ/m^2	(740.3 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.279 mm	(0.0110 in)	
T average	: 2?1.3	(J_{IC} at 0.20)	
J_{IC}(0.15)	: 110.0 kJ/m^2	(628.2 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.217 mm	(0.0085 in)	
T average	: 225.0	(J_{IC} at 0.15)	
K_{jc}	: 284.0 MPa-m$^{0.5}$		

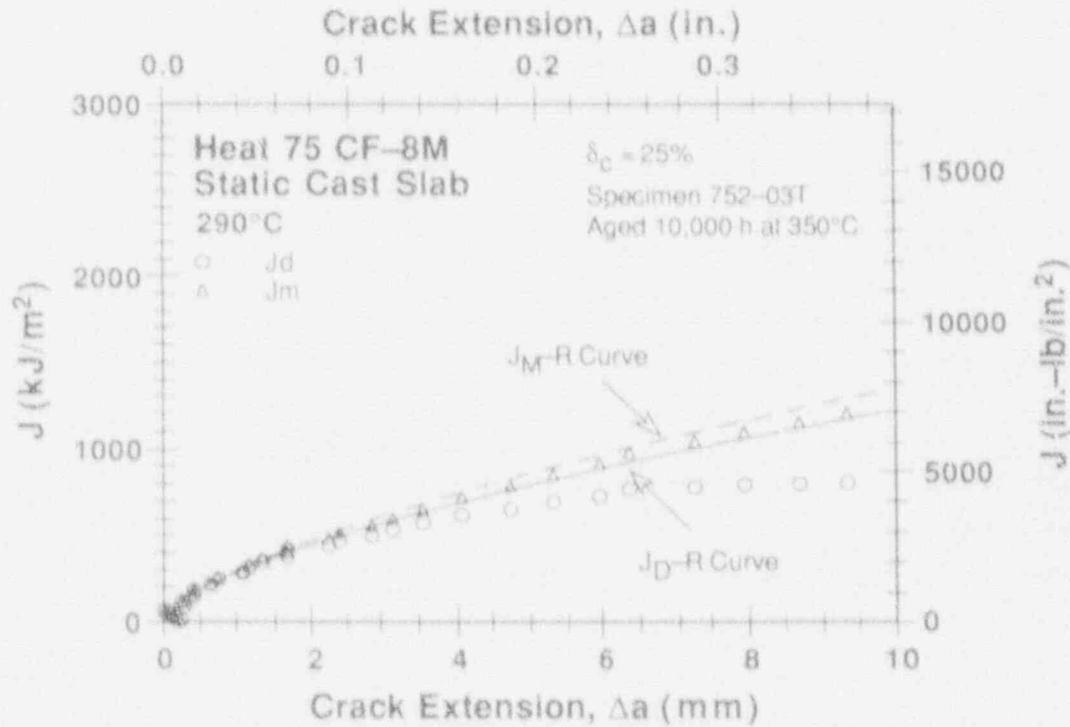

Figure C-56. Deformation and modified J-R curves at 290°C for Heat 75 aged 10,000 h at 350°C.

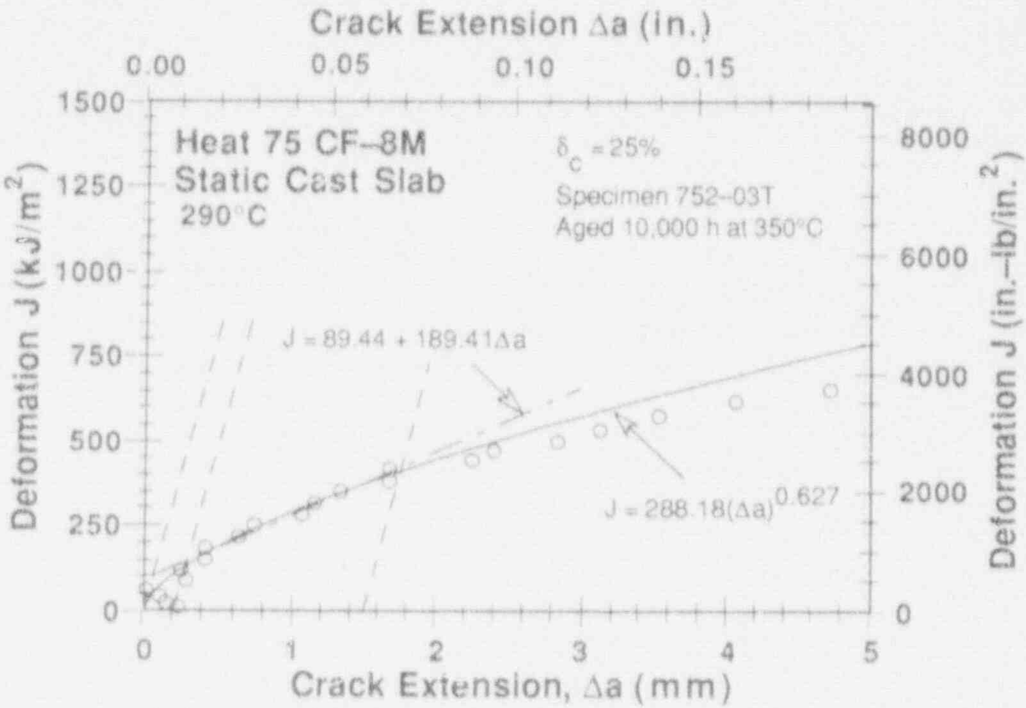

Figure C-57. Deformation J_{IC} at 290°C for Heat 75 aged 10,000 h at 350°C.

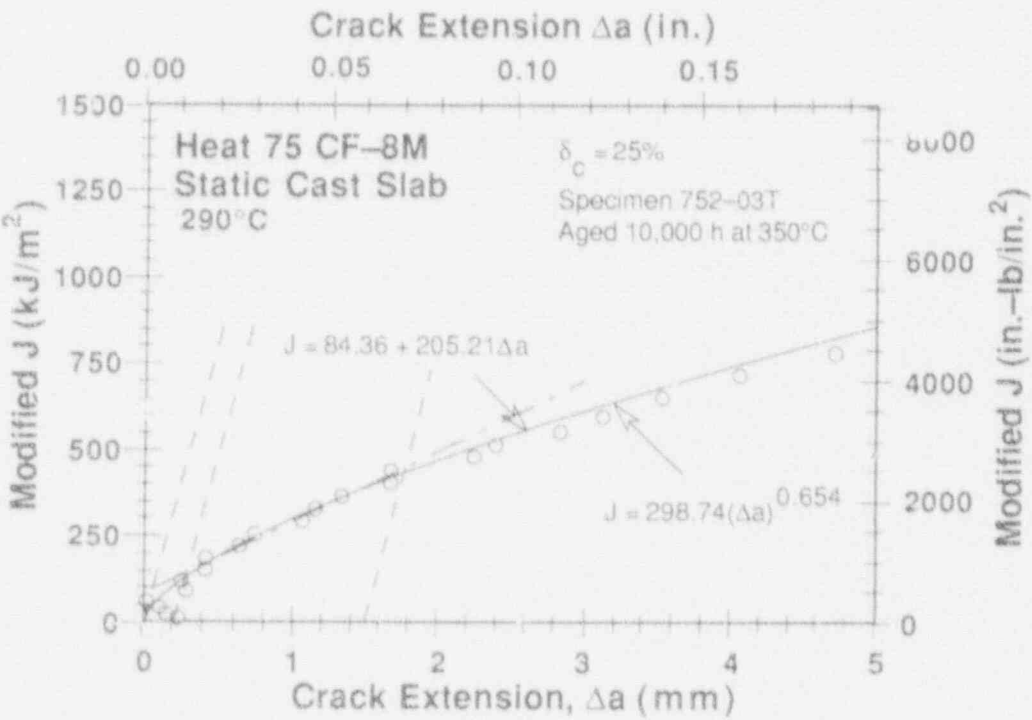

Figure C-58. Modified J_{IC} at 290°C for Heat 75 aged 10,000 h at 350°C.

Table C-59. Test data for specimen 752-05T

Test Number	: 0055	Test Temp.	: 290°C
Material Type	: CF-8M	Heat Number	: 75
Aging Temp.	: 350°C	Aging Time	: 30,000 h
Spec. Thickness	: 25.31 mm	Net Thickness	: 20.28 mm
Spec. Width	: 50.79 mm	Flow Stress	: 408.70 MPa

Unload Number	J_d (kJ/m^2)	J_m (kJ/m^2)	Δa (mm)	Load (kN)	Deflection (mm)
1	16.62	16.66	0.0828	18.037	0.301
2	31.68	31.77	0.1279	21.277	0.453
3	48.71	48.67	0.0658	23.380	0.605
4	67.57	68.06	0.2414	25.189	0.756
5	86.64	86.92	0.1911	26.533	0.906
6	107.33	108.50	0.3600	27.700	1.055
7	128.52	129.22	0.2862	28.678	1.206
8	158.51	161.01	0.5060	29.688	1.407
9	188.76	191.05	0.4905	30.449	1.609
10	219.13	225.04	0.7919	30.912	1.810
11	248.16	255.96	0.9300	31.344	2.007
12	278.47	290.64	1.2101	31.771	2.210
13	310.70	321.49	1.1324	32.141	2.407
14	342.11	359.87	1.4852	31.924	2.613
15	371.11	392.59	1.6564	31.613	2.812
16	397.13	426.01	1.9683	30.887	3.003
17	424.29	460.36	2.2486	30.766	3.209
18	448.18	493.82	2.5948	30.040	3.405
19	473.60	527.47	2.8720	29.472	3.609
20	496.66	560.54	3.1878	28.419	3.808
21	517.71	603.89	3.8442	27.531	4.060
22	548.57	650.95	4.2835	26.506	4.365
23	577.91	707.18	4.9522	25.066	4.710
24	610.08	769.41	5.6339	23.377	5.113
25	636.66	827.81	6.2994	21.682	5.511
26	657.71	885.04	7.0025	20.039	5.913
27	676.09	937.91	7.6284	18.207	6.311
28	686.57	989.09	8.3262	17.032	6.710
29	702.74	1043.21	8.9355	15.549	7.149
30	712.71	1084.85	9.4205	14.641	7.510
31	718.68	1131.59	10.0130	13.385	7.911

Table C-60. Deformation J_{IC} and J-R curve results for specimen 752-05T

Test Number	: 0055	Test Temp.	: 290°C
Material Type	: CF-8M	Heat Number	: 75
Aging Temp.	: 350°C	Aging Time	: 30,000 h
Spec. Thickness	: 25.31 mm	Net Thickness	: 20.28 mm
Spec. Width	: 50.79 mm	Flow Stress	: 408.70 MPa
Modulus E	: 186.80 GPa	(Effective)	
Modulus E	: 180.00 GPa	(Nominal)	
Init. Crack	: 29.1438 mm	Init. a/w	: 0.5738 (Measured)
Final Crack	: 39.6375 mm	Final a/w	: 0.7804 (Measured)
Final Crack	: 39.1568 mm	Final a/w	: 0.7709 (Compliance)
Linear Fit	**$J = B+M(\Delta a)$**		
Intercept B	: 71.597 kJ/m^2	Slope M	: 184.98 kJ/m^{2}mm
Fit Coeff. R	: 0.9797	(10 Data Points)	
J_{IC}	: 80.7 kJ/m^2	(461.0 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.049 mm	(0.0019 in)	
T average	: 206.9	(J_{IC} at 0.15)	
Power-Law Fit	**$J = C(\Delta a)^n$**		
Coeff. C	: 262.59 kJ/m^2	Exponent n	: 0.6689
Fit Coeff. R	: 0.9693	(10 Data Points)	
$J_{IC}(0.20)$	: 108.4 kJ/m^2	(618.8 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.266 mm	(0.0105 in)	
T average	: 202.1	(J_{IC} at 0.20)	
$J_{IC}(0.15)$	: 91.2 kJ/m^2	(520.8 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.206 mm	(0.0081 in)	
T average	: 205.2	(J_{IC} at 0.15)	
K_{Jc}	: 266.1 MPa-m$^{0.5}$		
J_{IC} Validity & Data Qualification (E 813-85)			
J_{max} allowed	: 589.84 kJ/m^2	($J_{max}=b_o\sigma_f/15$)	
Data Limit	: J_{max} Ignored		
Δa (max) allowed	: 1.732 mm	(at 1.5 exclusion line)	
Data Limit	: 1.5 Exclusion line		
Data Points	: Zone A = 4	Zone B = 3	
Data point spacing	: OK		
b_{net} and b_o size	: OK		
dJ/da at J_{IC}	: OK		
Initial crack shape	: OK		
Final crack shape	: OK		
Crack size estimate	: Inadequate	(by compliance)	
E Effective	: OK		
J_{IC} Estimate	: INVALID		
J-R Curve Validity & Data Qualification (E 1152-86)			
J_{max} allowed	: 414.50 kJ/m^2	($J_{max}=b_{net}\sigma_f/20$)	
Δa (max) allowed	: 2.165 mm	($\Delta a=0.1*b_o$)	
Δa (max) allowed	: 5.993 mm	($\omega=5$)	
Data Points	: Zone A = 1	Zone B = 15	
Data point spacing	: Inadequate		
J-R Curve Data	: INVALID		

Table C-61. Modified J_{IC} and J-R curve results for specimen 752-05T

Linear Fit	**$J = B+M(\Delta a)$**		
Intercept B	: 66.683 kJ/m^2	Slope M	: 199.87 kJ/m^2mm
Fit Coeff. R	: 0.9831	(10 Data Points)	
J_{IC}	: 76.0 kJ/m^2	(433.8 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.046 mm	(0.0018 in)	
T average	: 223.5	(J_{IC} at 0.15)	
Power-Law Fit	**$J = C(\Delta a)^n$**		
Coeff. C	: 272.29 kJ/m^2	Exponent n	: 0.6970
Fit Coeff. R	: 0.9722	(10 Data Points)	
J_{IC}(0.20)	: 108.3 kJ/m^2	(618.1 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.266 mm	(0.0105 in)	
T average	: 217.3	(J_{IC} at 0.20)	
J_{IC}(0.15)	: 90.3 kJ/m^2	(515.6 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.205 mm	(0.0081 in)	
T average	: 220.4	(J_{IC} at 0.15)	
K_{jc}	: 273.9 MPa-$m^{0.5}$		

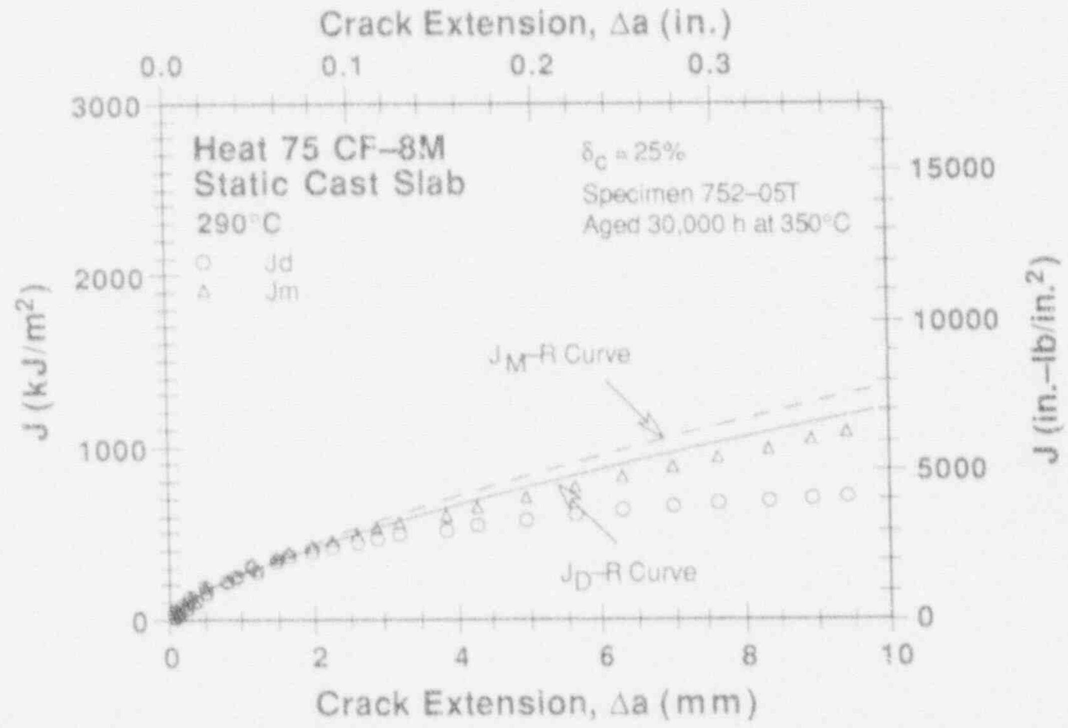

Figure C-59. Deformation and modified J-R curves at 290°C for Heat 75 aged 30,000 h at 350°C.

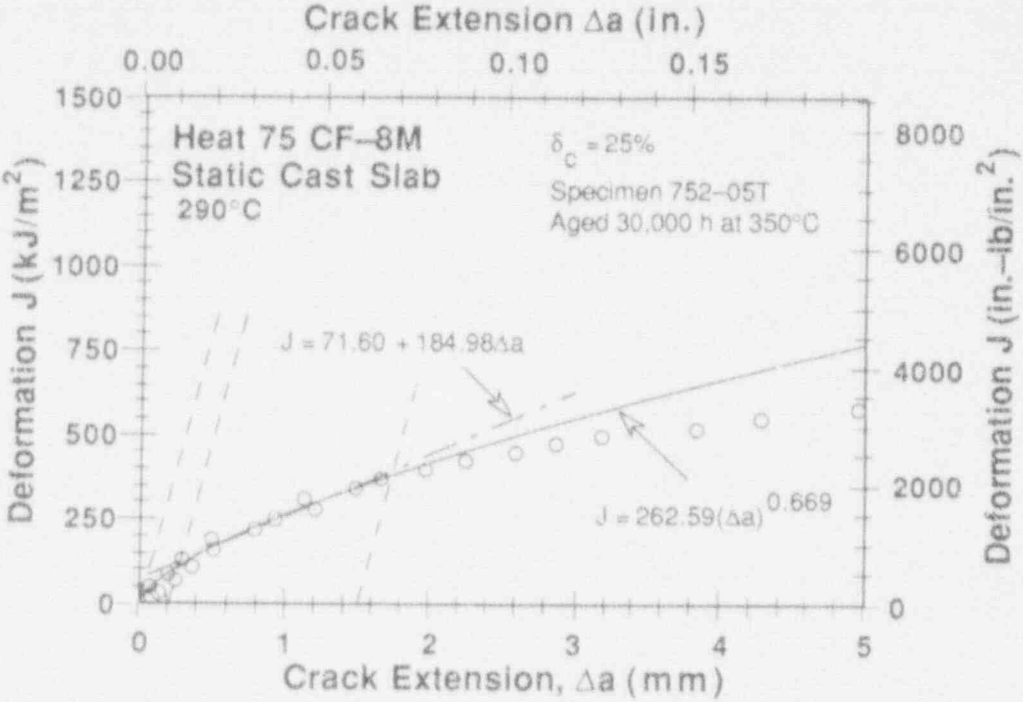

Figure C-60. Deformation J_{IC} at 290°C for Heat 75 aged 30,000 h at 350°C.

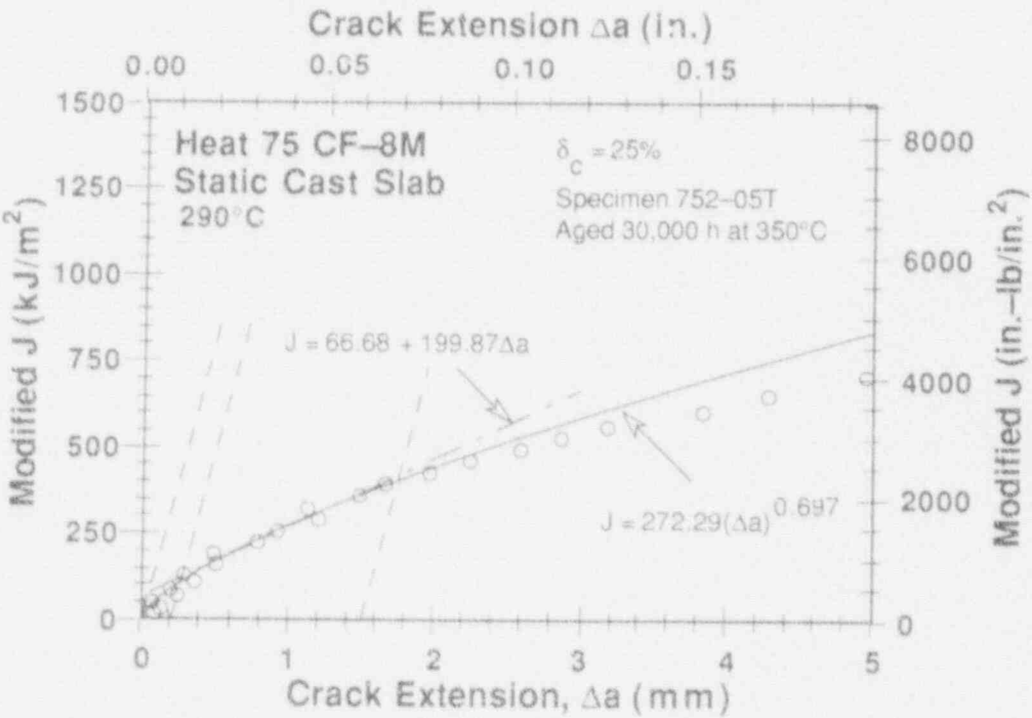

Figure C-61. Modified J_{IC} at 290°C for Heat 75 aged 30,000 h at 350°C.

Table C-62. Test data for specimen 751-05T

Test Number	: 0054	Test Temp.	: 290°C
Material Type	: CF-8M	Heat Number	: 75
Aging Temp.	: 400°C	Aging Time	: 3,000 h
Spec. Thickness	: 25.35 mm	Net Thickness	: 20.32 mm
Spec. Width	: 50.83 mm	Flow Stress	: 397.20 MPa

Unload Number	J_d (kJ/m^2)	J_m (kJ/m^2)	Δa (mm)	Load (kN)	Deflection (mm)
1	13.67	13.67	0.0172	17.994	0.263
2	29.27	29.34	0.0853	22.034	0.420
3	50.67	50.47	-0.0455	24.955	0.607
4	83.61	84.46	0.2314	27.827	0.855
5	119.17	118.79	0.0176	29.868	1.110
6	157.06	158.87	0.2954	31.359	1.356
7	194.42	198.50	0.5222	32.489	1.606
8	226.06	231.01	0.5953	33.258	1.808
9	257.59	265.44	0.8065	33.819	2.005
10	290.78	300.02	0.8943	34.206	2.209
11	322.39	336.20	1.1516	34.468	2.407
12	355.20	370.53	1.2274	34.345	2.608
13	387.26	409.73	1.5510	34.026	2.818
14	412.86	443.23	1.8814	33.570	3.008
15	441.83	478.46	2.1215	32.946	3.212
16	467.48	514.55	2.4946	32.560	3.411
17	493.59	548.11	2.7422	31.641	3.609
18	517.00	584.22	3.1385	31.034	3.812
19	548.08	624.97	3.4184	30.284	4.055
20	569.95	661.32	3.8138	29.468	4.263
21	599.70	711.53	4.3324	28.502	4.557
22	632.63	770.17	4.9292	26.447	4.913
23	661.95	832.98	5.6447	24.622	5.309
24	693.50	892.17	6.1911	23.057	5.711
25	713.38	950.96	6.9105	21.511	6.108
26	735.48	1005.39	7.4717	20.165	6.504
27	746.74	1061.05	8.1996	18.735	6.906
28	763.23	1112.01	8.7338	17.484	7.307
29	778.72	1163.18	9.2580	16.513	7.705
30	791.13	1213.65	9.7891	15.528	8.106
31	806.04	1261.65	10.2281	14.610	8.505

Table C-63. Deformation J_{IC} and J-R curve results for specimen 751-05T

Test Number	: 0054	Test Temp.	: 290°C
Material Type	: CF-8M	Heat Number	: 75
Aging Temp.	: 400°C	Aging Time	: 3,000 h
Spec. Thickness	: 25.35 mm	Net Thickness	: 20.32 mm
Spec. Width	: 50.83 mm	Flow Stress	: 397.20 MPa
Modulus E	: 183.90 GPa	(Effective)	
Modulus E	: 180.00 GPa	(Nominal)	
Init. Crack	: 28.6313 mm	Init. a/w	: 0.5632 (Measured)
Final Crack	: 39.1875 mm	Final a/w	: 0.7709 (Measured)
Final Crack	: 38.8594 mm	Final a/w	: 0.7645 (Compliance)
Linear Fit	**$J = B+M(\Delta a)$**		
Intercept B	: 105.785 kJ/m²	Slope M	: 190.88 kJ/m²mm
Fit Coeff. R	: 0.9904	(8 Data Points)	
J_{IC}	: 120.2 kJ/m²	(686.5 in.-lb/in.²)	
Δa (J_{IC})	: 0.076 mm	(0.0030 in)	
T average	: 222.5	(J_{IC} at 0.15)	
Power-Law Fit	**$J = C(\Delta a)^n$**		
Coeff. C	: 301.92 kJ/m²	Exponent n	: 0.5712
Fit Coeff. R	: 0.9918	(8 Data Points)	
J_{IC}(0.20)	: 150.2 kJ/m²	(857.7 in.-lb/in.²)	
Δa (J_{IC})	: 0.295 mm	(0.0116 in)	
T average	: 206.0	(J_{IC} at 0.20)	
J_{IC}(0.15)	: 131.3 kJ/m²	(749.5 in.-lb/in.²)	
Δa (J_{IC})	: 0.233 mm	(0.0092 in)	
T average	: 210.2	(J_{IC} at 0.15)	
K_{Jc}	: 277.0 MPa-m$^{0.5}$		
J_{IC} Validity & Data Qualification (E 813-85)			
J_{max} allowed	: 587.90 kJ/m²	($J_{max}=b_o\sigma_f/15$)	
Data Limit	: J_{max} ignored		
Δa (max) allowed	: 1.763 mm	(at 1.5 exclusion line)	
Data Limit	: 1.5 Exclusion line		
Data Points	: Zone A = 3	Zone B = 2	
Data point spacing	: OK		
b_{net} and b_o size	: OK		
dJ/da at J_{IC}	: OK		
a_o Measurement	: 9 outside limit		
a_o Measurement	: 1 outside limit		
Final crack shape	: OK		
Crack size estimate	: Inadequate	(by compliance)	
E Effective	: OK		
J_{IC} Estimate	: INVALID		
J-R Curve Validity & Data Qualification (E 1152-86)			
J_{max} allowed	: 403.56 kJ/m²	($J_{max}=b_{net}\sigma_f/20$)	
Δa (max) allowed	: 2.220 mm	($\Delta a=0.1*b_o$)	
Δa (max) allowed	: 5.211 mm	($\omega=5$)	
Data Points	: Zone A = 3	Zone B = 11	
Data point spacing	: OK		
J-R Curve Data	: INVALID		

Table C–64. Modified J_{IC} and J–R curve results for specimen 751–05T

Linear Fit	**J = B+M(Δa)**		
Intercept B	: 101.254 kJ/m²	Slope M	: 207.32 kJ/m²mm
Fit Coeff. R	: 0.9927	(8 Data Points)	
J_{IC}	: 116.4 kJ/m²	(664.9 in.–lb/in.²)	
Δa (J_{IC})	: 0.073 mm	(0.0029 in)	
T average	: 241.7	(J_{IC} at 0.15)	
Power–Law Fit	**J = C(Δa)ⁿ**		
Coeff. C	: 313.67 kJ/m²	Exponent n	: 0.5970
Fit Coeff. R	: 0.9922	(8 Data Points)	
J_{IC}(0.20)	: 151.4 kJ/m²	(864.7 in.–lb/in.²)	
Δa (J_{IC})	: 0.295 mm	(0.0116 in)	
T average	: 222.6	(J_{IC} at 0.20)	
J_{IC}(0.15)	: 131.3 kJ/m²	(750.0 in.–lb/in.²)	
Δa (J_{IC})	: 0.233 mm	(0.0092 in)	
T average	: 226.8	(J_{IC} at 0.15)	
K_{Jc}	285.2 MPa·m$^{0.5}$		

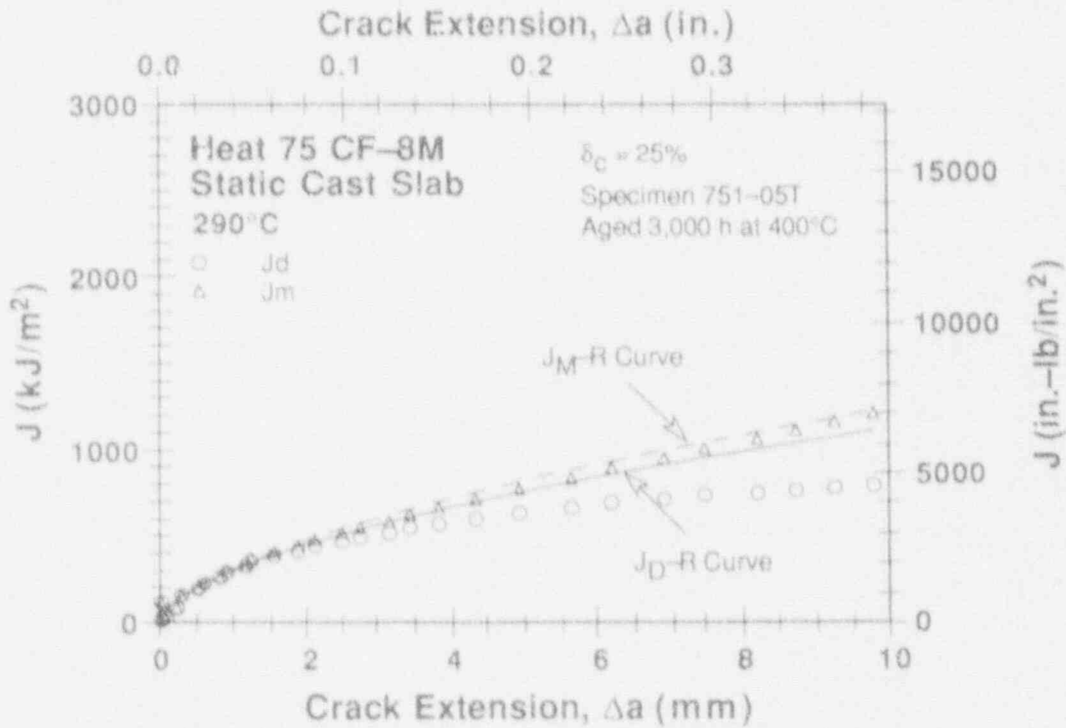

Figure C–62. Deformation and modified J–R curves at 290°C for Heat 75 aged 3,000 h at 400°C.

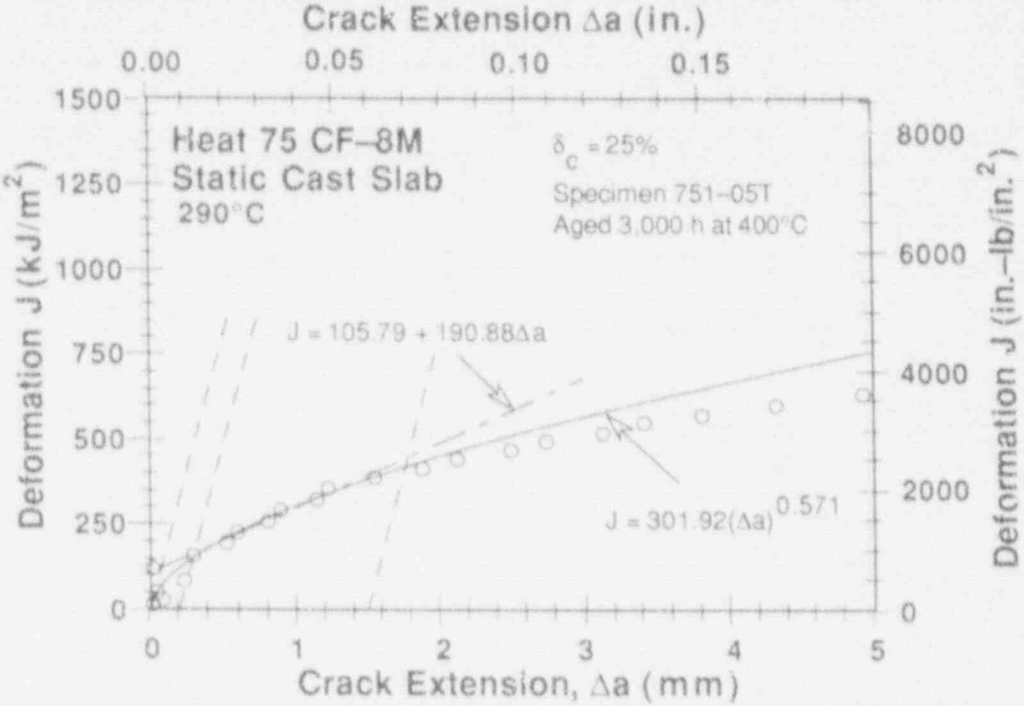

Figure C-63. Deformation J_{IC} at 290°C for Heat 75 aged 3,000 h at 400°C.

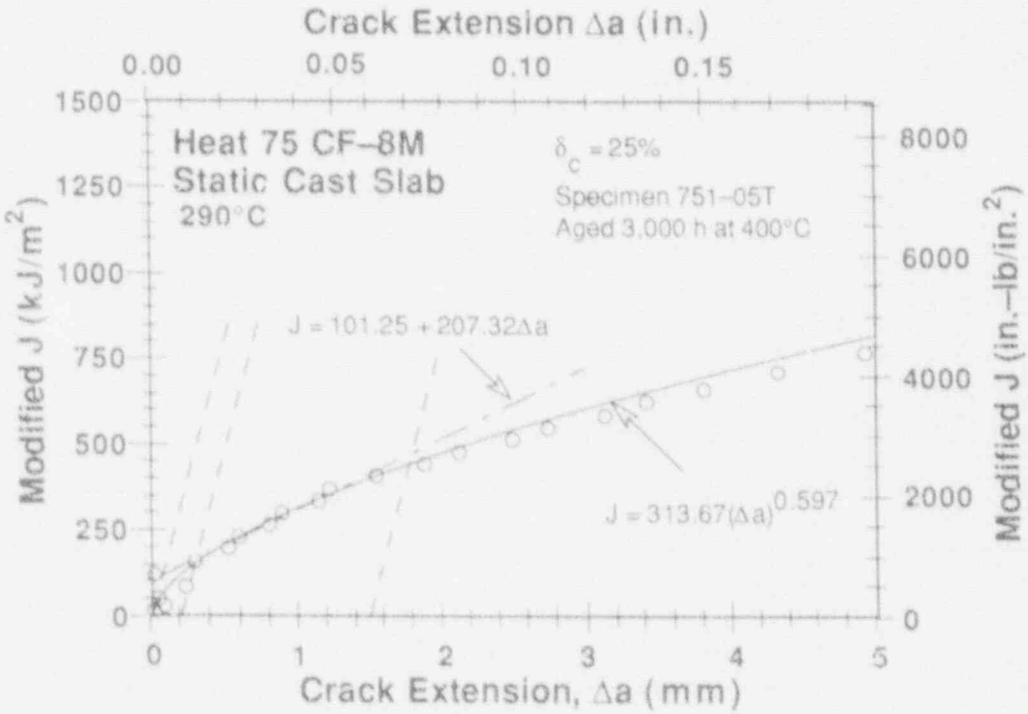

Figure C-64. Modified J_{IC} at 290°C for Heat 75 aged 3,000 h at 400°C.

Table C-65. Test data for specimen 751-02V

Test Number	: 0053	Test Temp.	: 290°C
Material Type	: CF-8M	Heat Number	: 75
Aging Temp.	: 400°C	Aging Time	: 10,000 h
Spec. Thickness	: 25.39 mm	Net Thickness	: 20.29 mm
Spec. Width	: 50.81 mm	Flow Stress	: 409.60 MPa

Unload Number	J_d (kJ/m^2)	J_m (kJ/m^2)	Δa (mm)	Load (kN)	Deflection (mm)
1	14.35	14.24	-0.3523	18.059	0.280
2	19.67	19.37	-0.6950	19.489	0.334
3	32.89	33.05	-0.2935	22.[illegible]19	0.453
4	48.95	48.96	-0.3697	24.486	0.604
5	74.76	75.52	-0.1403	26.829	0.805
6	101.95	102.70	-0.1430	28.761	1.008
7	130.75	132.45	0.0109	30.187	1.205
8	160.53	162.91	0.0958	31.400	1.405
9	192.02	193.94	0.0491	32.237	1.603
10	225.32	227.70	0.0881	33.008	1.804
11	253.92	258.06	0.2852	33.444	1.985
12	282.12	289.51	0.4411	33.729	2.167
13	309.26	320.90	0.6937	33.760	2.346
14	338.47	350.84	0.7326	33.814	2.527
15	366.72	384.34	0.9878	33.672	2.710
16	393.41	418.99	1.3413	32.922	2.906
17	419.17	448.86	1.5110	32.670	3.089
18	443.25	480.65	1.8069	32.239	3.268
19	468.35	510.32	1.9708	31.9[illegible]	3.447
20	499.33	555.85	2.4493	30.858	3.698
21	522.63	590.04	2.7860	30.249	3.909
22	543.79	623.47	3.1443	29.555	4.110
23	572.29	664.23	3.4782	28.586	4.357
24	596.39	705.51	3.9173	27.550	4.608
25	617.63	753.98	4.5691	26.121	4.905
26	642.09	797.85	5.0038	24.662	5.205
27	666.84	843.55	5.4468	23.803	5.507
28	688.02	903.72	6.2116	21.736	5.905
29	703.67	958.41	6.9314	20.244	6.306
30	718.08	1010.40	7.5847	18.674	6.706
31	739.37	1061.49	8.0733	17.852	7.107
32	759.17	1112.13	8.5500	16.652	7.506
33	779.00	1161.88	8.9880	15.838	7.905
34	800.38	1211.15	9.3743	14.979	8.311
35	811.77	1258.78	9.8534	13.928	8.706
36	818.48	1303.65	10.3345	13.004	9.106

Table C-66. Deformation J_{IC} and J-R curve results for specimen 751-02V

Test Number	: 0053	Test Temp.	: 290°C
Material Type	: CF-8M	Heat Number	: 75
Aging Temp.	: 400°C	Aging Time	: 10,000 h
Spec. Thickness	: 25.39 mm	Net Thickness	: 20.29 mm
Spec. Width	: 50.81 mm	Flow Stress	: 409.60 MPa
Modulus E	: 171.06 GPa	(Effective)	
Modulus E	: 180.00 GPa	(Nominal)	
Init. Crack	: 28.9219 mm	Init. a/w	: 0.5693 (Measured)
Final Crack	: 40.0656 mm	Final a/w	: 0.7886 (Measured)
Final Crack	: 39.2564 mm	Final a/w	: 0.7727 (Compliance)
Linear Fit	**$J = B+M(\Delta a)$**		
Intercept B	: 234.029 kJ/m^2	Slope M	: 123.52 kJ/m^2mm
Fit Coeff. R	: 0.9810	(6 Data Points)	
J_{IC}	: 253.1 kJ/m^2	(1445.3 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.154 mm	(0.0061 in)	
T average	: 125.9	(J_{IC} at 0.15)	
Power-Law Fit	**$J = C(\Delta a)^n$**		
Coeff. C	: 363.55 kJ/m^2	Exponent n	: 0.3204
Fit Coeff. R	: 0.9848	(6 Data Points)	
$J_{IC}(0.20)$	: 262.0 kJ/m^2	(1494.4 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.360 mm	(0.0142 in)	
T average	: 120.7	(J_{IC} at 0.20)	
$J_{IC}(0.15)$	: 247.5 kJ/m^2	(1413.1 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.301 mm	(0.0119 in)	
T average	: 124.4	(J_{IC} at 0.15)	
K_{Jc}	: 273.2 MPa-$m^{0.5}$		
J_{IC} Validity & Data Qualification (E 813-85)			
J_{max} allowed	: 597.56 kJ/m^2	($J_{max}=b_o\sigma_f/15$)	
Data Limit	: J_{max} Ignored		
Δa (max) allowed	: 1.766 mm	(at 1.5 exclusion line)	
Data Limit	: 1.5 Exclusion line		
Data Points	: Zone A = 1	Zone B = 2	
Data point spacing	: OK		
b_{net} and b_o size	: OK		
dJ/da at J_{IC}	: OK		
Initial crack shape	: OK		
Final crack shape	: OK		
Crack size estimate	: Inadequate	(by compliance)	
E Effective	: OK		
J_{IC} Estimate	: INVALID		
J-R Curve Validity & Data Qualification (E 1152-86)			
J_{max} allowed	: 415.58 kJ/m^2	($J_{max}=b_{net}\sigma_f/20$)	
Δa (max) allowed	: 2.188 mm	($\Delta a=0.1^*b_o$)	
Δa (max) allowed	: 3.059 mm	($\omega=5$)	
Data Points	: Zone A = 6	Zone B = 7	
Data point spacing	: Inadequate		
J-R Curve Data	: INVALID		

Table C-67. Modified J_{Ic} and J-R curve results for specimen 751-02V

Linear Fit	**J = B+M(Δa)**		
Intercept B	: 231.319 kJ/m^2	Slope M	: 144.64 kJ/m^{2}mm
Fit Coeff. R	: 0.9868	(6 Data Points)	
J_{IC}	: 253.7 kJ/m^2	(1448.8 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.155 mm	(0.0061 in)	
T average	: 147.5	(J_{IC} at 0.15)	
Power-Law Fit	**J = C(Δa)^n**		
Coeff. C	: 382.54 kJ/m^2	Exponent n	: 0.3559
Fit Coeff. R	: 0.9880	(6 Data Points)	
J_{IC}(0.20)	: 266.6 kJ/m^2	(1522.6 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.363 mm	(0.0143 in)	
T average	: 139.9	(J_{IC} at 0.20)	
J_{IC}(0.15)	: 250.0 kJ/m^2	(1427.4 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.303 mm	(0.0119 in)	
T average	: 143.9	(J_{IC} at 0.15)	
K_{Jc}	: 283.6 MPa-m$^{0.5}$		

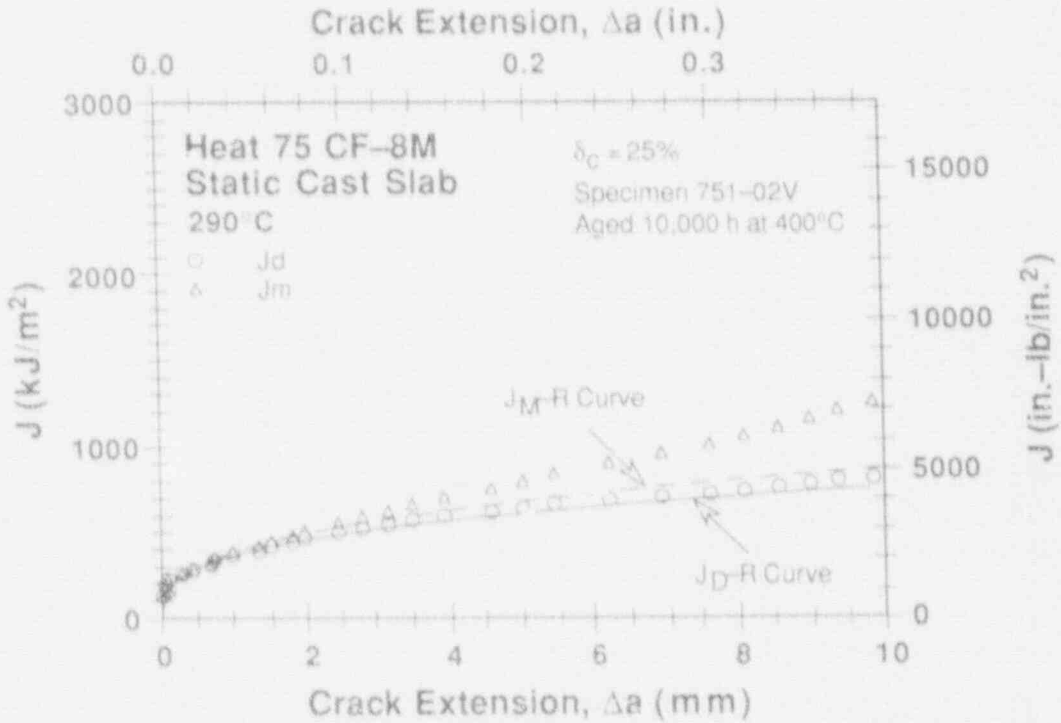

Figure C-65. Deformation and modified J-R curves at 290°C for Heat 75 aged 10,000 h at 400°C.

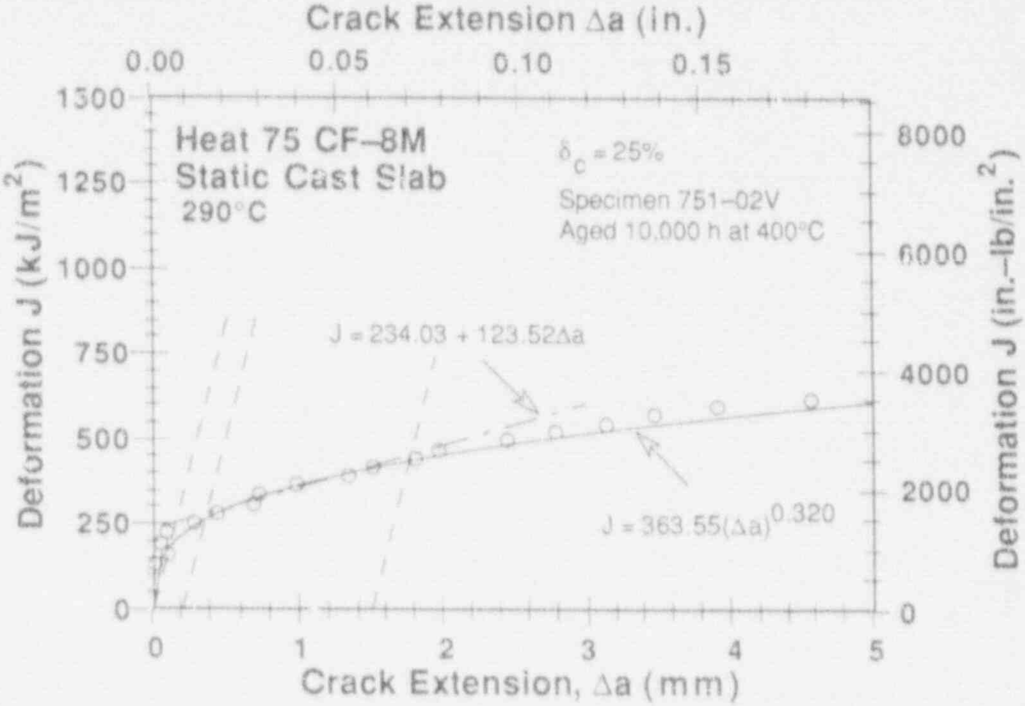

Figure C-66. Deformation J_{IC} at 290°C for Heat 75 aged 10,000 h at 400°C.

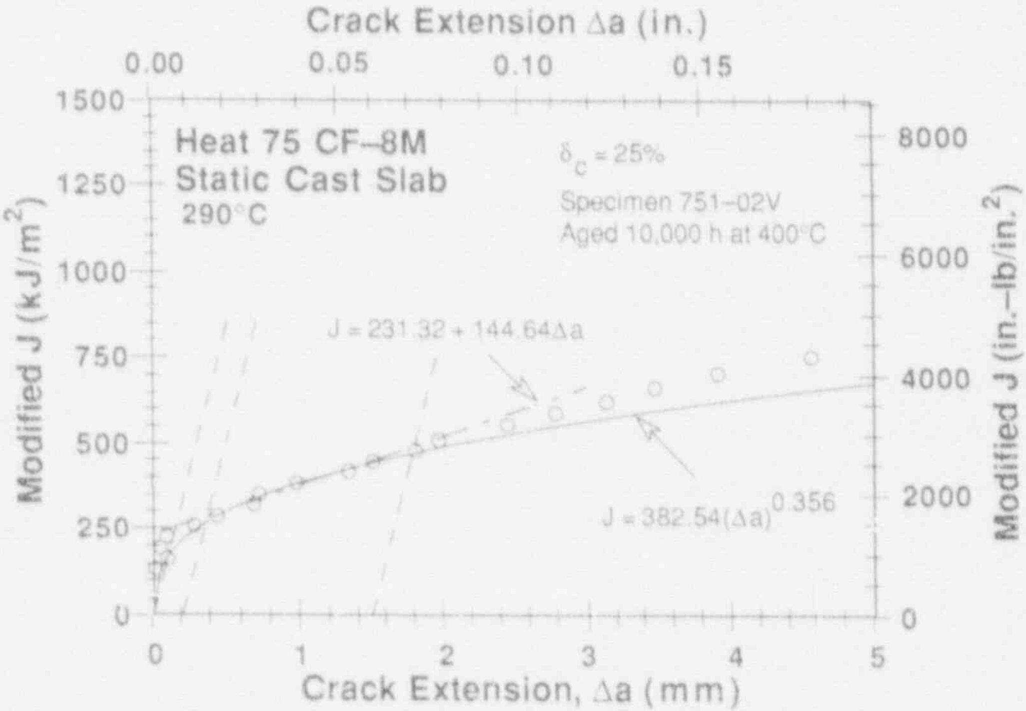

Figure C-67. Modified J_{IC} at 290°C for Heat 75 aged 10,000 h at 400°C.

Table C-68. Test data for specimen 751-02T

Test Number	: 0073	Test Temp.	: 290°C
Material Type	: CF-8M	Heat Number	: 75
Aging Temp.	: 400°C	Aging Time	: 10,000 h
Spec. Thickness	: 25.33 mm	Net Thickness	: 20.30 mm
Spec. Width	: 50.79 mm	Flow Stress	: 409.60 MPa

Unload Number	J_d (kJ/m^2)	J_m (kJ/m^2)	Δa (mm)	Load (kN)	Deflection (mm)
1	17.72	17.83	0.2287	18.962	0.304
2	38.87	39.12	0.3346	23.180	0.506
3	62.92	62.48	0.0748	25.751	0.706
4	91.21	91.56	0.2635	27.906	0.908
5	116.17	115.81	0.1369	29.307	1.086
6	143.12	144.93	0.4426	30.499	1.264
7	155.33	155.40	0.2183	31.043	1.350
8	184.06	187.02	0.5246	31.856	1.529
9	212.02	214.71	0.5003	32.435	1.710
10	240.07	247.14	0.8413	32.920	1.891
11	269.05	274.98	0.7630	33.148	2.071
12	295.43	309.79	1.2774	33.040	2.251
13	321.83	337.35	1.3418	32.764	2.431
14	346.07	371.35	1.8331	32.634	2.610
15	375.02	403.43	1.9759	32.256	2.811
16	400.14	440.76	2.4879	31.612	3.011
17	429.00	471.67	2.5668	30.801	3.212
18	451.49	509.66	3.1214	30.132	3.414
19	482.36	548.92	3.3972	29.319	3.661
20	511.71	592.49	3.8284	28.633	3.913
21	535.03	633.49	4.3269	26.980	4.162
22	555.76	672.44	4.8092	25.794	4.411
23	580.15	718.41	5.3410	24.479	4.706
24	600.28	762.80	5.9011	23.089	5.002
25	617.91	807.51	6.4900	21.871	5.308
26	640.97	864.38	7.1699	20.075	5.707
27	652.05	919.15	7.9945	18.623	6.109
28	661.43	968.14	8.6978	16.720	6.506
29	675.97	1016.26	9.2599	15.631	6.906
30	690.57	1065.67	9.8078	14.358	7.318
31	695.94	1110.60	10.3999	13.352	7.709

Table C-69. Deformation J_{IC} and J-R curve results for specimen 751-02T

Test Number	: 0073	Test Temp.	: 290°C
Material Type	: CF-8M	Heat Number	: 75
Aging Temp.	: 400°C	Aging Time	: 10,000 h
Spec. Thickness	: 25.33 mm	Net Thickness	20.30 mm
Spec. Width	: 50.79 mm	Flow Stress	: 409.60 MPa
Modulus E	: 183.03 GPa	(Effective)	
Modulus E	: 180.00 GPa	(Nominal)	
Init. Crack	: 28.8375 mm	Init. a/w	: 0.5678 (Measured)
Final Crack	: 39.3656 mm	Final a/w	: 0.7751 (Measured)
Final Crack	: 39.2374 mm	Final a/w	: 0.7726 (Compliance)
Linear Fit	**$J = B+M(\Delta a)$**		
Intercept B	: 137.383 kJ/m^2	Slope M	: 133.02 kJ/m^2mm
Fit Coeff. R	: 0.9315	(6 Data Points)	
J_{IC}	: 149.5 kJ/m^2	(853.8 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.091 mm	(0.0036 in)	
T average	: 145.1	(J_{IC} at 0.15)	
Power-Law Fit	**$J = C(\Delta a)^n$**		
Coeff. C	: 274.23 kJ/m^2	Exponent n	: 0.4618
Fit Coeff. R	: 0.9287	(6 Data Points)	
J_{IC}(0.20)	: 156.1 kJ/m^2	(891.6 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.295 mm	(0.0116 in)	
T average	: 144.7	(J_{IC} at 0.20)	
J_{IC}(0.15)	: 140.8 kJ/m^2	(803.8 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.236 mm	(0.0093 in)	
T average	: 148.4	(J_{IC} at 0.15)	
K_{Jc}	: 253.7 MPa-$m^{0.5}$		
J_{IC} Validity & Data Qualification (E 813-85)			
J_{max} allowed	: 599.31 kJ/m^2	($J_{max}=b_o\sigma_f/15$)	
Data Limit	: J_{max} Ignored		
Δa (max) allowed	: 1.715 mm	(at 1.5 exclusion line)	
Data Limit	: 1.5 Exclusion line		
Data Points	: Zone A = 2	Zone B = 2	
Data point spacing	: OK		
b_{net} and b_o size	: OK		
dJ/da at J_{IC}	: OK		
Initial crack shape	: OK		
Final crack shape	: OK		
Crack size estimate	: OK	(by compliance)	
E Effective	: OK		
J_{IC} Estimate	: VALID		
J-R Curve Validity & Data Qualification (E 1152-86)			
J_{max} allowed	: 415.74 kJ/m^2	($J_{max}=b_{net}\sigma_f/20$)	
Δa (max) allowed	: 2.195 mm	($\Delta a=0.1*b_o$)	
Δa (max) allowed	: 4.294 mm	($\omega=5$)	
Data Points	: Zone A = 3	Zone B = 12	
Data point spacing	: OK		
J-R Curve Data	: VALID		

Table C-70. Modified J_{IC} and J-R curve results for specimen 751-02T

Linear Fit	**J = B+M(Δa)**		
Intercept B	: 132.033 kJ/m^2	Slope M	: 148.39 kJ/m^{2}mm
Fit Coeff. R	: 0.9445	(6 Data Points)	
J_{IC}	: 145.2 kJ/m^2	(829.0 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.089 mm	(0.0035 in)	
T average	: 161.9	(J_{IC} at 0.15)	
Power-Law Fit	**J = C(Δa)^n**		
Coeff. C	: 284.38 kJ/m^2	Exponent n	: 0.4973
Fit Coeff. R	: 0.9404	(6 Data Points)	
J_{IC}(0.20)	: 154.8 kJ/m^2	(884.2 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.295 mm	(0.0116 in)	
T average	: 160.5	(J_{IC} at 0.20)	
J_{IC}(0.15)	: 138.2 kJ/m^2	(789.2 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.234 mm	(0.0092 in)	
T average	: 164.3	(J_{IC} at 0.15)	
K_{Jc}	: 261.4 MPa-m$^{0.5}$		

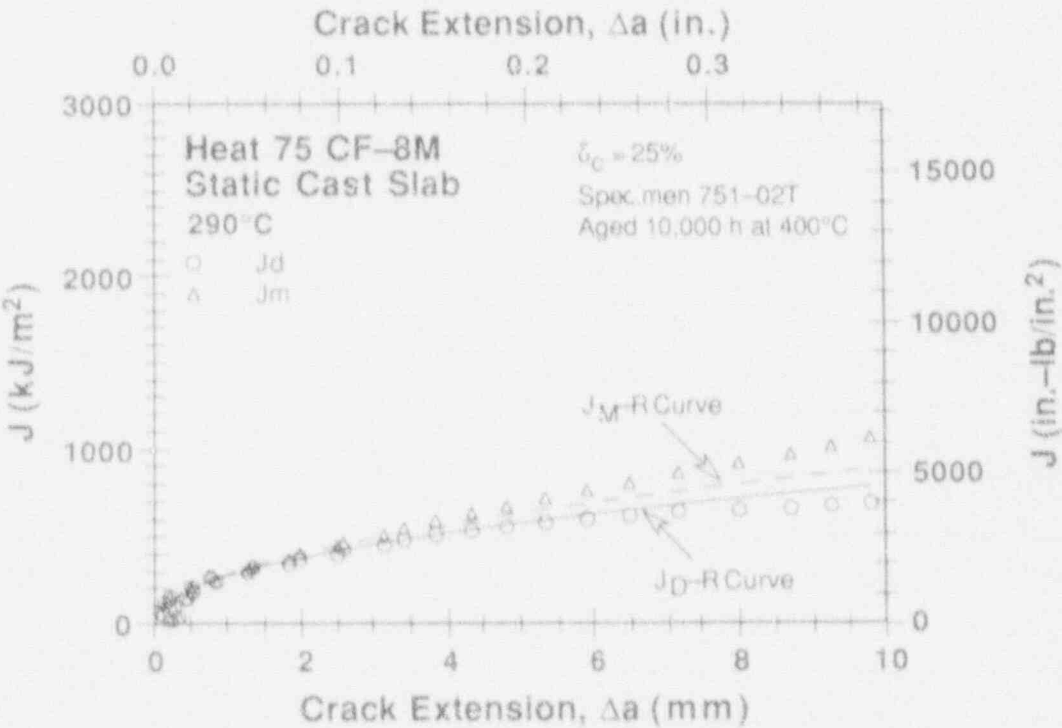

Figure C-68. Deformation and modified J-R curves at 290°C for Heat 75 aged 10,000 h at 400°C.

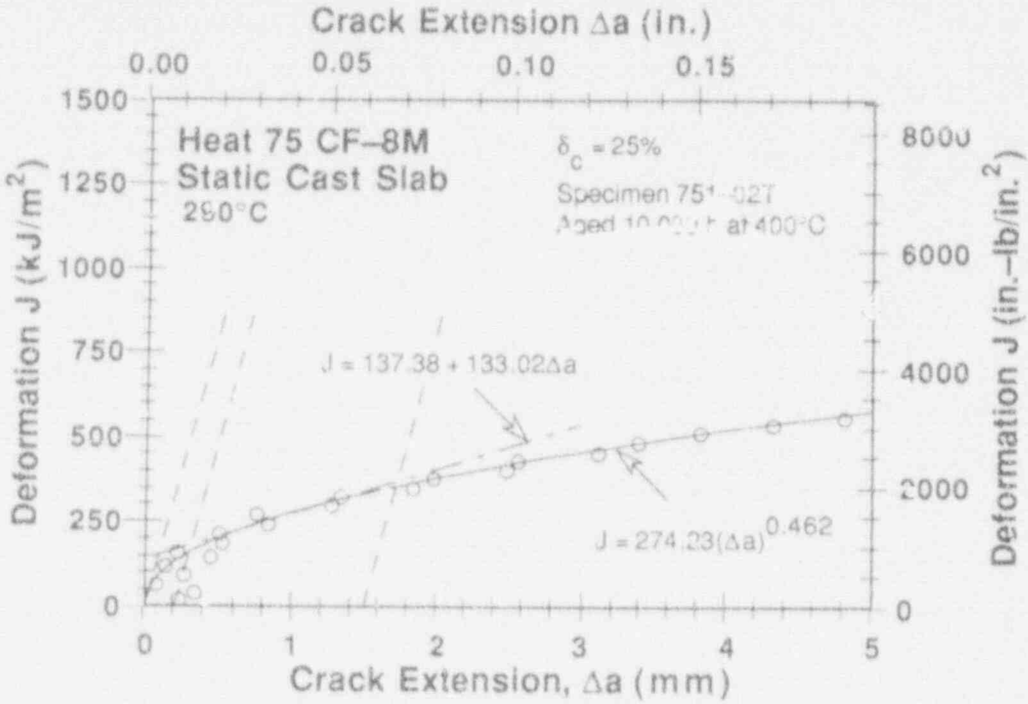

Figure C-69. Deformation J_{IC} at 290°C for Heat 75 aged 10,000 h at 400°C.

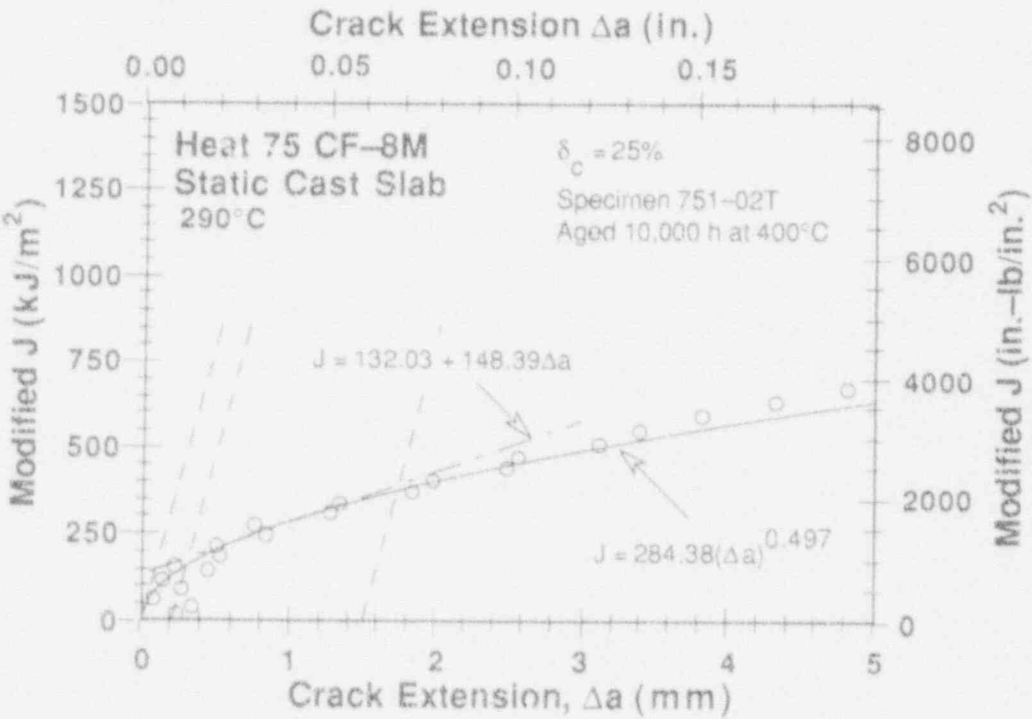

Figure C-70. Modified J_{IC} at 290°C for Heat 75 aged 10,000 h at 400°C.

Table C-71. Test data for specimen 751-03T

Test Number	: 0052	Test Temp.	: 290°C
Material Type	: CF-8M	Heat Number	: 75
Aging Temp.	: 450°C	Aging Time	: 3,000 h
Spec. Thickness	: 25.38 mm	Net Thickness	: 20.36 mm
Spec. Width	: 50.82 mm	Flow Stress	: 405.20 MPa

Unload Number	J_d (kJ/m^2)	J_m (kJ/m^2)	Δa (mm)	Load (kN)	Deflection (mm)
1	14.57	14.57	-0.0198	18.041	0.280
2	33.17	32.65	-0.4464	22.113	0.474
3	55.30	55.70	-0.0433	24.881	0.656
4	86.11	87.15	0.1193	27.500	0.907
5	120.41	121.76	0.1724	2[illegible].526	1.155
6	156.67	161.38	0.6032	31.025	1.407
7	186.04	190.53	0.5797	31.878	1.608
8	216.38	225.02	0.9435	32.200	1.808
9	245.86	256.98	1.1320	32.448	2.009
10	276.65	290.95	1.3419	32.431	2.211
11	305.59	324.51	1.6125	32.256	2.409
12	335.03	357.94	1.8208	31.529	2.613
13	354.[illegible]2	393.22	2.5673	30.163	2.810
14	373.26	423.40	3.0827	28.926	3.013
15	394.01	464.69	3.9141	27.451	3.267
16	418.41	499.16	4.2880	25.937	3.517
17	437.68	547.21	5.2609	23.816	3.819
18	458.65	584.48	5.7715	22.356	4.112
19	473.56	627.54	6.5890	20.715	4.416
20	486.62	664.46	7.2386	19.257	4.711
21	493.35	703.81	8.0751	17.550	5.021
22	505.26	738.99	8.6345	16.334	5.335
23	522.62	787.40	9.3253	14.896	5.738
24	533.71	833.99	10.0600	13.499	6.159

Table C-72. Deformation J_{IC} and J-R curve results for specimen 751-03T

Test Number	: 0052	Test Temp.	: 290°C
Material Type	: CF-8M	Heat Number	: 75
Aging Temp.	: 450°C	Aging Time	: 3,000 h
Spec. Thickness	: 25.38 mm	Net Thickness	: 20.36 mm
Spec. Width	: 50.82 mm	Flow Stress	: 405.20 MPa
Modulus E	: 178.21 GPa	(Effective)	
Modulus E	: 180.00 GPa	(Nominal)	
Init. Crack	: 28.4313 mm	Init. a/w	: 0.5594 (Measured)
Final Crack	: 38.7938 mm	Final a/w	: 0.7633 (Measured)
Final Crack	: 38.4913 mm	Final a/w	: 0.7574 (Compliance)
Linear Fit	**$J = B+M(\Delta a)$**		
Intercept B	: 92.477 kJ/m^2	Slope M	: 133.97 kJ/m^2mm
Fit Coeff. R	: 0.9817	(6 Data Points)	
J_{IC}	: 100.8 kJ/m^2	(575.6 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.062 mm	(0.0024 in)	
T average	: 145.4	(J_{IC} at 0.15)	
Power-Law Fit	**$J = C(\Delta a)^n$**		
Coeff. C	: 230.05 kJ/m^2	Exponent n	: 0.5773
Fit Coeff. R	: 0.9674	(6 Data Points)	
J_{IC}(0.20)	: 107.1 kJ/m^2	(611.7 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.266 mm	(0.0105 in)	
T average	: 151.1	(J_{IC} at 0.20)	
J_{IC}(0.15)	: 92.7 kJ/m^2	(529.5 in.-lb/in.^{2})	
Δa (J_{IC})	: 0.207 mm	(0.0082 in)	
T average	: 154.1	(J_{IC} at 0.15)	
K_{Jc}	: 235.7 MPa-m$^{0.5}$		
J_{IC} Validity & Data Qualification (E 813-85)			
J_{max} allowed	: 604.88 kJ/m^2	($J_{max}=b_o\sigma_f/15$)	
Data Limit	: J_{max} Ignored		
Δa (max) allowed	: 1.692 mm	(at 1.5 exclusion line)	
Data Limit	: 1.5 Exclusion line		
Data Points	: Zone A = 1	Zone B = 2	
Data point spacing	: OK		
b_{net} and b_o size	: OK		
dJ/da at J_{IC}	: OK		
a_f Measurement	: Near-surface	outside limit	
Initial crack shape	: OK		
Crack size estimate	: Inadequate	(by compliance)	
E Effective	: OK		
J_{IC} Estimate	: INVALID		
J-R Curve Validity & Data Qualification (E 1152-86)			
J_{max} allowed	: 412.51 kJ/m^2	($J_{max}=b_{net}\sigma_f/20$)	
Δa (max) allowed	: 2.239 mm	($\Delta a=0.1*b_o$)	
Δa (max) allowed	: 5.261 mm	($\omega=5$)	
Data Points	: Zone A = 2	Zone B = 7	
Data point spacing	: Inadequate		
J-R Curve Data	: INVALID		

Table C-73. Modified J_{IC} and J-R curve results for specimen 751-03T

Linear Fit	$J = B+M(\Delta a)$		
Intercept B	: 88.656 kJ/m²	Slope M	: 147.67 kJ/m²mm
Fit Coeff. R	: 0.9849	(6 Data Points)	
J_{IC}	: 97.5 kJ/m²	(557.0 in.-lb/in.²)	
Δa (J_{IC})	: 0.060 mm	(0.0024 in)	
T average	: 160.3	(J_{IC} at 0.15)	
Power-Law Fit	$J = C(\Delta a)^n$		
Coeff. C	: 240.00 kJ/m²	Exponent n	: 0.6087
Fit Coeff. R	: 0.9715	(6 Data Points)	
J_{IC}(0.20)	: 107.2 kJ/m²	(612.[illegible] in.-lb/in.²)	
Δa (J_{IC})	: 0.266 mm	(0.0105 in)	
T average	: 165.0	(J_{IC} at 0.20)	
J_{IC}(0.15)	: 91.9 kJ/m²	(525.0 in.-lb/in.²)	
Δa (J_{IC})	: 0.207 mm	(0.0081 in)	
T average	: 168.1	(J_{IC} at 0.15)	
K_{Jc}	: 243.3 MPa-m^0.5		

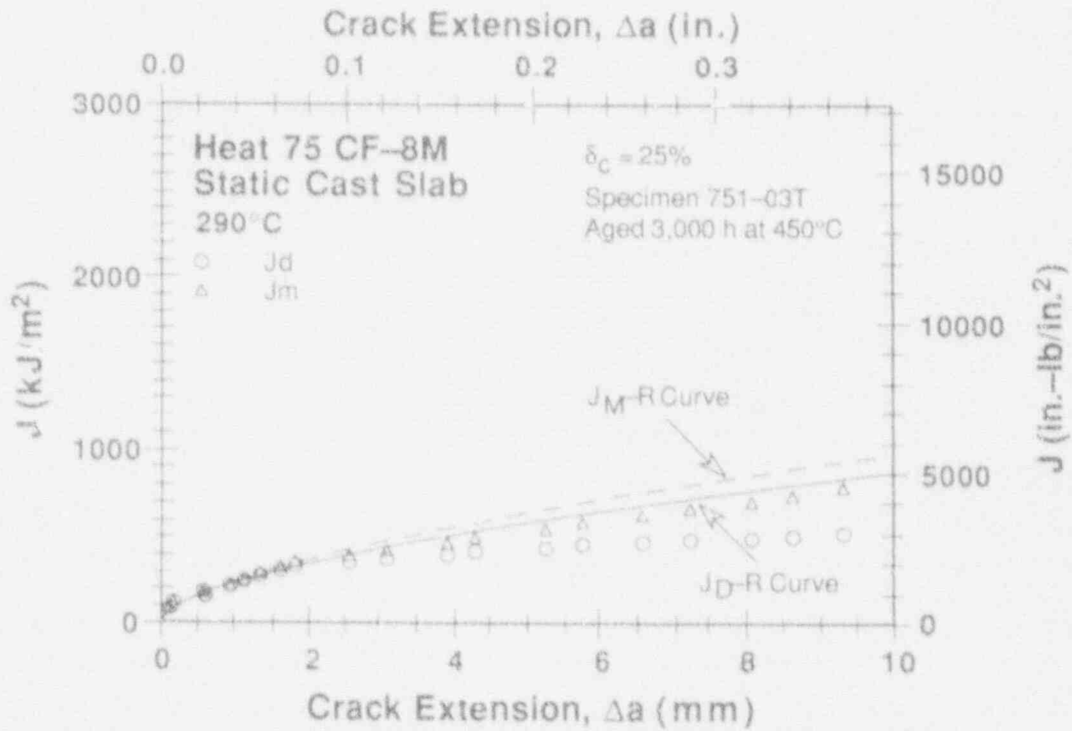

Figure C-71. Deformation and modified J-R curves at 290°C for Heat 75 aged 3,000 h at 450°C.

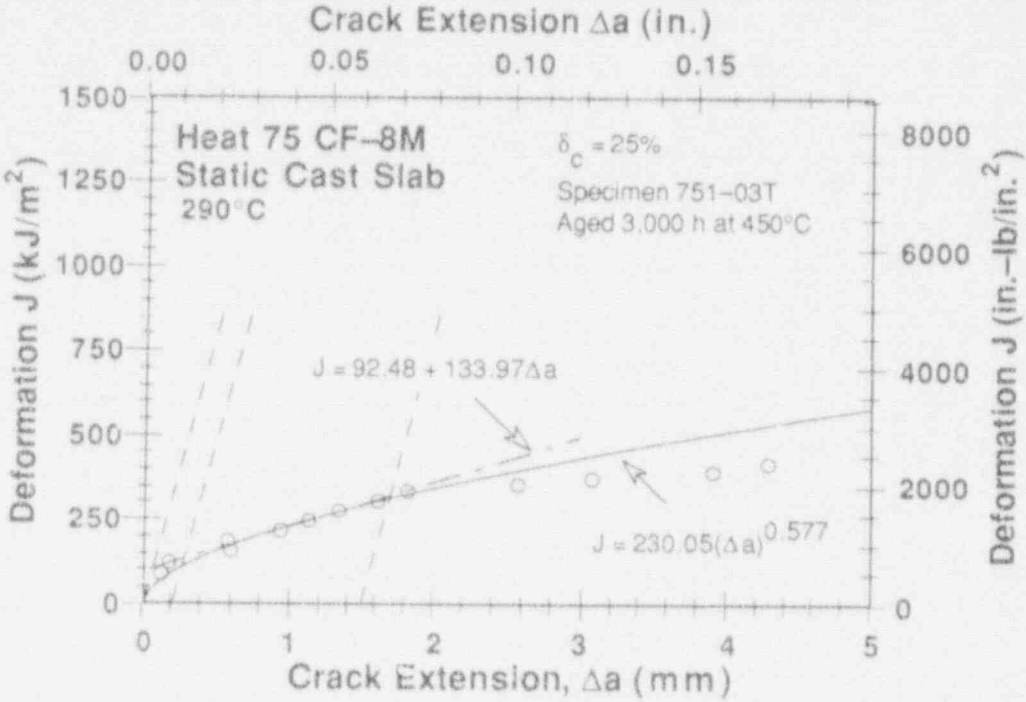

Figure C-72. Deformation J_{IC} at 290°C for Heat 75 aged 3,000 h at 450°C.

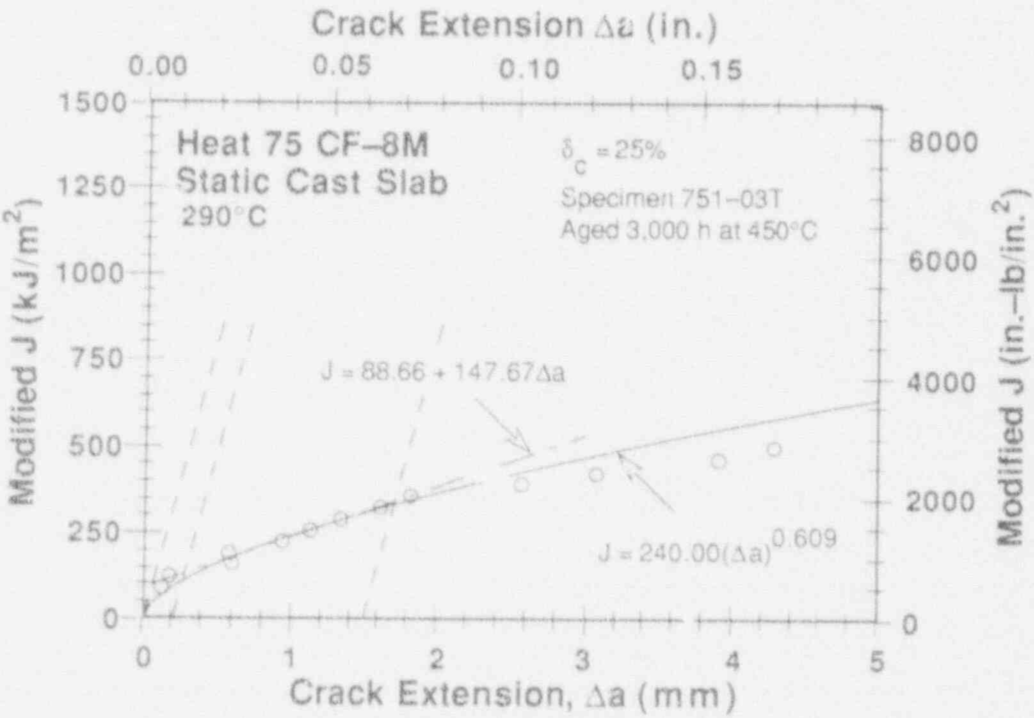

Figure C-73. Modified J_{IC} at 290°C for Heat 75 aged 3,000 h at 450°C.

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11. ABSTRACT (200 words or less)

This progress r[illegible] summarizes work performed by Argonne National Laboratory on long-term thermal embrittlement [illegible] duplex stainless steels in LWR systems during the six months from October 1990 to March 1991. [illegible]arpy-impact, tensile, and fracture toughness data are presented for several heats of cast stainless ste[illegible] that were aged up to 58,000 h at temperatures of 290-400°C. The results indicate that thermal aging increases the tensile stress and decreases the fracture toughness of the materials. In general, CF-3 steels are the least sensitive to thermal aging embrittlement and CF-8M steels are the most sensitive. The increase in flo[illegible]ess of fully aged cast stainless steels is ≈10% for CF-3 steels and ≈20% for CF-8 and CF-8M steels. [illegible]racture toughness J_{IC} and average tearing modulus for heats that are sensitive to thermal aging (e.g., CF-8M steels) are as low as ≈90 kJ/m^2 and ≈60, respectively.

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