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Tensile Properties of Irradiated Nuclear Grade Pressure Vessel Plate and Welds for the Fourth HSST Irradiation Series

J. J. McGowan

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METALS AND CERAMICS DIVISION

TENSILE PROPERTIES OF IRRADIATED NUCLEAR GRADE PRESSURE VESSEL PLATE AND WELDS FOR THE FOURTH 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's (NRC) Heavy-Section Steel Technology Program, which is directed by ORNL. The program is conducted as part of the ORNL Pressure Vessel Technology Program, of which C. E. Pugh is manager. The manager for the NRC is Milton Vagins.

This report is designated Heavy-Section Steel Technology Program Technical or Programmatic Manuscript 37. 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.
3. *HSST Intermediate Vessel Closure Analysis*, Technical Report E-1253(b), Teledyne Materials Research Company, Waltham, Mass., Mar. 25, 1970.
4. C. L. Segaser, *Feasibility Study, Irradiation of Heavy-Section Steel Specimens in the South Test Facility of the Oak Ridge Research Reactor*, ORNL/TM-3234, May 1971.
5. D. A. Canonico, *Transition Temperature Considerations for Thick-Wall Nuclear Pressure Vessels*, ORNL/TM-3114, October 1970.
6. F. J. Witt and R. G. Berggren, *Size Effects and Energy Disposition in Impact Specimen Testing of ASTM A533 Grade B Steel*, ORNL/TM-3030, August 1970.
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8. D. A. Canonico and R. G. Berggren, *Tensile and Impact Properties of Thick-Section Plate and Weldments*, ORNL/TM-3211, January 1971.
9. J. G. Merkle, L. F. Kooistra, and R. W. Derby, *Interpretations of the Drop Weight Test in Terms of Strain Tolerance (Gross Strain) and Fracture Mechanics*, ORNL/TM-3247, June 1971.
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11. N. Krishnamurthy, *Three-Dimensional Finite Element Analysis of Thick-Walled Vessel-Nozzle Junctions with Curved Transitions*, ORNL/TM-3315, July 1971.
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CONTENTS

TENSILE PROPERTIES OF IRRADIATED NUCLEAR GRADE PRESSURE VESSEL PLATE AND WELDS FOR THE FOURTH HSST IRRADIATION SERIES

J. J. McGowan

ABSTRACT

The Heavy Section Steel Technology (HSST) program office is conducting a number of experimental series to determine the effect of neutron irradiation on the fracture toughness of nuclear pressure vessel materials. One plate (HSST plate 02) and four welds of A 533 grade B class 1 steel were examined here as part of the Fourth Irradiation Series. The welds were made by current (about 1979) practices.

As part of this study, tensile properties were measured after irradiation to 2×10^{23} neutrons/m^2 (>1 MeV) at 288°C. The strength of all four welds increased with irradiation. Yield strength was about 10% more sensitive to irradiation than was ultimate strength. Tensile ductility was not affected significantly by irradiation.

INTRODUCTION

The Heavy Section Steel Technology (HSST) program is sponsored by the U.S. Nuclear Regulatory Commission. One of its objectives is better insight into the mechanisms that could embrittle reactor pressure vessels during neutron irradiation. To assess material behavior, the HSST program office at ORNL irradiated specimens to produce a variety of conditions representing those in reactor environments.

The HSST Fourth Irradiation Experiment was conducted to examine the effects of neutron irradiation on the fracture toughness of nuclear pressure vessel welds made by current (about 1979) practice. Tensile, fracture, and impact specimens were irradiated in ORNL's Bulk Shielding Reactor at 288°C to a target fast-neutron fluence (>1 MeV) of 2×10^{23} neutrons/m^2. The objective of the work reported here was to assess the tensile properties of a plate and four welds irradiated in the HSST Fourth Irradiation Experiment.

EXPERIMENTAL

MATERIALS AND SPECIMENS

Four submerged-arc welds were made in A 533 grade B class 1 base material by current (about 1979) practice. They are hereinafter referred to as 68W, 69W, 70W, and 71W. The weld parameters are summarized in Table 1 (refs. 1 and 2). One plate of A 533 grade B class 1 steel, hereinafter referred to as plate 02, also was studied. The chemical compositions of the materials in this study are given in Table 2.

Table 1. Weld parameter summary

HSST weld code	Manufacturer	Manufacturer's code	Thickness (m)	Linde flux	Postweld heat treatment		Comments
					Temperature (°C)	Time (h)	
68W[a]	CE for EPRI	CGS	0.178	91	621	25	Straight-wall groove
69W[a]	CE for EPRI	CHS	0.300	91	621	25	Double-U groove, cylindrical constraint
70W[b]	B&W	MK-W-124	0.175	124	607	48	Double-V groove
71W[b]	B&W	MK-W-80	0.175	80	607	48	Double-V groove

[a] *Source*: T. V. Marston et al., *Fracture Toughness of Ferritic Materials in Light-Water Nuclear Reactor Vessels*, MML-75-152, pp. 47–48, Combustion Engineering, Inc., Chattanooga, Tenn., October 13, 1975.

[b] *Source*: A. L. Lowe, Jr., and J. I. Qureshi, *Fabrication of Weldments Using Linde 80 and Linde 124 Weld Fluxes for HSST Irradiation Program*, BAW-1537, Babcock and Wilcox Nuclear Power Group, Lynchburg, Va., June 1981.

Table 2. Chemical composition of plate 02 and submerged-arc welds

Material	Average composition (wt %)									
	C	Mn	P	S	Si	Cr	Ni	Mo	Cu	V
Plate 02	0.23	1.55	0.009	0.014	0.20	0.04	0.67	0.53	0.14	0.003
Weld 68W	0.15	1.38	0.008	0.009	0.16	0.04	0.13	0.60	0.04	0.007
Weld 69W	0.14	1.19	0.010	0.009	0.19	0.09	0.10	0.54	0.12	0.005
Weld 70W	0.10	1.48	0.011	0.011	0.44	0.13	0.63	0.47	0.056	0.004
Weld 71W	0.124	1.58	0.011	0.011	0.54	0.12	0.63	0.45	0.046	0.005

The orientation of all tensile specimens was weld transverse. Miniature tensile specimens were used (Fig. 1). The specimen size and design were dictated primarily by the physical space available for irradiation.

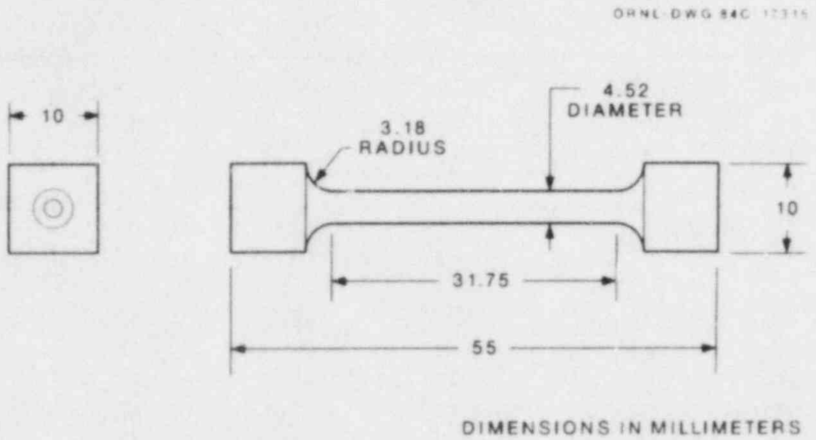

Fig. 1. Tensile specimen configuration.

TEST APPARATUS AND DATA ANALYSIS

Three testing machines were used: two 45-kN Instrons and one 490-kN MTS. All unirradiated testing was performed with the Instron systems, and the irradiated testing was performed with the MTS system. The unirradiated specimens were heated for testing at elevated temperature by a bath of water-soluble oil and were cooled for testing at low temperature by a bath of isopentane and dry ice. All the irradiated specimens were tested at room temperature or above in an air furnace. All testing was performed at a crosshead rate of 0.5 mm/min. Crosshead displacement versus load was recorded during each test, and the 0.2% offset yield strength was measured from that trace. Errors in yield strength determined from crosshead displacement (instead of extensometer movement) were established at less than 3% by use of an extensometer at room temperature. Upon completion of the test, neck diameter and final length were measured on 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 trace of load versus crosshead motion.

RESULTS AND DISCUSSION

The tensile properties for unirradiated and irradiated materials are summarized in Tables 3 and 4, respectively. Preirradiation strength and ductility values are similar for the five materials, with weld 69W 20 to 30% stronger than the other welds.

Table 3. Tensile properties of unirradiated weld and plate specimens

Specimen	Test temperature (°C)	Yield strength (MPa)	Ultimate strength (MPa)	Uniform strain (%)	Reduction of area (%)	Total elongation[a] (%)
68W1	−140	772	821	9.3	69.0	18.9
4	−140	816	847	11.6	67.0	20.3
8	−40	588	693	9.7	72.7	20.5
12	124	519	599	5.5	72.1	13.6
13	287	497	624	7.4	73.1	15.9
14	287	493	618	6.9	72.8	15.2
69W1	−140	873	927	12.4	65.8	21.5
2	−90	737	838	10.1	66.2	20.8
3	−40	678	780	9.2	69.9	17.3
4	27	642	723	7.6	68.3	16.2
5	123	600	688	6.5	68.0	13.9
7	204	571	696	7.3	67.4	14.8
8	287	572	714	9.1	59.2	16.3
10	−140	849	920	9.8	67.2	18.3
11	−40	679	779	8.4	67.9	16.8
16	27	635	721	6.8	71.1	15.4
19	122	601	681	5.9	70.5	13.6
20	287	582	708	6.8	60.5	13.4
70W1	−140	686	809	18.4	57.1	26.0
2	−90	574	715	11.8	64.2	23.3
3	−40	524	658	11.5	68.0	22.4
4	27	480	593	10.3	68.1	19.8
5	122	453	558	8.3	68.8	16.1
6	203	436	561	7.3	66.7	15.8
9	287	436	578	8.1	65.5	15.4
11	−140	664	784	12.7	62.7	22.9
12	−40	525	655	12.0	67.2	21.2
15	27	476	594	9.1	69.4	18.2
17	124	452	556	8.3	67.8	16.9
18	288	429	573	8.4	64.1	16.3
71W1	−140	669	795	13.7	60.8	21.9
2	−91	566	718	13.4	62.1	22.2
4	−40	506	659	12.5	64.2	20.9
5	27	469	600	9.3	67.3	18.2
7	122	447	557	8.7	66.1	16.0
8	203	429	557	8.3	64.2	15.9
10	289	430	581	8.2	59.6	14.6
12	−140	681	806	13.9	58.7	23.5
13	−40	511	658	12.4	65.2	20.5
14	27	469	598	10.0	68.3	19.4
16	122	442	558	8.7	64.9	16.0
18	289	428	568	8.7	60.9	15.1

Table 3. (continued)

Specimen	Test temperature (°C)	Yield strength (MPa)	Ultimate strength (MPa)	Uniform strain (%)	Reduction of area (%)	Total elongation[a] (%)
02GA510	28	466	621	9.1	68.2	17.8
511	28	468	623	9.1	69.4	18.9
514	−40	517	687	12.2	67.2	20.0
515	−40	505	683	11.1	68.1	19.9
516	−90	559	746	11.8	62.6	20.7
517	−90	569	755	12.2	55.8	18.8
518	122	448	569	7.5	68.1	15.2
519	123	441	584	7.3	65.7	15.2
520	203	426	586	7.9	66.9	15.5
521	203	423	582	7.7	65.5	15.3
523	289	433	622	9.6	56.8	18.0
524	−140	684	836	12.9	58.3	23.4
525	−140	678	846	12.8	55.4	20.1
532	289	432	621	9.0	59.5	16.5

[a] Length-to-diameter ratio was 7.

Irradiation to a fluence of 7 × 10^{22} to 20 × 10^{22} neutrons/m^2 (>1 MeV) at 288°C had a pronounced effect on the strength of all the materials (Figs. 2 through 6). Second degree curves in those figures for the unirradiated and irradiated strengths were determined by a least squares

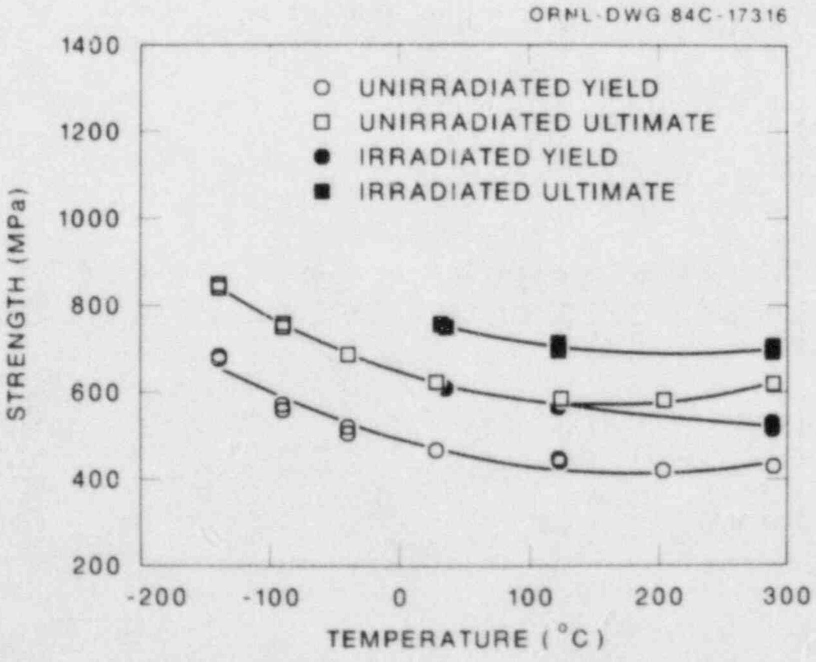

Fig. 2. Tensile strength of irradiated and unirradiated plate 02.

Table 4. Tensile properties of weld and plate specimens irradiated at 288°C

Specimen	Fluence (neutrons/m^2)	Test temperature (°C)	Yield strength (MPa)	Ultimate strength (MPa)	Uniform strain (%)	Reduction of area (%)	Total elongation[a] (%)
68W2	7.5 × 10^{22}	36	555	634	6.1	72.5	15.0
6	13.0	122	537	612	5.7	77.0	14.0
7	14.6	36	573	656	6.9	69.6	16.0
9	16.9	287	575	641	6.3	76.9	16.1
15	12.8	289	521	633	6.8	70.2	15.3
69W6	8.0	35	704	776	8.4	65.0	17.4
12	13.6	121	674	747	7.0	66.8	14.4
14	16.6	288	652	755	7.4	59.2	14.2
15	15.8	122	675	749	6.5	68.9	14.1
17	13.8	34	717	792	7.1	65.7	15.3
18	10.5	287	653	756	6.8	59.5	14.0
70W7	10.4	288	467	615	9.1	62.0	16.9
8	16.5	28	534	649	10.3	64.6	19.0
10	19.8	121	499	607	9.1	60.8	17.1
13	21.1	288	472	615	9.2	48.8	15.7
16	14.0	122	495	597	10.1	68.7	18.0
71W3	10.2	288	461	592	7.9	60.1	14.5
9	19.5	122	498	604	10.1	60.3	18.0
11	20.8	288	470	608	8.3	48.5	13.6
15	18.6	29	539	649	10.3	62.2	18.8
17	13.7	121	487	592	9.2	63.8	17.0
02GA503	17.6	34	609	749	10.4	61.1	18.1
504	22.5	288	533	706	8.5	50.3	14.7
505	22.0	121	581	712	8.2	54.4	14.4
506	21.4	31	617	753	9.4	52.9	16.8
508	13.9	121	566	699	9.5	62.5	16.1
509	13.6	288	519	696	9.3	61.3	15.3

[a] Length-to-diameter ratio was 7.

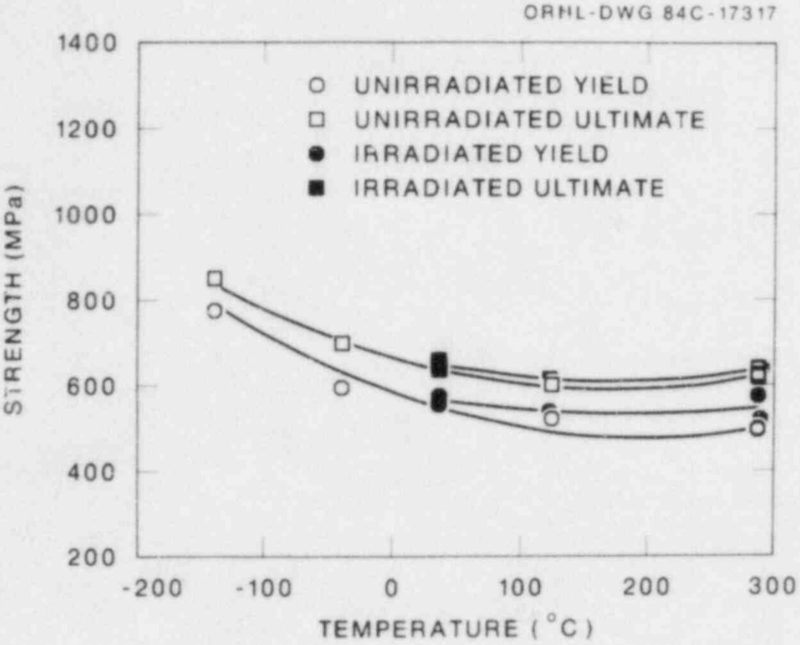

Fig. 3. Tensile strength of irradiated and unirradiated weld 68W.

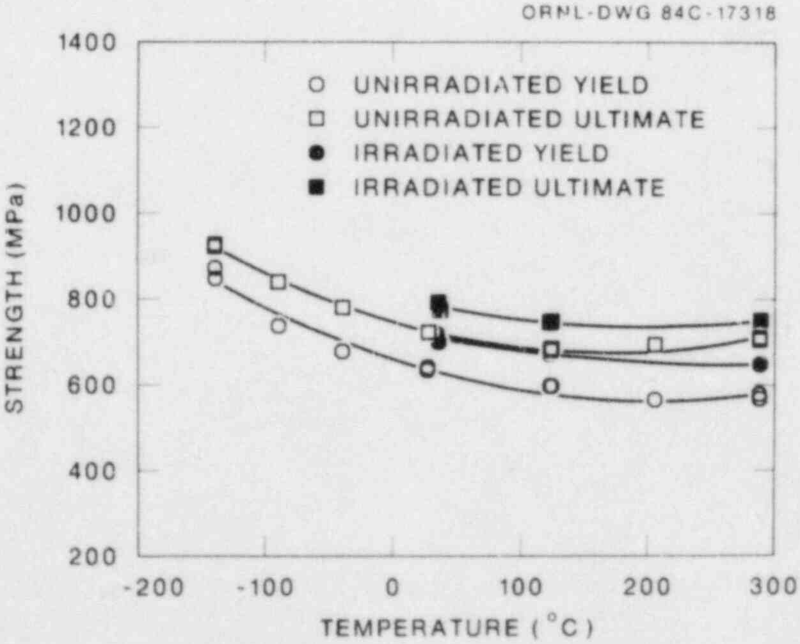

Fig. 4. Tensile strength of irradiated and unirradiated weld 69W.

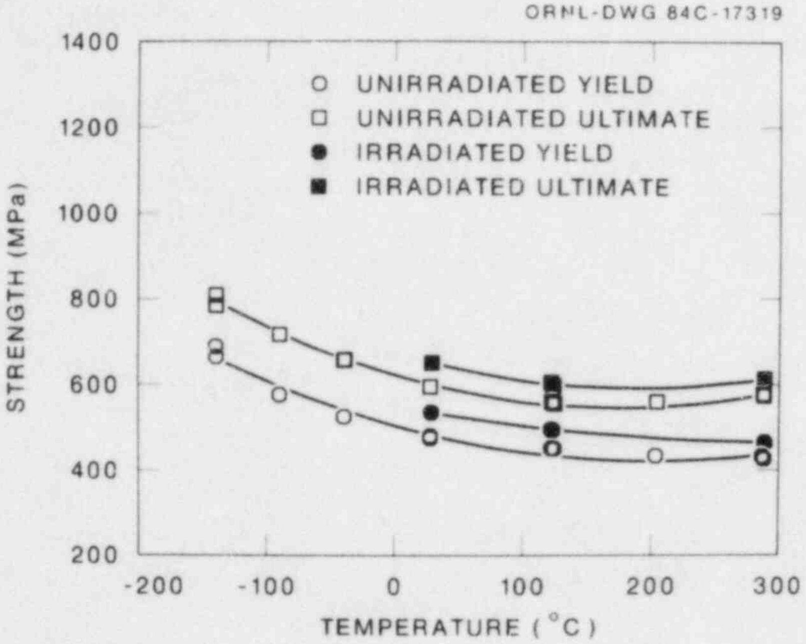

Fig. 5. Tensile strength of irradiated and unirradiated weld 70W.

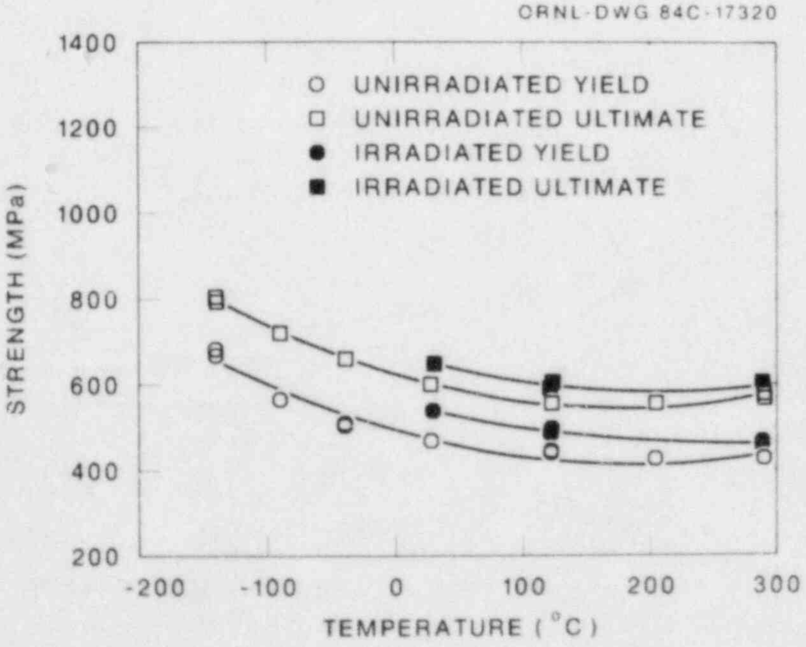

Fig. 6. Tensile strength of irradiated and unirradiated weld 71W.

procedure, and the coefficients for each material are listed in Table 5. Those curve fits were used to average the yield and ultimate strengths over the temperature range of 22 to 288°C. The averages, listed in Table 6, show that irradiation affected the yield strength more than it did the ultimate strength. Table 6 also shows that the strength of plate 02 was more sensitive to irradiation than were the strengths of the welds. That behavior was expected because plate 02 contained more copper and nickel than did the welds.

Irradiation to a fluence of 7×10^{22} to 20×10^{22} neutrons/m^2 (>1 MeV) at 288°C did not affect the tensile ductility significantly (Figs. 7 through 11). First degree curves are shown in those figures for ductility in the irradiated condition and second degree curves for ductility in the unirradiated condition. They were determined by a least squares procedure, and the coefficients for each material are listed in Table 7. Those curve fits were used to average the total elongation values over the temperature range 22 to 288°C. The averages, listed in Table 8, reflect the small effect of irradiation on the ductility of all four materials.

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			
68W	580	−1.075	0.00277	662	−0.864	0.00253
69W	660	−0.949	0.00239	746	−0.856	0.00262
70W	504	−0.816	0.00208	621	−0.868	0.00253
71W	493	−0.841	0.00226	624	−0.879	0.00250
Plate 02	492	−0.842	0.00234	646	−0.939	0.00300
			Irradiated specimens			
68W	581	−0.525	0.00143	668	−0.714	0.00211
69W	730	−0.589	0.00112	806	−0.699	0.00182
70W	548	−0.529	0.00089	671	−0.837	0.00224
71W	558	−0.700	0.00131	673	−0.878	0.00217
Plate 02	630	−0.547	0.00064	775	−0.808	0.00191

[a] Coefficients of $\sigma = c_0 + c_1 T + c_2 T^2$.

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)	$\frac{\sigma_{U,I} - \sigma_{U,U}}{\sigma_{U,U}}$ (%)
Plate 02	432	564	31	590	707	20
Weld 68W	496	590	19	604	620	3
Weld 69W	584	672	15	692	752	9
Weld 70W	440	493	12	562	608	8
Weld 71W	430	489	14	563	602	7

[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.

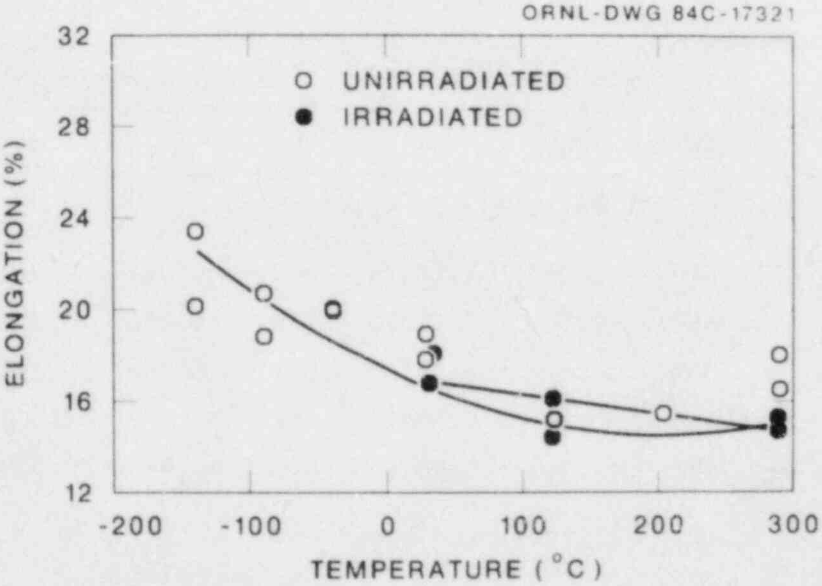

Fig. 7. Total elongation of irradiated and unirradiated plate 02.

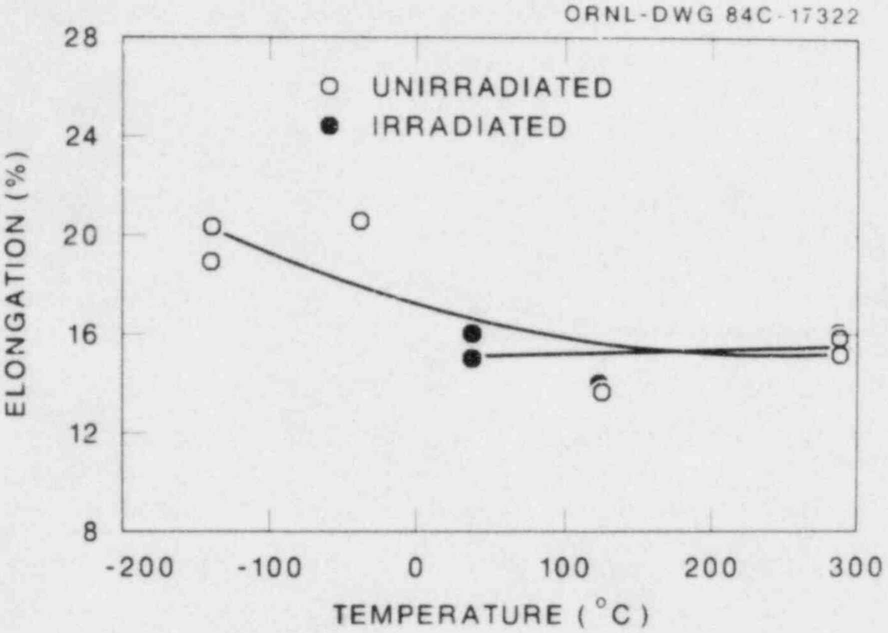

Fig. 8. Total elongation of irradiated and unirradiated weld 68W.

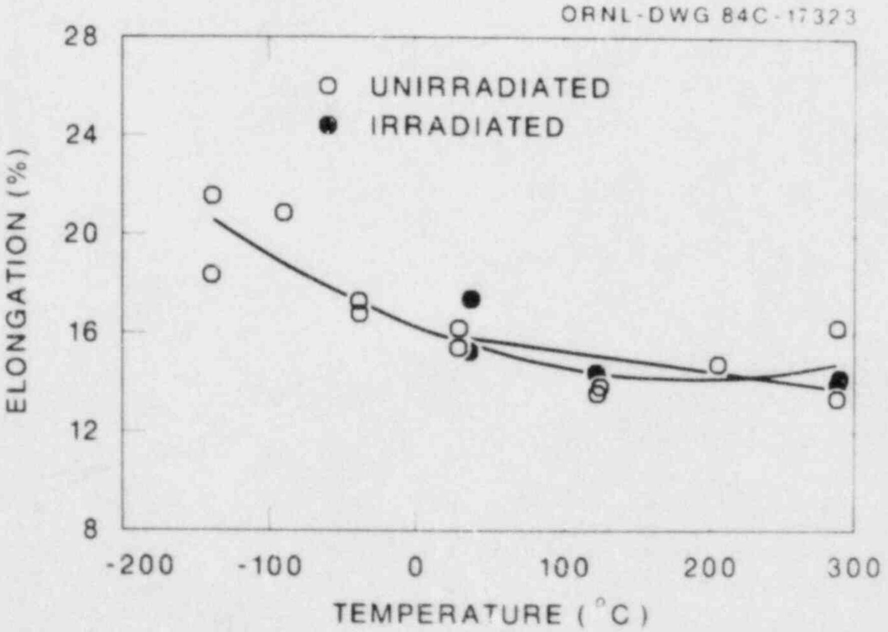

Fig. 9. Total elongation of irradiated and unirradiated weld 69W.

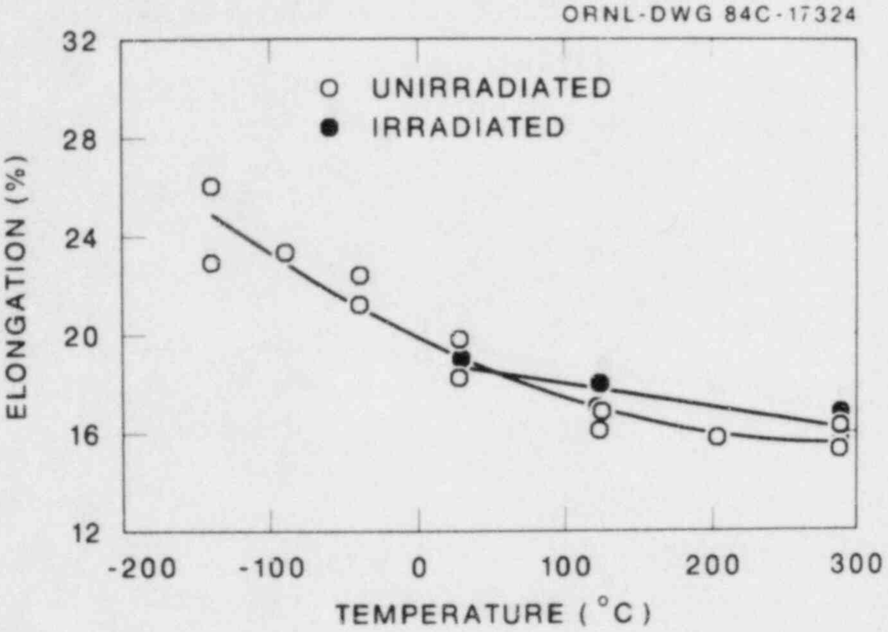

Fig. 10. Total elongation of irradiated and unirradiated weld 70W.

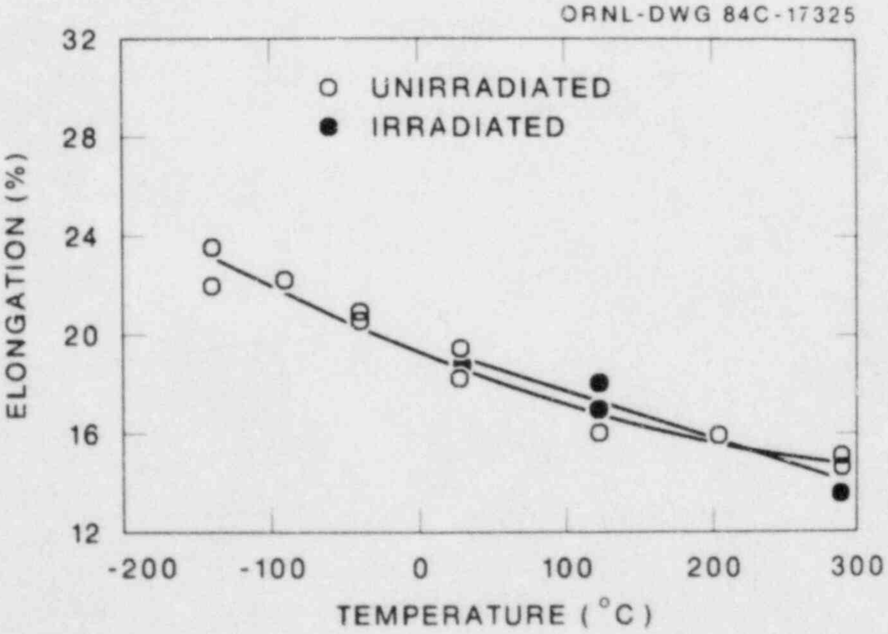

Fig. 11. Total elongation of irradiated and unirradiated weld 71W.

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_2	c_0	c_1
68W	17.14	−0.0170	3.604E-5	15.04	+0.0016
69W	16.23	−0.0224	6.106E-5	16.06	−0.0078
70W	19.83	−0.0293	5.119E-5	18.95	−0.0095
71W	19.24	−0.0239	2.861E-5	19.61	−0.0191
Plate 02	17.33	−0.0279	6.922E-5	17.15	−0.0085

[a] Where $\varepsilon_T = c_0 + c_1T + c_2T$ with ε_T^2 in percent and T in degrees C.

Table 8. Average total elongation[a]

Material	$\varepsilon_{T,U}$ (%)	$\varepsilon_{T,I}$ (%)	$\varepsilon_{T,I} - \varepsilon_{T,U}$ (%)
Plate 02	15	16	+1
Weld 68W	16	15	−1
Weld 69W	15	15	0
Weld 70W	17	17	0
Weld 71W	16	17	+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.

In a previous experiment, irradiation of welds with high copper content (0.2–0.35 wt %) increased the yield strength 20 to 30% over that of unirradiated welds.[3] The relatively low-copper (0.04–0.12 wt %) welds in the experiment reported here increased 10 to 20% in yield strength with respect to the unirradiated condition. In both studies irradiation did not affect the tensile ductility significantly.

CONCLUSIONS

Irradiation at fluences in the range 7×10^{22} to 20×10^{22} neutrons/m^2 (>1 MeV) strengthened all four weld materials, with the yield strength increases (12 to 19%) being greater than the ultimate strength increases (3 to 9%). The plate studied was strengthened more than the welds were, probably because of higher copper and nickel contents.

Irradiation did not significantly affect the tensile elongation of any of the materials.

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The Heavy Section Steel Technology (HSST) program office conducted a series of experiments to determine the effect of neutron irradiation on the fracture toughness of nuclear pressure vessel materials. One plate (HSST plate 02) and four welds of A 533 grade B class 1 steel were examined. The welds were made by current (about 1979) practice.

As part of this study, tensile properties were measured after irradiation to 2×10^{23} neutrons/m^2 (>1 MeV) at 288°C. The strength of all four welds increased with irradiation. Yield strength was about 10% more sensitive to irradiation than was ultimate strength. Tensile ductility was not affected significantly by irradiation.

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