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Tensile Properties of Irradiated Nuclear Grade Pressure Vessel Welds for the Third HSST Irradiation Series

J. J. McGowan

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METALS AND CERAMICS DIVISION

TENSILE PROPERTIES OF IRRADIATED NUCLEAR GRADE PRESSURE VESSEL WELDS FOR THE THIRD HSST IRRADIATION SERIES

J. J. McGowan

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FOREWORD

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

This report is designated Heavy-Section Steel Technology Program Technical or Programmatic Manuscript 36. Prior reports in this series are listed below:

1. *A Guide for Material Control and Data Control for the Heavy-Section Steel Technology Program* (prepared by the ORNL Inspection Engineering Department), Oak Ridge National Laboratory, June 15, 1968.

2. C. L. Segaser, *System Design Description of the Intermediate Vessel Tests for the Heavy-Section Steel Technology Program*, ORNL/TM-2849, revised, July 1973.

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CONTENTS

TENSILE PROPERTIES OF IRRADIATED NUCLEAR GRADE PRESSURE VESSEL WELDS FOR THE THIRD HSST IRRADIATION SERIES*

J. J. McGowan

ABSTRACT

The Heavy Section Steel Technology (HSST) Program conducted a series of experiments to investigate the effect of neutron irradiation on the fracture toughness of nuclear pressure vessel materials. Four welds of A 508 class 2 steel were examined in this Third HSST Irradiation Series. The welds were fabricated according to "early" (pre-1972) light-water reactor weld practice (i.e., copper-coated electrodes). As part of this study, tensile properties were measured after irradiation to 2 to 10 × 10^{22} neutrons/m^2 (E > 1 MeV) at temperatures between 250 and 290°C. Strength properties of all four welds increased with exposure to irradiation. Yield strength was more sensitive to irradiation than was ultimate strength. Tensile ductility was not affected significantly by exposure to irradiation.

INTRODUCTION

The Heavy Section Steel Technology (HSST) program is sponsored by the Nuclear Regulatory Commission with one objective of gaining better insight into the mechanisms that could potentially cause embrittlement of reactor pressure vessels after neutron irradiation. To assess material behavior, irradiations were conducted at Oak Ridge National Laboratory (ORNL) to produce a variety of irradiated material conditions representative of reactor environments. The Third HSST Irradiation Series was conducted to examine the effects of neutron irradiation on the fracture toughness of "early" (pre-1972) practice nuclear pressure vessel welds (i.e., welds made with copper-coated electrodes). Tensile, fracture toughness, and Charpy impact specimens were irradiated in the ORNL Bulk Shielding Reactor[1] at temperatures near 288°C to a fast neutron fluence (E > 1 MeV) of 2 to 10 × 10^{22} neutrons/m^2. Temperature control on the tensile specimens was only moderately successful, with large variations of temperature (±24°C for some specimens) over the length of exposure. The objective of the work reported herein was to assess the irradiated tensile properties of four irradiated weld materials in the HSST Third Series.

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EXPERIMENTAL

MATERIALS AND SPECIMENS

Four welds of A 508 class 2 base material (hereafter referred to as 64W, 65W, 66W, and 67W) were fabricated by use of early (pre-1972) practice. All welds were made by the submerged arc process with Linde 80 flux and a single wire feed of 1/8-in. MnMoNi steel; the parameters used in the fabrication are listed in Table 1 (ref. 2). The chemical compositions of welds 64W, 65W, 66W, and 67W are given in Table 2. The analysis represents the range of compositions determined from Charpy specimens and from weld analyses supplied by vendors. All tensile specimens were oriented transversely to the weld. Two types of miniature tensile specimens were used in this study (Fig. 1). Specimen sizes and designs were primarily dictated by the physical space available for specimen irradiation. The specimen gage diameter was 4.52 mm; both short- (29.24-mm) and long-gage-length (31.75-mm) specimens were tested.

TEST APPARATUS AND DATA ANALYSIS

The tests were conducted at room temperature and at 150 and 290°C. Three testing systems were used: two separate 45-kN Instron and one 490-kN MTS testing machine. All unirradiated testing was performed with the Instron systems, and the irradiated testing was performed with the MTS system. The unirradiated specimens were tested at elevated temperature in a bath of water-soluble oil. The irradiated specimens were all tested at room temperature and above in an air furnace. All testing was performed at a crosshead rate of 0.51 mm/min (0.02 in./min), and during

Table 1. Submerged arc weld parameters

HSST weld code	Volts	Current (A)	Postweld heat treatment conditions	
			Temperature (°C)	Time (h)
64W	34	500	600 ± 14	48
65W	*a*	*a*	607 ± 14	80
66W	*a*	*a*	607 ± 14	48
67W	*a*	*a*	*a*	*a*

[a]Not available.

Source: A. L. Lowe, Jr., "Description of Weld Materials Furnished for Second and Third HSST Irradiation Experiments," BAW-1382, to be published by Babcock and Wilcox, Lynchburg, Va.

Table 2. Mean chemical composition of submerged arc welds

Material	Average composition[a] (wt %)									
	C	Mn	P	S	Si	Cr	Ni	Mo	Cu	V
64W	0.085	1.59	0.014	0.015	0.520	0.092	0.660	0.420	0.350	0.007
	0.070/0.10	1.54/1.64	0.012/0.017	0.014/0.016	0.445/0.600	0.074/0.110	0.600/0.720	0.410/0.430	0.310/0.390	0.006/0.008
65W	0.080	1.45	0.015	0.015	0.480	0.088	0.597	0.385	0.215	0.006
	0.070/0.090	1.42/1.49	0.014/0.017	0.013/0.017	0.450/0.610	0.076/0.100	0.585/0.610	0.370/0.400	0.180/0.250	0.005/0.008
66W	0.092	1.63	0.018	0.009	0.540	0.105	0.595	0.400	0.420	0.009
	0.075/0.110	1.59/1.67	0.017/0.020	0.009/0.010	0.480/0.600	0.090/0.120	0.580/0.610	0.380/0.420	0.350/0.490	0.007/0.012
67W	0.082	1.44	0.011	0.012	0.500	0.089	0.590	0.390	0.265	0.007
	0.070/0.095	1.40/1.48	0.010/0.013	0.012/0.013	0.410/0.590	0.067/0.110	0.580/0.600	0.370/0.410	0.220/0.310	0.005/0.010

[a]Numbers shown below each entry indicate range of composition measurements.

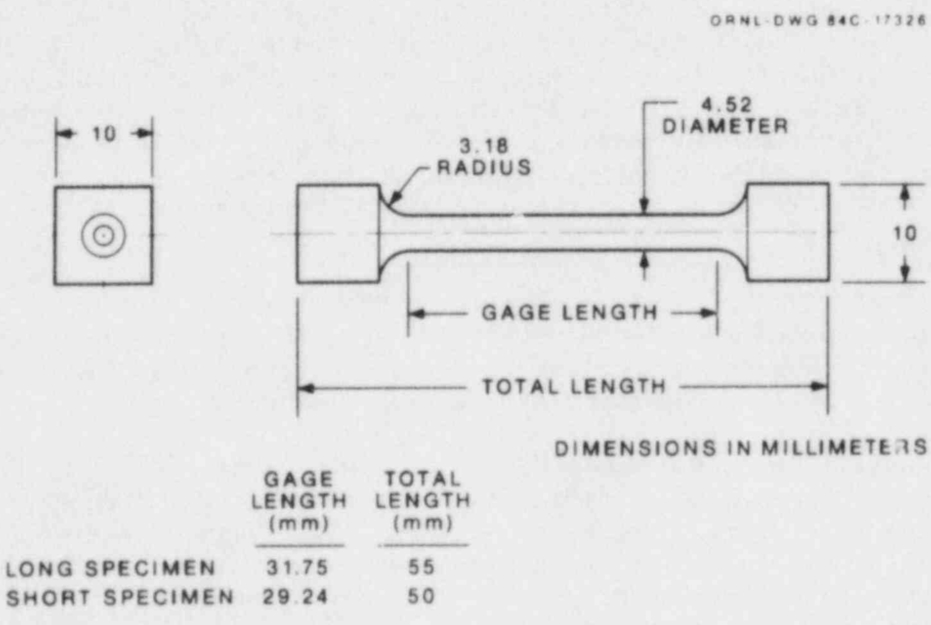

Fig. 1. Tensile specimen configurations used in Third HSST Irradiation Series.

each test crosshead displacement versus load was recorded. The 0.2% offset yield strength was measured from this trace. Errors in yield strength from crosshead displacement (instead of extensometer movement) were established at less than 3% by use of an extensometer at room temperature. On completion of the test, neck diameter and final length were measured for each specimen. Unirradiated specimens were measured with vernier calipers; irradiated specimens were measured with a digital toolmaker's microscope. The uniform strain was determined from the plastic displacement to maximum load on the load-versus-crosshead-motion trace.

RESULTS AND DISCUSSION

The tensile properties are summarized for both unirradiated materials and irradiated materials in Tables 3 and 4, respectively. Preirradiation strength and ductility values are similar for all four welds, with weld 66W showing only slightly higher strength (10–15%) than the other three welds.

Irradiation to a fluence of 2 to 10 × 10^{22} neutrons/m^2 ($E > 1$ MeV) at 250 to 290°C produced a pronounced effect on the strengths of all four welds, as illustrated in Figs. 2 through 5. On these figures second-degree curves are shown for the unirradiated and irradiated strengths. These curves were determined by a least-squares procedure, and the coefficients for each material are listed in Table 5. Using these curve fits, the yield and ultimate strengths were averaged over the temperature range 22 to 288°C (Table 6). As expected, weld 65W has the lowest yield and ultimate strengths after irradiation, because it had the lowest copper level (0.25%). Weld 66W had the highest yield and ultimate strengths after irradiation, because it had the highest copper level (0.42%). The percentage change in strength for weld 66W is deceptively small because it had a relatively high unirradiated strength due to slightly higher C, Mn, and Si levels. Welds 64W and 67W had intermediate levels of copper, resulting in intermediate strength increases. Nickel content in the welds was near 0.6% and did not affect the relative ordering of the tensile strengths. In general, the yield strength for the welds was increased more than was the ultimate strength.

As noted in Table 4, the controls on the irradiation fluence and irradiation temperature were inadequate because of improper capsule design. Table 4 shows that these problems in design resulted in no significant variation in tensile properties at the target fluence.

Irradiation to a fluence of 2 to 10 × 10^{22} neutrons/m^2 ($E > 1$ MeV) at 252 to 290°C produced no significant effect on the tensile ductility, as illustrated in Figs. 6 through 9. On these figures first-degree curves are shown for the ductility in the irradiated and unirradiated conditions. These curves were determined by a least-squares procedure; the coefficients for each material are listed in Table 7. Using these curve fits, the total elongation values over the temperature range 22 to 288°C were averaged. These average values, listed in Table 8, reflect the small effect of irradiation on the ductility of all four materials.

Table 3. Tensile properties of unirradiated welds

Specimen	Test temperature (°C)	Yield strength (MPa)	Ultimate strength (MPa)	Uniform strain (%)	Reduction of area (%)	Total elongation[a] (%)
64W10[b]	27	467	583	9.9	65.8	19.5
11[b]	27	469	581	9.6	64.5	18.8
12[b]	151	426	539	9.0	65.5	17.2
13	151	418	533	9.9	67.4	18.9
14[b]	286	398	547	8.4	60.0	16.0
15[b]	288	398	549	9.6	52.7	15.8
16[b]	27	458	575	10.1	64.1	18.4
17[b]	151	407	519	9.0	66.7	17.4
18[b]	286	398	533	8.6	51.5	14.4
65W10[b]	27	461	572	10.1	63.9	19.6
11[b]	27	460	571	9.5	64.4	17.2
12[b]	151	425	535	7.7	62.9	15.4
13[b]	150	428	538	8.0	63.6	15.2
14[b]	288	423	550	7.5	55.5	13.3
15[b]	288	414	548	7.8	57.3	14.3
16[b]	27	451	571	9.5	67.2	17.6
17[b]	150	416	526	7.4	66.0	15.2
18[b]	288	398	550	9.3	61.1	16.9
66W1	27	533	639	8.4	63.3	17.1
2	150	507	599	7.2	64.9	14.7
6	287	496	610	6.8	46.3	12.7
7	27	534	639	6.8	63.4	14.8
8	149	506	595	6.2	63.5	13.5
10	288	500	607	6.4	47.0	11.7
67W1	27	445	569	8.2	65.8	16.2
2	27	461	581	8.5	67.7	17.2
3	150	424	538	6.5	67.9	14.3
5	149	429	543	6.5	63.9	13.7
6	288	431	565	7.3	61.0	13.9
7	288	433	567	7.7	55.1	13.8
8	27	479	600	11.4	66.1	20.2
10	148	433	544	7.3	64.6	15.0
11	288	427	554	7.3	57.7	12.8

[a]Elongation for 31.75-mm gage length; length-to-diameter ratio of 7.

[b]Short specimens; all others are long specimens.

Table 4. Tensile properties of irradiated welds

Specimen	Fluence (10^{22} neutrons/m^2)	Irradiation temperature (°C)	Test temperature (°C)	Yield strength (MPa)	Ultimate strength (MPa)	Uniform strain (%)	Reduction of area (%)	Total elongation[a] (%)
64W1	4.5	273 ± 11	288	519	640	7.5	39.0	11.9
4[b]	6.7	281 ± 12	33	610	709	10.0	58.4	17.1
5[b]	6.7	282 ± 5	288	527	656	8.3	40.4	14.0
6[b]	2.4	289 ± 1	33	594	688	10.9	56.5	17.1
7[b]	2.4	290 ± 1	289	525	658	7.2	52.1	12.2
8[b]	6.4	273 ± 1	149	524	626	7.5	56.5	14.8
65W3	3.8	281 ± 7	151	476	612	9.3	61.3	16.6
4[b]	7.6	279 ± 13	28	582	676	11.2	63.0	20.2
5[b]	7.5	284 ± 8	287	507	644	9.3	53.6	16.7
6[b]	2.0	288 ± 3	288	504	627	8.2	62.1	14.7
7[b]	2.0	287 ± 9	28	562	662	10.6	57.7	18.6
8[b]	6.0	268 ± 6	150	493	592	9.1	62.4	17.1
9[b]	6.0	270 ± 4	288	475	601	8.0	49.5	15.0
66W3	6.4	284 ± 24	149	599	684	6.7	67.4	13.4
4	5.6	284 ± 24	149	603	692	6.8	52.4	13.3
5	5.2	279 ± 13	287	573	683	7.1	50.8	12.8
9	4.0	279 ± 13	34	635	715	6.8	59.3	14.8
11[b]	8.7	286 ± 12	290	580	683	6.0	42.2	11.2
12[b]	8.7	281 ± 7	34	671	746	8.0	60.8	18.2
67W4	5.4	282 ± 13	149	566	645	6.7	66.3	13.5
9	4.2	282 ± 12	149	553	655	7.5	60.8	13.9
15[b]	9.5	261 ± 3	288	519	632	7.1	60.7	13.0
16[b]	9.5	252 ± 2	288	511	627	7.1	52.7	12.8
17[b]	1.8	284 ± 3	34	613	691	8.6	61.4	15.4
18[b]	1.8	236 ± 1	288	529	655	8.0	59.7	13.3

[a]Elongation for 31.75-mm gage length; length-to-diameter ratio of 7.

[b]Short specimens; all others are long specimens.

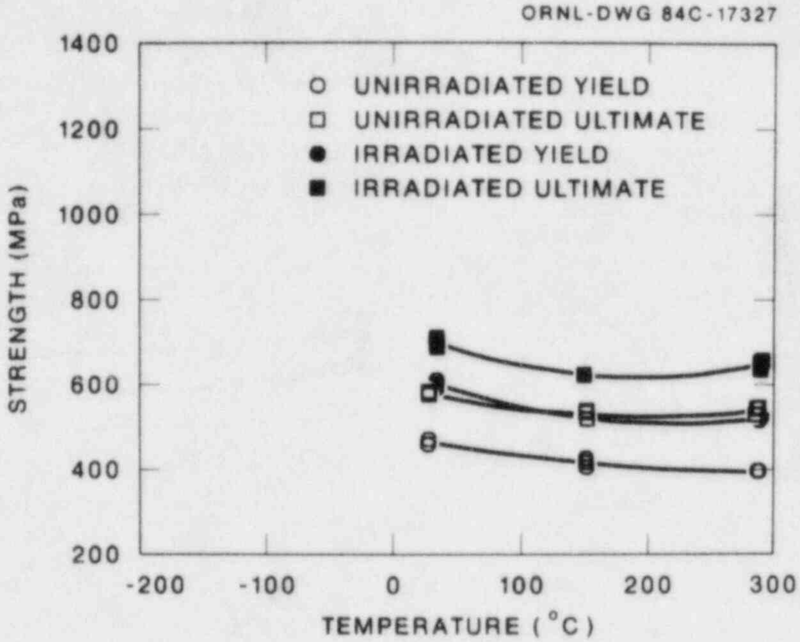

Fig. 2. Tensile strength versus temperature of irradiated and unirradiated weld 64W.

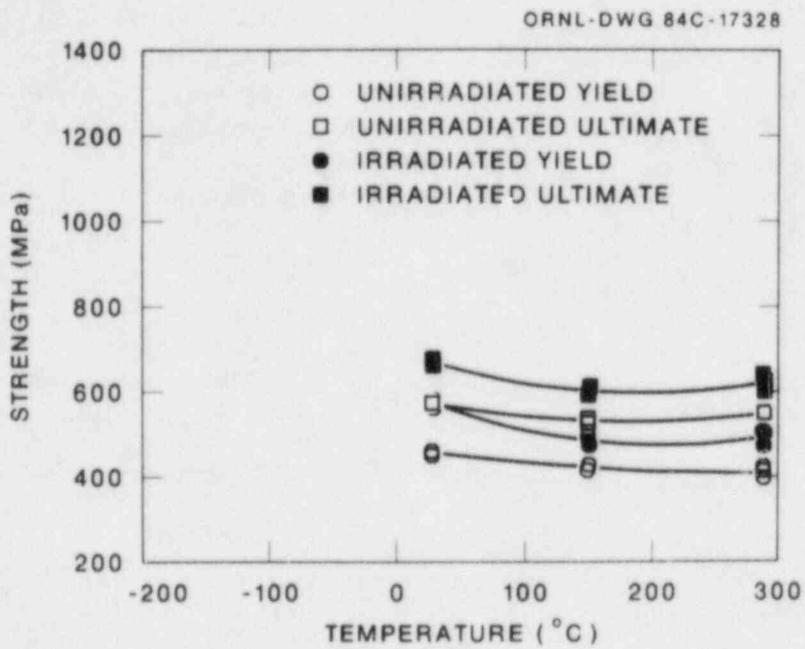

Fig. 3. Tensile strength versus temperature of irradiated and unirradiated weld 65W.

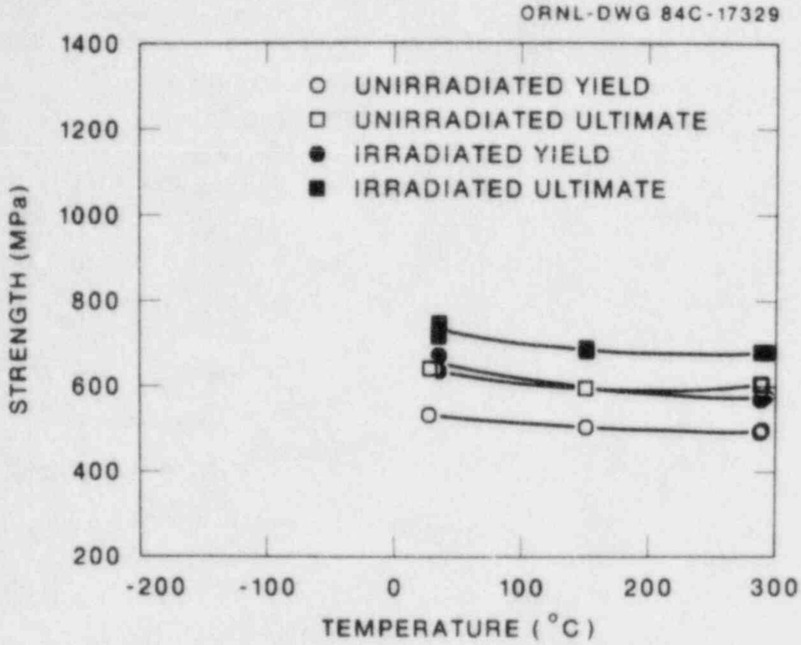

Fig. 4. Tensile strength versus temperature of irradiated and unirradiated weld 66W.

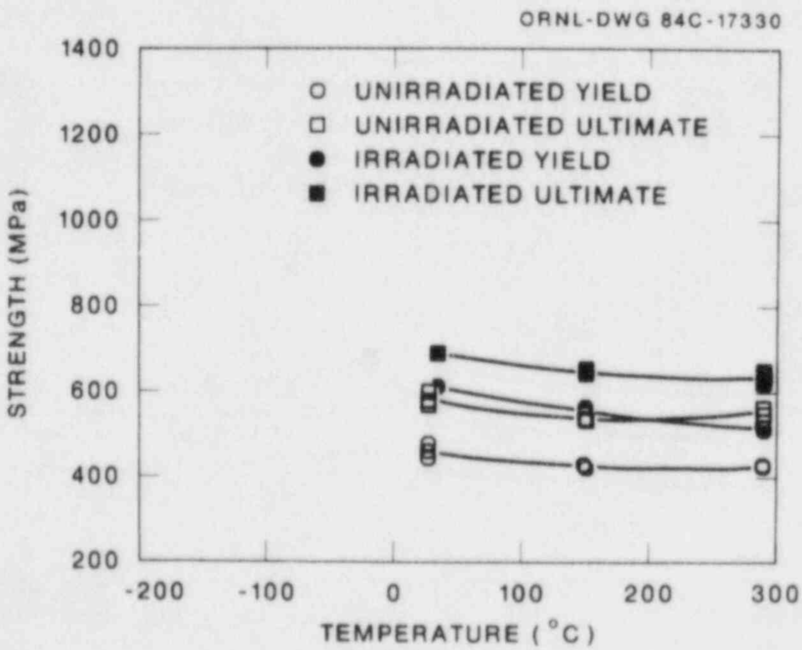

Fig. 5. Tensile strength versus temperature of irradiated and unirradiated weld 67W.

Table 5. Curve fit coefficients for yield and ultimate strengths

Material	Yield strength[a]			Ultimate strength[a]		
	c_0	c_1	c_2	c_0	c_1	c_2
Unirradiated specimens						
64W	479	−0.552	0.00094	598	−0.736	0.00090
65W	468	−0.412	0.00075	586	−0.603	0.00165
66W	542	−0.326	0.00060	655	−0.631	0.00163
67W	473	−0.461	0.00108	600	−0.671	0.00187
Irradiated specimens						
64W	637	−1.150	0.00263	735	−1.202	0.00317
65W	605	−1.258	0.00305	696	−1.029	0.00271
66W	674	−0.653	0.00109	750	−0.609	0.00131
67W	632	−0.594	0.00070	709	−0.551	0.00106

[a]Coefficients of $\sigma = c_0 + c_1 T + c_2 T^2$, with σ in megapascals and T in degrees C.

Table 6. Average tensile strength[a]

Material	$\sigma_{Y,U}$ (MPa)	$\sigma_{Y,I}$ (MPa)	$\frac{\sigma_{Y,I} - \sigma_{Y,U}}{\sigma_{Y,U}}$ (%)	$\sigma_{U,U}$ (MPa)	$\sigma_{U,I}$ (MPa)	$\frac{\sigma_{U,I} - \sigma_{U,U}}{\sigma_{U,U}}$ (%)
64W	422	537	27	541	644	19
65W	427	501	18	542	590	9
66W	509	608	19	606	695	15
67W	434	561	29	552	655	19

[a]Where $\sigma_{Y,U}$ = average unirradiated yield strength from 22 to 288°C, $\sigma_{Y,I}$ = average irradiated yield strength from 22 to 288°C, $\sigma_{U,U}$ = average unirradiated ultimate strength from 22 to 288°C, and $\sigma_{U,I}$ = average irradiated ultimate strength from 22 to 288°C.

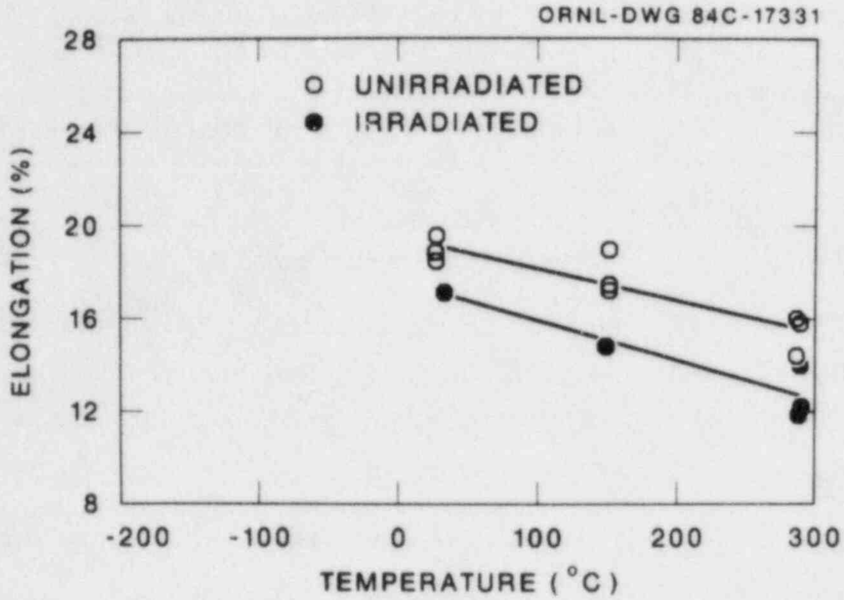

Fig. 6. Total elongation versus temperature of irradiated and unirradiated weld 64W.

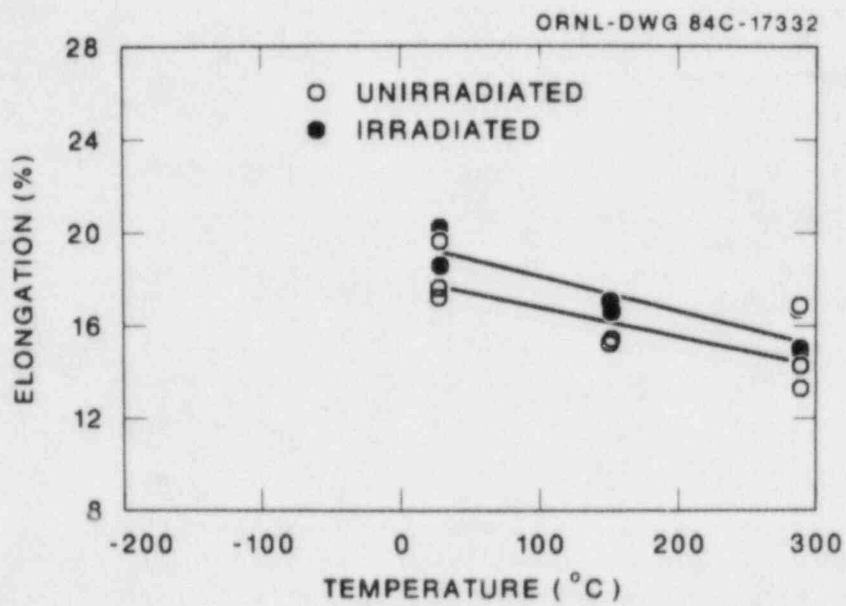

Fig. 7. Total elongation versus temperature of irradiated and unirradiated weld 65W.

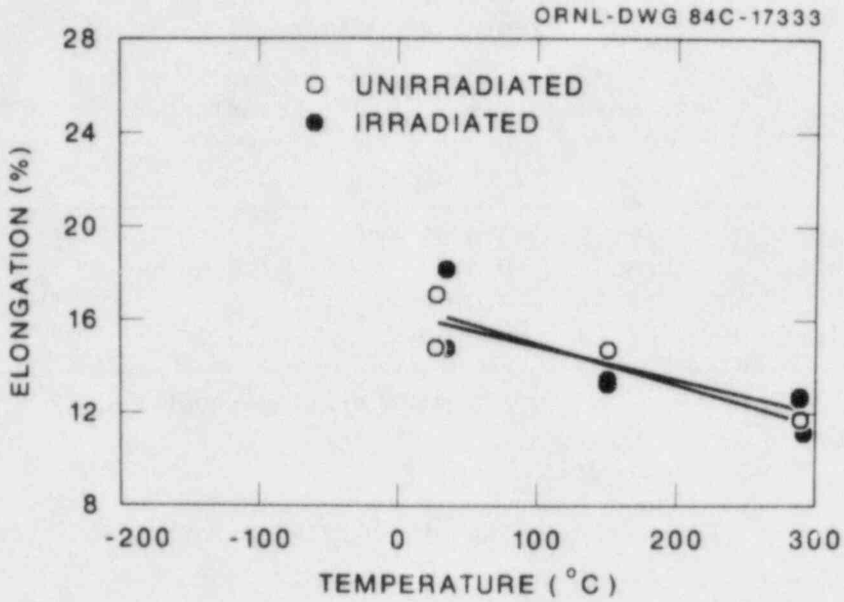

Fig. 8. Total elongation versus temperature of irradiated and unirradiated weld 66W.

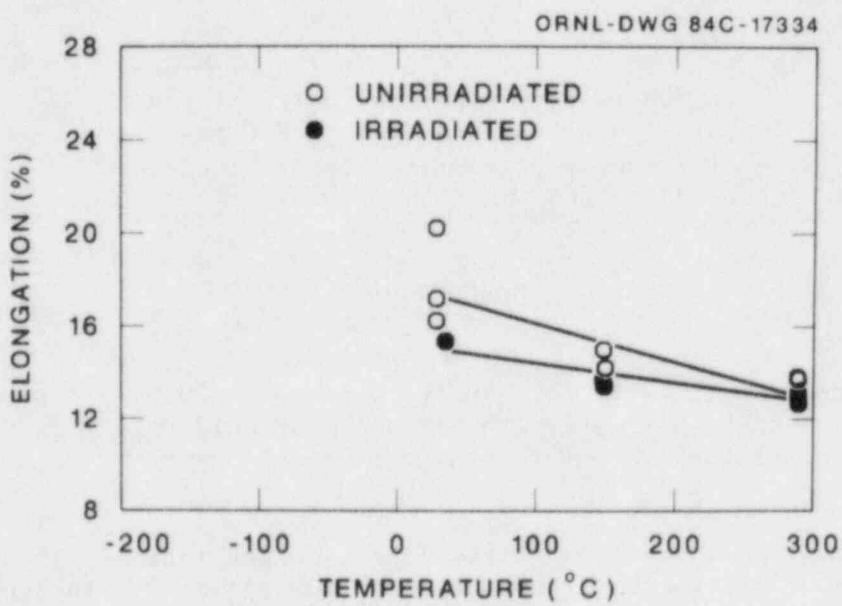

Fig. 9. Total elongation versus temperature of irradiated and unirradiated weld 67W.

Table 7. Curve fit coefficients for total elongation values

Material	Unirradiated; $\varepsilon_{T,U}$ (%)[a]		Irradiated; $\varepsilon_{T,I}$ (%)[a]	
	c_0	c_1	c_0	c_1
64W	19.48	−0.0135	17.60	−0.0171
65W	18.01	−0.0125	19.56	−0.0148
66W	16.31	−0.0144	16.69	−0.0174
67W	17.78	−0.0165	15.28	−0.0082

[a]Where $\varepsilon_T = c_0 + c_1 T$, with ε_T in percent and T in degrees C.

Table 8. Average total elongation[a]

Material	$\varepsilon_{T,U}$ (%)	$\varepsilon_{T,I}$ (%)	$\varepsilon_{T,I} - \varepsilon_{T,U}$ (%)
64W	17	15	-2
65W	16	17	1
66W	14	14	0
67W	15	14	-1

[a]Where $\varepsilon_{T,U}$ = average unirradiated total elongation from 22 to 288°C and $\varepsilon_{T,I}$ = average irradiated total elongation from 22 to 288°C.

CONCLUSIONS

1. Irradiation to fluences in the range 2 to 10 × 10^{22} neutrons/m^2 (E > 1 MeV) significantly strengthened all four weld materials; yield strength (18–29%) increases were greater than ultimate strength increases (9–19%).

2. Welds 65W and 66W exhibited less strength increase than did welds 64W and 67W. These differences may be associated with chemical composition variations.

3. Tensile elongation was not affected significantly by irradiation for any of the materials examined.

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16. ABSTRACT (200 words or less)

The Heavy Section Steel Technology (HSST) Program conducted a series of experiments to investigate the effect of neutron irradiation on the fracture toughness of nuclear pressure vessel materials. Four welds of A 508 class 2 steel were examined in this Third HSST Irradiation Series. The welds were fabricated according to "early" (pre-1972) light-water reactor weld practice (i.e., copper-coated electrodes). As part of this study, tensile properties were measured after irradiation to 2 to 10 × 10^{22} neutrons/m^2 ($E > 1$ MeV) at temperatures between 250 and 290°C. Strength properties of all four welds increased with exposure to irradiation. Yield strength was more sensitive to irradiation than was ultimate strength. Tensile ductility was not affected significantly by exposure to irradiation.

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