CONF-920673 23
JUL 29 1983
OSTI

**EFFECTS OF IRRADIATION TEMPERATURE ON CHARPY
AND TENSILE PROPERTIES OF HIGH-COPPER,
LOW UPPER-SHELF, SUBMERGED-ARC WELDS***

Randy K. Nanstad and Reynold G. Berggren

Metals and Ceramics Division
OAK RIDGE NATIONAL LABORATORY
P.O. Box 2008
Oak Ridge, TN 37831-6151

*Research sponsored by the Office of Nuclear Regulatory Research,
U.S. Nuclear Regulatory Commission, under Interagency Agreement
DOE 1886-8109-8L with the U.S. Department of Energy under contract
DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

The submitted manuscript has been authored
by a contractor of the U.S. Government under
contract No. DE-AC05-84OR21400.
Accordingly, the U.S. Government retains a
nonexclusive, royalty-free license to publish or
reproduce the published form of this
contribution, or allow others to do so, for U.S.
Government purposes.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

MASTER

da
DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Randy K. Nanstad¹ and Reynold G. Berggren²

**EFFECTS OF IRRADIATION TEMPERATURE ON CHARPY AND TENSILE PROPERTIES
OF HIGH-COPPER, LOW UPPER-SHELF, SUBMERGED-ARC WELDS**

REFERENCE: Nanstad, R. K., and Berggren, R. G., "Effects of Irradiation Temperature on Charpy and Tensile Properties of High-Copper, Low Upper-Shelf, Submerged-Arc Welds," *Effects of Radiation on Materials: 16th. International Symposium, ASTM STP 1175*, Arvind S. Kumar, David S. Gelles, Randy K. Nanstad, and Edward A. Little, Editors, American Society for Testing and Materials, Philadelphia, 1993.

ABSTRACT: The Heavy-Section Steel Irradiation Program conducted the Second and Third Irradiation Series to investigate the effects of irradiation on the ductile fracture toughness of seven commercially fabricated low upper-shelf welds. All seven submerged-arc welds were fabricated with copper-coated wire and Linde 80 flux and have average bulk copper contents ranging from 0.21 to 0.42% with nickel levels of about 0.6%. The preirradiation upper-shelf energies range from 74 to 111 J (55-82 ft-lb). Compact specimens up to 101.6 mm (4 in.) thick, 4TC(T), were irradiated at nominally 288°C in the Bulk Shielding Reactor at Oak Ridge National Laboratory to fluences ranging from about 4 to 12×10^{18} neutrons/cm² (>1 MeV). Charpy V-notch and tensile specimens were included in the capsules at available locations which were subject to wide variations in irradiation temperature and fluence.

This paper presents analyses of the Charpy impact and tensile test data, including adjustments for irradiation temperature and fluence normalization which make possible comparison of the irradiation sensitivity of the different welds. Analyses revealed a dependence of yield and ultimate strength on irradiation temperature of -1.1 and -0.8 MPa/°C, respectively. Similarly, the Charpy impact energy changes due to irradiation temperature were -0.5°C/°C for transition temperature shift and -0.05 J/°C for the upper-shelf energy decrease. After adjustment to an irradiation temperature of 288°C and normalization to a fluence of 8×10^{18} neutrons/cm², percentage increases in yield strength due to irradiation ranged from about 21 to 35% while those for ultimate strength ranged from about 13 to 20%. The Charpy transition temperature shifts ranged from 59 to 123°C while the postirradiation upper-shelf energies ranged from 58 to 79 J.

KEYWORDS: Charpy V-notch impact, copper content, fracture toughness, irradiation, irradiation temperature, light-water reactors, Linde 80 flux, neutron fluence, reactor pressure vessels, submerged-arc welds, surveillance, tensile strength, transition temperature shift, upper-shelf energy drop, yield strength

¹Leader of Fracture Mechanics Group, Metals and Ceramics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831-6151.

²Retired from Oak Ridge National Laboratory.

Prevention of reactor pressure vessel (RPV) failure in light-water moderated nuclear power reactors depends primarily on maintaining the RPV material fracture toughness at levels that will resist fracture, either brittle or ductile, during plant operation, including normal and emergency conditions. When RPV steels exhibit Charpy V-notch (CVN) upper-shelf energy levels of less than 68 J, the requirements of *Title 10, Code of Federal Regulations, Part 50 (10CFR50)*, Appendix G [1] are not met. The regulations require, as an option, that a fracture mechanics analysis be performed that conservatively demonstrates adequate safety margins for continued operation. An acceptable method of analysis is described in the report [2] covering Generic Safety Issue A-11 on Reactor Vessel Materials Toughness. In resolving this issue, the U.S. Nuclear Regulatory Commission (NRC) has suggested that, under elastic-plastic conditions, the vessel be evaluated in terms of the tearing instability concept of Paris et al. [3]. Merkle has recently provided an overview of the safety margin issue associated with low upper-shelf toughness materials in RPVs [4].

A number of reactor vessels in commercial pressurized water reactor plants fabricated by Babcock and Wilcox Co. (B&W) include welds with both relatively low initial Charpy upper-shelf energies and high copper concentrations that make them highly sensitive to neutron irradiation. As a result the Charpy upper-shelf energies of many welds are expected to fall below 68 J (50 ft-lb) prior to reaching design life. The Heavy-Section Steel Technology (HSST) Program Second and Third HSST Irradiation Series (now designated the Heavy-Section Steel Irradiation (HSSI) Program Second and Third Irradiation Series) were conducted to examine irradiation effects on the elastic-plastic fracture toughness of such welds. This paper presents results from these irradiation experiments with seven "low upper-shelf" weld metals and incorporated tensile and CVN impact tests. A more detailed presentation is given in ref. 5 while ref. 6 provides a summary of all the irradiation series conducted under the HSST Program.

EXPERIMENT CONCEPT

The materials for these experiments were chosen to represent critical early (before 1972) RPV welds, i.e., they should have CVN upper-shelf energy levels of about 68 J (50 ft-lb) after irradiation. The largest practical fracture toughness specimen that could be irradiated, considering many factors, was a 101.6-mm-thick compact specimen [4TC(T)] [7]. (The irradiation capsules were rotated 180° during the irradiation period to keep the neutron fluence distribution in the large specimens as symmetrical as possible.) In addition to the 4TC(T) fracture toughness specimens, 0.5, 0.8, and 1.6TC(T) (12.7, 20.3, and 40.6 mm thick, respectively), CVN and tensile specimens were included in the irradiation capsules to provide data on size effects and facilitate correlation of tearing resistance with Charpy upper-shelf results. Charpy and tensile specimens were installed in the notches and loading holes of the 4TC(T) specimens to conserve irradiation space. The irradiations were conducted in the Bulk Shielding Reactor at ORNL, a 2-MW pool-type reactor. The target fast neutron fluence was 1×10^{19} neutrons/cm² (>1 MeV) at an irradiation temperature of 288°C (550°F).

MATERIALS

The seven submerged-arc welds in this study, identified as HSST 61W through 67W, were fabricated with materials and procedures used in early pressurized-water reactor (PWR) pressure vessels. These welds had average copper levels ranging from 0.21 to 0.42% with nickel levels of around 0.6% and, thus, were considered "sensitive" to neutron irradiation embrittlement and typical of some early pressure vessel welds. The use of Linde 80 flux produced welds with large contents of

very small inclusions. Although this results in the welds having improved radiographs, they will have relatively low upper-shelf Charpy energies in the unirradiated condition. All seven welds were made with 3.17-mm-diam (0.125-in.) MnMoNi copper-coated wire. Complete welding parameter information was supplied only for weld HSST 62W [8]. The following welding parameters were employed for this weld:

Preheat temperature: 121 to 204°C (250-400°F)
Interpass temperature: 149 to 260°C (300-500°F)
Amperage: 450 to 540 A
Voltage: 30 to 34 V
Travel speed: 254 to 305 mm/min (10-12 in./min)

Although complete welding parameter information for the other welds is not available, it may be assumed that they are close to the above parameters. The welding of all welds was an automatic single-wire submerged-arc process (multiple pass).

Postweld stress relief treatments were as follows [9]:

<u>Weld</u>	<u>Stress Relief</u>
61W	25 h at 593 to 621°C (1100-1150°F)
62W	8 cycles of 6 h at 593 to 621°C (1100-1150°F)
63W	48 h at 593 to 621°C (1100-1150°F)
64W	48 h at 593 to 621°C (1100-1150°F)
65W	80 h at 593 to 621°C (1100-1150°F)
66W	48 h at 593 to 621°C (1100-1150°F)
67W	not available

Chemical compositions for the welds are presented in Table 1. For 62W, one weld wire (A) was used for a fraction of the through-thickness weld, while a different weld wire (B) was used for the remainder. All Charpy and tensile test specimens were machined from weld wire B (HSST 62WB) and no Charpy data for weld wire A (HSST 62WA) are available.

SPECIMEN DESIGNS AND WELDMENT CUTTING

All test specimens were prepared by the suppliers (Westinghouse Electric Corp. and B&W). The miniature tensile test specimens are shown in Fig. 1 and were designed to the overall size of a Charpy test specimens to fit into the irradiation capsules. Two lengths of specimens were used to fit in the available spaces in the irradiation capsules. The Charpy specimens were ASTM standard CVN impact specimens (type A).

IRRADIATION CAPSULE DESIGN AND OPERATION

The design of the irradiation capsules was based on the design of the capsules used in the First HSST Irradiation Series [7,10] conducted by Westinghouse Electric Corp. at the Battelle Research Reactor (BRR). Because of neutron flux gradients through the 101.6-mm (4-in.) thickness of the largest specimens, the capsule design provided for 180° rotation of the capsules periodically during the irradiations. This rotation was scheduled to provide the same neutron fluences on both faces of the 4TC(T) specimens. The capsules were exposed in the original orientation for the first 40% of the total irradiation period, exposed in the 180° rotated position for an additional 50% of the total irradiation period, and back to the original position for the final 10% of the total irradiation period. The resulting fast neutron fluence profile at the crack front of a 4TC(T) specimen revealed a through-thickness deviation of about ±20%. Each capsule also contained an array of neutron activation dosimeters to provide postirradiation fluence data. The neutron flux for the specimens varied dependent on location in the capsule but averaged about 1×10^{12} neutrons/cm² (>1 MeV) [11].

TABLE 1--Chemical composition of HSSI welds 61W through 67W

Weld	Average ^a composition (wt %)									
	C	Mn	P	S	Si	Cr	Ni	Mo	Cu	V
61W	0.09	1.48	0.020	0.014	0.57	0.16	0.63	0.37	0.23	0.005
	0.07	1.45	0.018	0.014	0.55	0.16	0.62	0.36	0.26	0.005
	0.10	1.52	0.021	0.015	0.58	0.17	0.64	0.38	0.31	0.005
62W ^b	0.083	1.51	0.016	0.007	0.59	0.120	0.537	0.377	0.210	0.010
	0.078	1.41	0.013	0.007	0.55	0.067	0.490	0.365	0.160	0.010
	0.088	1.61	0.020	0.008	0.63	0.173	0.585	0.390	0.260	0.011
62WA ^b	0.083	1.51	0.013	0.007	0.59	0.075	0.510	0.377	0.200	0.010
	0.078	1.41	0.012	0.007	0.55	0.070	0.480	0.365	0.140	0.010
	0.088	1.61	0.014	0.008	0.63	0.090	0.540	0.390	0.270	0.011
62WB ^b	0.083	1.51	0.018	0.007	0.59	0.170	0.550	0.377	0.177	0.011
	0.078	1.41	0.016	0.007	0.55	0.160	0.540	0.365	0.160	0.010
	0.088	1.61	0.020	0.008	0.63	0.180	0.600	0.390	0.230	0.012
63W	0.098	1.65	0.016	0.011	0.630	0.095	0.685	0.427	0.299	0.007
	0.088	1.62	0.015	0.010	0.580	0.073	0.663	0.415	0.272	0.006
	0.109	1.67	0.017	0.013	0.675	0.118	0.707	0.440	0.326	0.008
64W	0.085	1.59	0.014	0.015	0.520	0.092	0.660	0.420	0.350	0.006
	0.070	1.54	0.012	0.014	0.445	0.074	0.600	0.410	0.310	0.005
	0.100	1.64	0.017	0.016	0.600	0.110	0.720	0.430	0.390	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	1.42	0.014	0.013	0.450	0.076	0.585	0.370	0.180	0.005
	0.090	1.49	0.017	0.017	0.610	0.100	0.610	0.400	0.250	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	1.59	0.017	0.009	0.480	0.090	0.580	0.380	0.350	0.007
	0.010	1.67	0.020	0.010	0.600	0.120	0.610	0.420	0.490	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	1.40	0.010	0.012	0.410	0.067	0.580	0.370	0.220	0.005
	0.095	1.48	0.013	0.013	0.590	0.110	0.600	0.410	0.310	0.010

^aTop entry is the average value, while numbers shown below each entry indicate the range of composition measurements.

^bWeld 62W is a duplex weld with designations 62WA and 62WB (see text).

FIG. 1--Tensile specimen configurations used in the Second and Third HSSI Irradiation Series.

The subcapsules installed in the notches of the 4TC(T) specimen contained 0.5TC(T), CVN, and tensile specimens. The primary temperature control was at the fatigue crack front of the 4TC(T) specimens. Since there was no independent control of temperatures for the small specimens, they operated at temperatures above or below the desired temperatures, depending on their location in the capsules and the degree of thermal contact between them and the 4TC(T) specimens. An extreme example of temperature distribution in a capsule is shown in Fig. 2. Temperatures in this capsule ranged from 238 to 346°C (460-655°F) in the forward position and from 254 to 340°C (490-645°F) in the reverse position. Although the temperatures in the central region of the 4TC(T) crack fronts are near the desired 288°C (550°F), the extreme temperatures were recorded for the small specimens. Thus, the irradiation temperature for each specimen is an average of the temperatures experienced in the forward and reverse positions. The temperature variation for some specimens was as much as $\pm 25^{\circ}\text{C}$ ($\pm 45^{\circ}\text{F}$), but a more typical variation was $\pm 8^{\circ}\text{C}$ ($\pm 15^{\circ}\text{F}$). Because irradiation embrittlement is dependent on irradiation temperature, these variations would affect the results. In this study, however, no attempt was made to account for the variable temperature exposures for the individual specimens. Additional details of capsule design and operation are contained in ref. 5.

TEST PROCEDURES

Tensile tests of specimens from the Second HSSI Irradiation Series (welds HSST 61W, 62W, and 63W) were conducted by Hanford Engineering Development Laboratory (HEDL) and tests from the Third HSSI Irradiation Series (welds HSST 64W, 65W, 66W, and 67W) were conducted by Oak Ridge National Laboratory (ORNL). Reference 12 provides details of test procedures and results for the fracture toughness tests.

Tensile Tests

The tensile test procedures used by HEDL for specimens of welds HSST-61W, -62W, and -63W, and by ORNL for HSST-64W, -65W, -66W, -67W, are given elsewhere [13,14]. Tests at HEDL on both unirradiated and irradiated specimens were conducted at room temperature, 149, and 288°C using an extensometer. Specimen strain rates calculated from extensometer data were in the range of 10^{-4} to $10^{-3}/\text{s}$. Tests at ORNL

FIG. 2--Extreme example of wide temperature distribution in one capsule of the Second HSSI Irradiation Series, forward position.

were conducted at the same temperatures used for the HEDL tests. An extensometer was not used and yield strengths were based on crosshead displacement data. Errors in yield strength values determined from crosshead displacement were established to be less than 3% by use of an extensometer at room temperature [14]. Specimen strain rates, based on crosshead displacements, were 2.7 to $2.9 \times 10^{-4}/s$.

Charpy V-Notch Impact Tests

Charpy V-notch impact tests were conducted by ORNL in accordance with ASTM Standard Practice E 184. The testing machines were calibrated using standard specimens [15] and were instrumented to provide load-time records for each test. In addition to visual estimation of percent ductile fracture, the load-time records were used to estimate the percent ductile fracture in each specimen through a correlation with the fast load drop [16,17]. In order to compare impact machines, the hot cell machine was also used for some of the unirradiated specimens.

RESULTS AND DISCUSSION

Tensile Tests

Table 2 provides a summary of the unirradiated results by test temperature for each weld. As stated earlier, the irradiation temperatures for the various tensile specimens were quite varied. Because the normal operating temperature of RPVs is considered to be $288^{\circ}C$, the tensile data were analyzed to allow for estimates of the irradiation-induced increases in the yield and ultimate strengths at the irradiation temperature of $288^{\circ}C$. Not all of the welds were represented by adequate numbers of test results for such analysis. To provide a comprehensive analysis of all the tensile results for the seven welds, the room temperature results for 61W through 63W were used to obtain average changes vs irradiation temperature. The resulting average changes were -1.15 MPa/ $^{\circ}C$ for yield strength, -0.79 MPa/ $^{\circ}C$ for ultimate strength, and $-0.014\%/^{\circ}C$ for total elongation. Table 3 provides a summary of the irradiated tensile results for each weld adjusted to an irradiation temperature of $288^{\circ}C$. The results not annotated by a note were taken directly from the actual value obtained from the regression analysis. The annotated results were obtained by adjusting the observed test results for irradiation temperature using the multipliers given above.

Then, because the available data were not generally adequate for fluence normalization using the individual data points as described earlier, all the data from Table 3 were adjusted to a fluence of 8×10^{18} neutrons/cm². Using the typical square root dependence on fluence [18] for the irradiation-induced yield strength change resulted in strength increases that did not appear reasonable. Thus, the irradiation-induced yield strength changes obtained at an irradiation temperature of $288^{\circ}C$ ($\pm 4^{\circ}C$) were plotted vs neutron fluence and fit to a power curve. The result showed a very low dependence on fluence for these welds over the fluence range examined (4.5 to 11.4×10^{18} neutrons/cm² (>1 MeV)). The exponent obtained by the analysis was 0.07 and the differences in strength (the ultimate strength changes were normalized using the same factor) between the unirradiated values in Table 2 and the irradiated values in Table 3 were multiplied by the factor, $(8 \times 10^{18}/\text{Average Fluence})^{0.07}$. In this way, a consistently analyzed set of tensile results are presented in Table 4 for all seven welds and represent best estimates of the tensile properties for welds 61W through 67W irradiated at $288^{\circ}C$ to a fluence of 8×10^{18} neutrons/cm². The fluences are varied and the average values are given in Table 3. Figure 3 shows a plot of the normalized results compared to the unirradiated curves for weld 61W. The total elongation results were not normalized for fluence. Similar plots for the other welds are given in ref. 5.

**TABLE 2--Summary of unirradiated tensile results
for HSSI welds 61W through 67W**

Weld	Test temperature (°C)	Strength (MPa)		Uniform strain (%)	Reduction in area (%)	Total elongation (%)
		Yield	Ultimate			
61W	26	480	599	10.4	65.8	18.4
	149	444	548	8.3	65.4	17.7
	288	418	536	7.0	63.8	16.0
62W	26	473	591	9.9	66.0	18.8
	149	428	534	9.4	68.6	15.8
	288	385	514	8.0	63.5	14.7
63W	26	482	600	10.2	66.4	20.4
	149	432	545	8.6	67.2	18.0
	288	410	530	7.6	63.4	16.6
64W	27	465	580	9.9	64.8	18.9
	150	417	530	9.7	66.5	17.8
	288	398	543	8.9	54.7	15.4
65W	27	457	571	9.7	65.1	18.1
	150	423	533	7.7	64.2	15.3
	288	412	549	8.2	58.0	14.8
66W	27	534	639	7.6	63.4	16.0
	150	506	597	6.7	64.2	14.1
	288	498	608	6.6	46.6	12.2
67W	27	462	583	9.4	66.5	17.9
	150	429	542	6.8	65.5	14.3
	288	430	562	9.9	57.9	13.5

The final adjusted results were all fit with second-order polynomials and the curve fit coefficients are given in ref. 5. Table 5 provides a summary of the radiation-induced changes in the yield and ultimate strengths of those welds, expressed both in terms of the measured strength changes and as percentage changes at the three nominal test temperatures. As the table shows, irradiation-induced strength increases at room temperature range from 107 to 162 MPa for yield strength and from 86 to 123 MPa for ultimate strength. Relative to the unirradiated strengths, those changes represent increases of 20.8 to 35.1% for yield strength and 13.5 to 20.5% for ultimate strength. Thus, the changes in yield strength were greater than those for ultimate strength, as is usually observed.

Charpy V-Notch Impact Tests

As mentioned earlier, some unirradiated specimens from each weld were tested on the machine in the hot cell to allow for a determination of machine differences. Figure 4 shows a plot of the CVN energy vs test temperature for unirradiated weld 61W. The curves shown are fits to each data set using a hyperbolic tangent function that includes partial

TABLE 3--Summary of irradiated tensile results for HSSI welds 61W through 67W adjusted to an irradiation temperature of 288°C

Weld	Test temperature (°C)	Fluence (n/cm ² × 10 ⁻¹⁸)	Number of tests	Strength ^a (MPa)		Total elongation ^a (%)
				Yield	Ultimate	
61W	30	9.2	6	628	723	17.7
	150	11.9	1	562 ^b	663 ^b	17.3 ^b
	288	9.5	2	527	647	16.4
62W	30	11.4	5	606	697	19.0
	150	10.2	2	537 ^c	631 ^c	15.4 ^c
	288	9.3	2	479 ^c	605 ^c	15.4 ^c
63W	30	9.0	6	619	709	16.9
	150	13.1	1	576 ^d	675 ^d	15.6 ^d
	288	8.3	2	523	640	16.9
64W	30	4.6	2	596	691	17.1
	150	6.4	1	506 ^e	614 ^e	14.6 ^e
	288	4.5	3	526	658	12.8
65W	30	4.8	2	560	660	18.4
	150	4.9	2	467	623	16.3
	288	5.2	3	508	638	15.6
66W	30	6.4	2	643 ^f	724 ^f	16.4 ^f
	150	6.0	2	596 ^g	684 ^g	13.2 ^g
	288	7.0	2	582	683	10.7
67W	30	1.8	1	608 ^h	687 ^h	15.3 ^h
	150	4.8	2	552 ⁱ	645 ⁱ	13.6 ⁱ
	288	6.9	3	531	656	13.3

^aInsufficient data for regression at the irradiation temperatures indicated below. Results shown were adjusted by -1.146 MPa/°C for yield strength, -0.7907 MPa/°C for ultimate strength, and -0.0136%/°C for total elongation.

^b277°C.
^c272°C.
^d279°C.
^e273°C.
^f280°C.
^g284°C.
^h284°C.
ⁱ282°C.

TABLE 4--Summary of irradiated tensile results for HSSI welds 61W through 67W adjusted to an irradiation temperature of 288°C and fluence of 8×10^{18} neutrons/cm²

Weld ^a	Test temperature (°C)	Number of tests	Strength (MPa)		Total elongation ^b (%)
			Yield	Ultimate	
61W	30	6	626	722	17.7
	150	1	559	660	17.3
	288	2	526	646	16.4
62W	30	5	603	694	19.0
	150	2	535	630	15.4
	288	2	478	604	15.4
63W	30	6	618	708	16.9
	150	1	571	671	15.6
	288	2	523	640	16.9
64W	30	2	601	695	17.1
	150	1	507	615	14.6
	288	3	531	663	12.8
65W	30	2	564	663	18.4
	150	2	468	626	16.3
	288	3	511	641	15.6
66W	30	2	645	725	16.4
	150	2	598	686	13.2
	288	2	583	684	10.7
67W	30	1	624	698	15.3
	150	2	557	649	13.6
	288	3	532	657	13.3
^a For actual neutron fluences, see Table 3. ^b Not normalized for fluence.					

differentials to allow for a sloping upper shelf. As expected, the curve using all the data falls between the other two curves. The upper-shelf energy determined on the hot cell machine was 85 J compared to about 96 J determined on the laboratory machine. Similar analyses were performed for welds 62W through 67W and the results showed the same consistent trends. Both machines met the calibration requirements [15] and the reasons for these consistent machine differences were not ascertained. The 41-J transition temperatures are varied and, because testing in the lower transition region was limited, a comparison is not considered very reliable. Even so, the differences that do result are less than about 20°C.

FIG. 3--Average of irradiated yield and ultimate strengths for HSSI weld 61W after adjustment for irradiation temperature to 288°C and normalized to a fluence of 8×10^{18} neutrons/cm² (<1 MeV). The unirradiated curves are shown for comparison and the equations of fit shown in the legend are represented by the curves drawn on the graph.

TABLE 5--Summary of irradiation effects on tensile properties of HSSI welds 61W through 67W adjusted to an irradiation temperature of 288°C and a fluence of 8×10^{18} neutrons/cm²

Weld	Strength change, MPa (%)					
	Yield			Ultimate		
	30°C	150°C	288°C	30°C	150°C	288°C
61W	146 (30.4)	115 (25.9)	108 (25.8)	123 (20.5)	112 (20.4)	108 (20.5)
62W	130 (27.5)	107 (25.0)	93 (24.1)	103 (17.4)	95 (17.8)	90 (17.5)
63W	136 (28.2)	139 (32.2)	113 (27.6)	108 (18.0)	126 (23.1)	110 (20.7)
64W	136 (29.2)	90 (21.6)	133 (33.4)	115 (19.8)	85 (16.0)	120 (22.1)
65W	107 (23.4)	45 (10.6)	99 (24.0)	92 (16.1)	93 (17.4)	92 (16.7)
66W	111 (20.8)	92 (18.2)	85 (17.1)	86 (13.5)	89 (14.9)	76 (12.5)
67W	162 (35.1)	138 (32.2)	102 (23.7)	115 (19.7)	107 (19.7)	95 (16.9)

FIG. 4--Unirradiated Charpy V-notch impact energy vs test temperature for HSSI weld 61W showing comparison between laboratory test machine and hot cell machine. The curves shown are best fits using a hyperbolic tangent with the lower shelf fixed at 3 J and a sloping upper shelf.

Because large differences between laboratory and hot cell machine data on the ductile shelf exist for many of the welds, the hot cell machine data will be used as the reference data for unirradiated results. Table 6 provides the upper-shelf energies at 200°C and the 41-J transition temperatures for each weld. The 41-J transition temperatures vary from -41 to 13°C (-42 to 55°F) while the ductile shelf energies vary from 74 to 111 J (55-82 ft-lb). The lowest unirradiated ductile shelf energy of 74 J (55 ft-lb) was exhibited by weld 66W and is only slightly above the 68-J (50 ft-lb) minimum required by 10CFR50 for irradiated material. The current minimum unirradiated upper-shelf energy required in 10CFR50 is 102 J (75 ft-lb). Welds 64W, 65W, and 67W are the only welds that meet that minimum and are at or only slightly above the 102-J level.

TABLE 6--Summary of Charpy 41-J temperature and upper-shelf energy for unirradiated HSSI welds 61W through 67W

Weld	Charpy impact parameters			
	41-J temperature		Upper-shelf energy	
	(°C)	(°F)	(J)	(ft-lb)
61W	-17	1	85	63
62W	-13	9	94	69
63W	-26	-15	90	66
64W	7	45	102	75
65W	-24	-11	111	82
66W	13	55	74	55
67W	-41	-42	103	76

The irradiated CVN tests were all conducted in the hot cell on the same machine used for the previously presented unirradiated hot cell tests. The irradiated tests were grouped according to irradiation temperature and the data for each weld were separated according to either transition region tests or ductile shelf tests (zero fast load drop). Some groups have only one specimen. Within each group, there are also fluence variations. Figures 5(a) through 5(f) show plots of the irradiated CVN results for weld 61W. The plot with all the data [Fig. 5(a)] shows the large variability through the test temperature range, while Figs. 5(b) through 5(f) show the data for each group by irradiation temperature. The curve shown in each plot is the hyperbolic tangent fit to the unirradiated data obtained in the hot cell. For welds 62W through 67W, similar plots were produced and are available in ref. 5.

The data from each irradiated weld were not fit with curves because of the variations in irradiation temperature and neutron fluence. To account for fluence differences, each test result was normalized to a fluence of 8×10^{18} neutrons/cm². For the transition region data, the normalization was performed by multiplying the observed transition temperature increase (ΔT) for each test result [e.g., the temperature difference between the irradiated result and the reference curve for the unirradiated material at the energy level measured as shown in Fig. 5(d)] by the square root of the ratio of 8×10^{18} neutrons/cm² to the fluence of the test specimen. An exponent of 0.5 was used because that is a typical value for the Charpy shift dependence on fluence for pressure vessel steel welds irradiated in test reactors [18]. For example, for specimen 61224 the fracture energy was 51.5 J. At that energy level, the temperature increase relative to that of the hyperbolic tangent curve for unirradiated 61W was 70.1°C. After normalization, the temperature increase is 68.9°C. Normalization decreased the transition temperature change because the fluence for that specimen was greater than 8×10^{18} . For specimens with fluences lower than 8×10^{18} , the normalized transition temperature will be greater than the observed value. For the upper-shelf data (test results at 100% ductile fracture), the normalization was performed in the same manner except that the observed energy change (in percent) will be normalized to a greater change for specimens with fluences less than 8×10^{18} .

Figure 6(a) shows all the transition temperature region data for 61W plotted as the observed transition temperature increase vs irradiation temperature. The hyperbolic tangent curves for each unirradiated weld (based on the unirradiated specimens tested in the hot cell) are used as the reference curves in all the analyses. Thus, the transition temperature increase for each irradiated test result is relative to the unirradiated curve at the measured energy level. Figure 6(b) is a similar plot using the results normalized for fluence. Although the results are somewhat scattered, the trend is certainly one of lower transition temperature increases with higher irradiation temperatures. Figures 6(c) and 6(d) are similar plots for the decrease in ductile shelf energy (percent change). As expected, the effects of irradiation on the ductile shelf energy become less at higher irradiation temperatures. Except for the normalized upper-shelf data for 63W and the normalized transition region data for 64W, the results for all the welds show the same trends of decreasing effects of irradiation with increasing irradiation temperature.

As with the tensile results, the CVN data were analyzed to allow for estimates of the transition temperature and ductile shelf energy changes at an irradiation temperature of 288°C. For 61W, for example, this analysis required fitting the observed and normalized results and extrapolating to 288°C. For other welds, interpolation was used. Both linear and quadratic fits were performed but the range of irradiation temperatures for most of the welds was too small for the quadratic

FIG. 5--Irradiated Charpy V-notch impact energy vs test temperature for HSSI weld 61W irradiated at various temperatures, (a) all tests, (b) 298°C, (c) 311°C, (d) 323°C, (e) 329°C, and (f) 345°C. The curves show the hyperbolic tangent fit to the data for the unirradiated specimens tested with the hot cell machine.

FIG. 5--(continued)

FIG. 5--(continued)

FIG. 6--Radiation-induced change in Charpy V-notch impact toughness for HSSI weld 61W, (a) transition temperature increase vs irradiation temperature for all data, (b) transition temperature increase vs irradiation temperature for data normalized to 8×10^{18} neutrons/cm² (>1 MeV), (c) upper-shelf energy decrease vs irradiation temperature, and (d) upper-shelf energy decrease vs irradiation temperature for data normalized to 8×10^{18} neutrons/cm² (>1 MeV). All measures of change are relative to the hyperbolic tangent curve fit to the unirradiated data obtained on the hot cell machine. The curves shown are linear fits to the data.

FIG. 6--(continued)

analysis to be meaningful. Thus, linear fits have been used to relate the observed transition temperature increase, ΔT , and the upper-shelf energy decrease, ΔUSE , to irradiation temperature according to

$$\Delta T = A_1 + B_1 T, \text{ } ^\circ\text{C} , \quad (1)$$

and

$$\Delta USE = A_2 + B_2 T, \text{ J} . \quad (2)$$

The normalized transition temperature increase results for 65W, 66W, and 67W show an average standard error value on B_1 of close to one, whereas those for 61W through 64W are much less, indicating a more favorable data set for performing estimations. Using the regression results for 61W through 64W gives average dependencies on irradiation temperature of $-0.413^\circ\text{C}/^\circ\text{C}$ for transition temperature and $-0.058 \text{ J}/^\circ\text{C}$ for upper-shelf energy change. Interestingly, using the observed changes results in average dependencies of $-0.415^\circ\text{C}/^\circ\text{C}$ and $-0.066 \text{ J}/^\circ\text{C}$. Tables 7 and 8 summarize the results of transition temperature increase and upper-shelf energy decrease estimates, respectively. These tables provide the mean fluence, fluence standard deviation, and number of observations in the population for each weld, as well as the estimated changes at an irradiation temperature of 288°C for both the observed and normalized data. Finally, the 41-J temperatures and upper-shelf energies (at 200°C) estimated for an irradiation temperature of 288°C are provided and compared to the estimates from *Regulatory Guide 1.99* (Rev. 2) [19].

Using the linear fits, the transition temperature increases range from 57 to 108°C (103 to 194°F) for the observed results and from 59 to 123°C (106 - 221°F) for the normalized results. Normalization resulted in substantial changes to the estimates for welds 64W through 67W. The mean fluences for those four welds are much further removed from the normalization fluence than are those for 61W through 63W. Regarding the upper-shelf changes, the decreases range from 16.2 to 26.2% for the observed results and from 15.7 to 37.0% for the normalized results. As with the transition region data, the fluences for 64W through 67W were relatively low and normalization resulted in substantial increases in the estimates. It is interesting to compare the estimates derived from these analyses with predictions based on *Regulatory Guide 1.99* (Rev. 2) [19] without the "margin" specified in the *Regulatory Guide*. Tables 7 and 8 give those predictions and show that, for the observed transition temperature increases, the *Regulatory Guide 1.99* predictions exceed the observed results in every case except for 63W where the difference is only 2°C . For the normalized case (i.e., for a fluence of 8×10^{18} neutrons/cm²), the *Regulatory Guide 1.99* predictions exceed the test results in every case except for 63W and 64W. For the upper-shelf energy decreases (percent decrease), the *Regulatory Guide 1.99* predictions exceed the weld results in every case except for 65W. Most of the measured upper-shelf energy decreases for the welds were much less than the *Regulatory Guide 1.99* predictions. The 41-J temperature given for each irradiated weld was calculated by adding the estimated transition temperature increase of the normalized data to the 41-J temperature for the unirradiated results. The results indicate that, for an irradiation temperature of 288°C and a neutron fluence of 8×10^{18} neutrons/cm² ($>1 \text{ MeV}$), the welds in this program would have 41-J temperatures from 46 to 130°C (115 - 266°F) and upper-shelf energies (at 200°C) from 58 to 79 J (43 - 58 ft-lb).

Charpy and Tensile Correlations and Comparisons

Various comparisons of CVN test results were examined for potential use as correlations. Regarding the effects of irradiation temperature on yield strength, Odette and Lucas [20] reported an average change of $-1.8 \text{ MPa}/^\circ\text{C}$ for high-copper alloys irradiated at high fluxes. As presented earlier, the tensile results for the low upper-shelf welds

TABLE 7--Radiation-induced Charpy impact transition temperature results for
HSSI welds 61W through 67W adjusted to irradiation temperature of 288°C

Weld	Observed fluence ^a (n/cm ² × 10 ⁻¹⁶)	Number of tests	Charpy transition temperature increase (°C)				41-J temperature [°C (°F)]	
			Observed fluence		Normalized fluence ^b		Observed	Normalized ^b
			Observed result	RG 1.99 prediction	Observed result	RG 1.99 prediction		
61W	8.14 ± 1.86	24	79	100	74	100	62 (144)	57 (135)
62W	9.37 ± 2.35	19	63	85	59	81	50 (122)	46 (115)
63W	7.75 ± 1.01	22	108	106	112	107	82 (180)	86 (187)
64W	4.00 ± 0.61	23	86	92	123	115	93 (199)	130 (266)
65W	3.65 ± 0.82	10	57	66	74	86	33 (91)	50 (122)
66W	5.25 ± 0.90	6	81	105	104	120	94 (201)	117 (243)
67W	5.20 ± 1.24	7	80	82	92	94	39 (102)	51 (124)

^a±1 standard deviation.

^bNormalized to fluence of 8×10^{16} neutrons/cm².

TABLE 8--Radiation-induced Charpy impact upper-shelf energy results for HSSI welds 61W through 67W adjusted to irradiation temperature of 288°C

Weld	Observed fluence ^a (n/cm ² × 10 ⁻¹⁸)	Number of tests	Charpy upper-shelf decrease						Upper-shelf energy, [J (ft-lb)]	
			Observed result (J)	Normalized ^b result (J)	Observed fluence (%)		Normalized fluence (%)			
					Observed result	RG 1.99 prediction	Observed result	RG 1.99 prediction		
			Observed result	Normalized ^b result	Observed result	RG 1.99 prediction	Normalized result	RG 1.99 prediction	Observed	Normalized ^b
61W	8.32 ± 1.70	35	14.9	13.4	17.7	41	15.8	40	70 (52)	72 (53)
62W	8.93 ± 1.73	40	15.0	14.5	16.2	35	15.7	34	79 (58)	79 (58)
63W	8.34 ± 1.82	39	22.8	21.4	25.6	41	24.0	41	57 (49)	68 (50)
64W	4.05 ± 0.70	38	25.8	36.5	25.3	37	35.8	41	76 (56)	65 (48)
65W	3.72 ± 0.67	51	28.0	39.6	26.2	24	37.0	34	83 (61)	70 (52)
66	5.04 ± 0.72	19	12.0	16.2	16.4	37	22.1	41	62 (46)	58 (43)
67W	5.20 ± 1.75	18	25.0	28.6	25.2	30	28.4	37	78 (57)	74 (55)

^a±1 standard deviation.
^bNormalized to fluence of 8 × 10¹⁸ neutrons/cm².

^a±1 standard deviation.

^bNormalized to fluence of 8 × 10¹⁸ neutrons/cm².

in this study exhibited an average dependence of yield strength on irradiation temperature of $-1.15 \text{ MPa}/^\circ\text{C}$, in reasonably good agreement with the average results of ref. 20 considering the wide variations discussed in their paper.

In ref. 20, Odette and Lucas provide an extensive discussion of the hardening (i.e., increase in yield strength) dependence on neutron fluence. The power law dependencies are quite variable depending on flux, composition, fluence, material form, and irradiation temperature. Although they conclude that an exponent of about 0.5 is a good overall average, they presented data that indicated exponents varying from less than 0.1 to greater than 1. As mentioned earlier, the data in this study were relatively sparse but a power law fit to the yield strength results gave an exponent of about 0.07, quite low compared to the average results in ref. 20 even considering the reported scatter. It is noted, however, that the fluence range for the welds in this study was relatively small, less than one order of magnitude.

Regarding correlations between Charpy impact and tensile data, Odette, Lombrozo, and Wullaert [21] reported an average relationship between Charpy 41-J shift and yield strength increase as

$$\Delta TT_{41} = C * (\Delta \sigma_y) , \quad (3)$$

where the parameter C is about $0.65^\circ\text{C}/\text{MPa}$ for welds. For welds 61W through 67W irradiated at 288°C to a fluence of 8×10^{18} neutrons/cm², the average value of C is $0.70 \text{ MPa}/^\circ\text{C}$ (the individual values ranging from 0.454 to 0.937), in excellent agreement with those of ref. 21.

As discussed earlier, the Charpy impact data obtained at the measured fluences were normalized to a fluence of 8×10^{18} neutrons/cm² using an exponential dependence on fluence of 0.5. That value is reported by Odette and Lucas [18] to be an average result for high flux irradiations in test reactors. It is interesting to note that they report an exponent of 0.18 for welds irradiated in surveillance capsules to intermediate fluences. In the same reference, they report an approximate sensitivity to bulk copper concentration such that

$$\Delta TT_{41} \approx C(\text{Cu} - 0.1)^{0.5} , \quad (4)$$

where $C = 200 \pm 25^\circ\text{C}$. A similar analysis of welds 61W through 67W gives

$$\Delta TT_{41} = 234 * (\text{Cu} - 0.01)^{0.57} , \quad (5)$$

in reasonably good agreement with those of ref. 18.

Regarding the dependence of Charpy impact transition temperature shift on irradiation temperature, Odette and Lucas [18] report changes from -0.4 to $-2^\circ\text{C}/^\circ\text{C}$ with the majority around $-1 \pm 0.2^\circ\text{C}/^\circ\text{C}$. Those results are averaged for all materials over the irradiation temperature range from 250 to 310°C . For the low upper-shelf welds of this study, a similar range of values was found. However, only welds 61W through 64W experienced sufficiently wide ranges of irradiation temperatures for adequate analysis. The average dependence on irradiation temperature for those four welds was determined to be $-0.413 \pm 0.21^\circ\text{C}/^\circ\text{C}$ (± 1 standard deviation). Lowe [22] performed an analysis for welds 61W through 63W and determined a dependence of $-0.668 \pm 0.141^\circ\text{C}/^\circ\text{C}$ (his result was reported as $^\circ\text{F}/^\circ\text{F}$). Using only 61W through 63W in this study yields a dependence of $-0.535 \pm 0.043^\circ\text{C}/^\circ\text{C}$, closer to the value reported by Lowe. In this study, the dependence of upper-shelf energy on irradiation temperature was determined to be $-0.058 \text{ J}/^\circ\text{C}$. Lowe's analysis [22] showed a change of about $-0.23 \text{ J}/^\circ\text{C}$ (he reported $-0.094 \text{ ft-lb}/^\circ\text{F}$). That value is quite different from that determined in this analysis and inspection of the unirradiated upper-shelf energies

used by Lowe show them to be substantially higher than those used in the present study. That undoubtedly reflects the fact that he used all the reported unirradiated Charpy test results as opposed to this study, which used only the lower tending results from the hot cell Charpy impact machine.

Berggren and Stallman [23] performed nonlinear regression analyses of the Charpy data for 61W through 67W and developed model equations dependent on fluence, irradiation temperature, and copper content. Transition temperature and upper-shelf energy regions were fitted separately and linear expressions describing the energy vs test temperature relationship in both the transition and upper-shelf regions for unirradiated results were fitted to the data. For both the transition and upper-shelf regions, the temperature differences between the irradiated data and the linear fit of unirradiated data were entered into the fitting program. The authors note that the models must be applied with caution outside the ranges of the variables within which they were developed.

Heller and Lowe [24] developed models for Linde 80 submerged-arc welds as part of a large study on low upper-shelf welds by B&W. The equation they developed for Charpy shift includes fluence, Cu, and Ni, while that for upper-shelf energy change includes fluence, Cu, Ni, Mo, and Cr.

Tables 9 and 10 provide a comparison between the predictions using the models from Berggren and Stallman [23] and those of Heller and Lowe [24] with the results obtained in this study. All the values shown are based on an irradiation temperature and a fluence of 8×10^{18} neutrons/cm² (>1 MeV). Table 9 shows that, for the transition temperature shift, the model predictions compare fairly well for the seven welds. The mean shifts predicted by the models are less than the results from this study for 63W, 64W, and 67W. For the Heller and Lowe model, the upper tolerance bound would exceed the current results by a large margin. Regarding the upper-shelf energy, Table 10 shows that the Berggren and Stallman model overpredicts the drop for all welds except 65W. The model predictions from Heller and Lowe are mixed, with underpredictions in four cases and overpredictions in three cases. The upper tolerance bound from the latter model would encompass all the results. The two models do not compare very well for the upper-shelf case, probably as a result of the different values used for some of the unirradiated upper-shelf energies. More details concerning these models are presented in ref. 5.

COMPARISON OF TEST REACTOR AND SURVEILLANCE PROGRAMS RESULTS

Comparison of these test reactor irradiation results with those from commercial power reactor surveillance programs is not generally possible because the correspondence between the HSST welds and the B&W weld designations is not presently available. Lowe [22] presented analyses of the data from the Second and Third Irradiation Series and compared the results with several power reactor surveillance program results with the same welds, 63W, 65W, 66W, and 67W. That report listed the surveillance program specimen irradiation temperature as 304°C. A later paper [25] gives the irradiation temperature as 293°C for those same results.

To compare surveillance results with the results from this study, the surveillance results provided by Lowe [22] were adjusted to an effective irradiation temperature of 288°C and an effective fluence of 8×10^{18} neutrons/cm². Table 11 shows the surveillance results before and after adjustment. Since the irradiation temperature was given as 293°C, and using the previously determined temperature dependence of

TABLE 9--Model predictions of Charpy transition temperature shift compared with results for irradiations at 288°C to 8×10^{18} neutrons/cm²

Weld	Content (wt %)			Transition temperature shift (°C)			
	Cu	Ni	P	Result ^a	S-B ^b	H-L ^c	RG 1.99 ^d
61W	0.28	0.63	0.020	74	91	98	100
62W	0.21	0.54	0.016	59	71	72	81
63W	0.30	0.69	0.016	112	94	109	107
64W	0.35	0.66	0.014	123	106	113	115
65W	0.22	0.60	0.015	74	73	84	86
66W	0.42	0.60	0.018	104	123	112	120
67W	0.27	0.59	0.011	92	86	88	94

^aResults from this study.
^bFrom F. W. Stallmann and R. G. Berggren.
^cFrom A. S. Heller and A. L. Lowe, Jr.
^dFrom Regulatory Guide 1.99, Rev. 2, without margin.

TABLE 10--Model predictions of Charpy upper-shelf energy decrease compared with results for irradiations at 288°C to 8×10^{18} neutrons/cm²

Weld	Content (wt %)			Upper-shelf energy decrease (%)			
	Cu	Ni	P	Result ^a	S-B ^b	H-L ^c	RG 1.99 ^d
61W	0.28	0.63	0.020	16	39	25	40
62W	0.21	0.54	0.016	16	32	27	34
63W	0.30	0.69	0.016	24	39	19	41
64W	0.35	0.66	0.014	36	35	23	41
65W	0.22	0.60	0.015	37	29	21	34
66W	0.42	0.60	0.018	22	51	29	41
67W	0.27	0.59	0.011	28	44	23	37

^aResults from this study.
^bFrom F. W. Stallmann and R. G. Berggren.
^cFrom A. S. Heller and A. L. Lowe, Jr.
^dFrom Regulatory Guide 1.99, Rev. 2, without margin.

about -0.5°C/°C, the transition temperature shifts were decreased by 3°C (rounded from 2.5°C). The temperature adjusted values were then normalized for fluence by using the fluence dependence term from Regulatory Guide 1.99 (Rev. 2) [19]. This procedure was used because the Regulatory Guide 1.99 model is based on power reactor surveillance data; the power exponent is about 0.3 rather than the 0.5 value used in this study to adjust the test reactor data. The same procedure was followed for the Charpy upper-shelf energy results except that the irradiation temperature adjustment was based on the previously determined dependence of -0.058 J/°C. As the table shows, the results are mixed for both the transition temperature shifts and upper-shelf energy decreases.

TABLE 11--Comparison of test reactor and power reactor irradiations on Charpy impact toughness for HSSI welds

Weld	Power reactor, observed results				Adjusted results			
					$\Delta T T$ (°C)		$\Delta U S E$ (J)	
	Temperature (°C)	Fluence ($n/cm^2 \times 10^{-18}$)	$\Delta T T$ (°C)	$\Delta U S E$ (J)	Power reactor*	Test reactor	Power reactor*	Test reactor
63W	293	7.8	119	32.5	123	112	32.4	21.4
65W	293	5.1	82	29.8	98	74	34.0	39.6
66W	293	6.6	75	17.6	83	104	18.4	16.2
67W	293	10.3	79	28.5	76	92	26.2	28.6
*Adjusted from observed irradiation temperature to 288°C by $-0.5^\circ C/^\circ C$. Adjusted from observed fluence to 8×10^{18} neutrons/cm ² (>1 MeV) using the fluence dependence factor from Regulatory Guide 1.99, Rev. 2.								

Considering the variations of irradiation temperature and fluence in the Second and Third Irradiation Series experiments, as well as the uncertainties associated with the temperature histories of the surveillance specimens, it is difficult to evaluate the relationship between the test reactor and power reactor surveillance results. As the overall data base for surveillance results increases, the developing view seems to be that a given material irradiated in a power reactor will experience somewhat greater effects of irradiation than the same material irradiated in a test reactor at the same temperature and to the same fluence. In other words, there appears to be a flux effect such that irradiating at lower fluxes produces greater radiation damage [20,21,26,27]. However, that is a complicated phenomenon that may depend on fluence, neutron spectrum, material parameters, etc. The availability of data with which to make direct comparison is very sparse and, thus, comparisons between power reactor and test reactor effects will likely continue to be done from a statistical viewpoint.

SUMMARY AND CONCLUSIONS

The HSSI Second and Third Irradiation Series had the primary objective of investigating the effects of irradiation on the ductile fracture toughness of seven commercially fabricated low upper-shelf submerged-arc welds. All the welds were fabricated with copper-coated weld wire and Linde 80 flux that produced welds having relatively low Charpy upper-shelf energies in the unirradiated condition and relatively high sensitivity to neutron radiation.

Irradiation of the compact specimens at a nominal temperature of 288°C to an average fluence of about 8×10^{18} neutrons/cm² (>1 MeV) was relatively successful. However, the Charpy impact and tensile specimens were located at positions in the capsule where temperature control was less effective and the irradiation temperatures spanned the range 235 to 345°C for those specimens. Additionally, the neutron fluences varied from about 4 to 13×10^{18} neutrons/cm² (>1 MeV). Although not desirable within the intended context of the experiments, those variations did provide the opportunity to investigate the effects of irradiation temperature and fluence (over the ranges observed) on the tensile and Charpy impact properties of these low upper-shelf welds. The data available for such analyses were limited from a statistical viewpoint, yet did allow for some reasonable observations that could be compared

with results from other studies. For most of those comparisons, the Charpy and tensile results were normalized for fluence variations to an average fluence of 8×10^{18} .

It is clear from the results obtained that all the welds experienced significant radiation-induced Charpy impact transition temperature shifts, from 59 to 123°C, and upper-shelf energy decreases, from 16 to 37%. Likewise, the increases in yield and ultimate tensile strengths as a consequence of irradiation were significant, 21 to 35% and 13 to 20%, respectively, at room temperature.

Analyses of the effects of irradiation temperature on tensile properties and Charpy impact data showed that, within the irradiation temperature range experienced by these welds and for a constant fluence, the radiation-induced increase in yield strength changes $-1.15 \text{ MPa/}^\circ\text{C}$, while the ultimate strength and total elongation change $-0.79 \text{ MPa/}^\circ\text{C}$ and $-0.014\%/^\circ\text{C}$, respectively. For the Charpy impact data, the effect of irradiation temperature on transition temperature shift is about $-0.5^\circ\text{C/}^\circ\text{C}$, meaning that a 1°C increase in irradiation temperature will cause a 0.5°C decrease in the transition temperature shift. Likewise, the effect on upper-shelf energy decrease is about $-0.05 \text{ J/}^\circ\text{C}$, meaning that a 1°C increase in irradiation temperature will cause a 0.05-J decrease in the upper-shelf energy drop. A correlation for the seven welds shows that the radiation-induced increase in Charpy transition temperature in degrees Celsius is about 70% that of the yield strength increase in megapascals, i.e., 0.70°C/MPa . Only the yield strength data were analyzed for the dependence on fluence (over a range of less than a factor of 10) and showed a power law exponent of 0.07, which is much lower than that reported for other materials.

A comparison of the Charpy results from this study with those from commercial reactor surveillance programs with the same materials showed mixed results. Out of the four common materials for which results are available, the transition temperature shifts and upper-shelf energy decreases from the surveillance programs, with no adjustments for fluence or irradiation temperature, exceeded those from the test reactor irradiations. From the analyses conducted in this study using all the data for each weld adjusted to a common irradiation temperature and fluence, the surveillance results exceeded those from the test reactor in two cases and vice versa.

The important observations and conclusions that can be stated based on the Charpy impact and tensile results from the HSSI Second and Third Irradiation Series are enumerated below.

1. Analyses of irradiated tensile data showed a dependence on irradiation temperature of $-1.15 \text{ MPa/}^\circ\text{C}$ for yield strength, $-0.79 \text{ MPa/}^\circ\text{C}$ for ultimate strength, and $-0.014\%/^\circ\text{C}$ for total elongation.

2. Analyses of irradiated Charpy data showed a dependence on irradiation temperature of about $-0.5^\circ\text{C/}^\circ\text{C}$ for transition temperature shift and $-0.05 \text{ J/}^\circ\text{C}$ for upper-shelf energy drop.

3. The results indicated that the radiation-induced changes in yield strengths in megapascals and Charpy transition temperature shifts in degrees Celsius for the seven welds can be expressed as $\Delta T_{T_1} = 0.70 \cdot \Delta \sigma_y$.

4. The Charpy results indicated a dependence on copper concentration that can be expressed as $\Delta T_{T_1} = 234 \cdot (\text{Cu} - 0.1)^{0.57}$, where ΔT_{T_1} is degrees Celsius and copper (Cu) is weight percent.

5. Comparison of the Charpy results with data for the same materials irradiated in power reactor surveillance programs showed mixed results with the power reactor changes being greater in some cases and the test reactor changes greater in others.

ACKNOWLEDGMENTS

The authors would like to acknowledge the contributions of Domenic A. Canonico (now with ABB-Combustion Engineering) and G. D. Whitman (now retired) for guidance and leadership in formulating and initiating the program, Walter J. Stelzman (deceased) for assistance with irradiation capsule construction and operation, and T. N. Jones (now retired) for tensile and Charpy testing and hot cell coordination. We also thank William R. Corwin, HSSI Program Manager, and Alfred Taboada, former NRC Technical Monitor, for financial support. Finally, in preparation of the paper, we express our thanks to Julia L. Bishop for manuscript preparation, and John G. Merkle and Fahmy M. Haggag for technical review.

REFERENCES

- [1] *Title 10, Code of Federal Regulations, Parts 0 to 199*, U.S. Government Printing Office, January 1987.
- [2] R. E. Johnson, Ed., *Resolution of the Task A-11 Reactor Vessel Materials Toughness Safety Issue*, Volumes 1 and 2, NUREG-0744 (Rev. 1), U.S. Nuclear Regulatory Commission, October 1982.
- [3] P. C. Paris, H. Tada, A. Zahoor, and H. Ernst, "The Theory of Instability of the Tearing Mode of Elastic-Plastic Crack Growth," pp. 5-36 in *Elastic-Plastic Fracture*, ASTM STP 668, J. D. Landes, J. A. Begley, and G. A. Clarke, Eds., American Society for Testing and Materials, Philadelphia, 1979.
- [4] J. G. Merkle, *An Overview of the Low-Upper-Shelf Toughness Safety Margin Issue*, NUREG/CR-5552 (ORNL/TM-11314), Martin Marietta Energy Systems, Oak Ridge Natl. Lab., Oak Ridge, Tenn., August 1990.
- [5] R. K. Nanstad and R. G. Berggren, *Irradiation Effects on Charpy Impact and Tensile Properties of Low Upper-Shelf Welds, HSSI Series 2 and 3*, NUREG/CR-5696 (ORNL/TM-11804), Martin Marietta Energy Systems, Oak Ridge Natl. Lab., Oak Ridge, Tenn., August 1991.
- [6] R. K. Nanstad, "Summary of the Heavy-Section Steel Technology Program Irradiation Series," pp. 319-53 in *Proceedings of the U.S. Nuclear Regulatory Commission Sixteenth Water Reactor Safety Information Meeting*, Gaithersburg, Maryland, October 24-27, 1988, NUREG/CP-0097, Vol. 2, Office of Nuclear Regulatory Research, Washington, D.C., March 1989.
- [7] S. A. Legge, T. R. Mager, and P. C. Riccardella, "Fracture Toughness Characterization of Irradiated A 533, Grade B, Class 1 Steel Using 4T Compact-Tension Specimens," pp. 25-35 in *Heavy-Section Steel Technology Program Semiann. Prog. Rep. for Period Ending August 31, 1972*, ORNL-4855, Union Carbide Corp. Nuclear Div., Oak Ridge Natl. Lab., Oak Ridge, Tenn., April 1973.
- [8] Babcock and Wilcox Co., Alliance, Ohio, and Lynchburg, Virginia, *An Investigation of Mechanical Properties and Chemistry Within a Thick MnMoNi Submerged Arc Weldment*, EPRI NP-373, Electric Power Research Institute, Palo Alto, Calif., February 1977.

- [9] A. L. Lowe, Jr. and R. R. Seeley, *Description of Weld Materials Furnished for the Second and Third Irradiation Series, Heavy-Section Steel Technology Program*, BAW-1478, Babcock and Wilcox Co., to be published.
- [10] J. A. Williams, *The Irradiated Fracture Toughness of ASTM A533, Grade B, Class 1 Steel Measured with a Four-Inch-Thick Compact Tension Specimens*, HEDL-TME 75-10, Hanford Engineering Development Laboratory, Richland, Washington, January 1975.
- [11] F. W. Stallman and F. B. K. Kam, *Neutron Spectral Characterization of the Second Nuclear Regulatory Commission Heavy Section Steel Technology 4T-CT Irradiation Experiment*, NUREG/CR-0505 (ORNL/NUREG/TM-285), Union Carbide Corp. Nuclear Div., Oak Ridge Natl. Lab., Oak Ridge, Tenn., December 1978.
- [12] A. L. Hiser, F. J. Loss, and B. H. Menke, *J-R Curve Characterization of Irradiated Low Upper Shelf Welds*, NUREG/CR-3506, MEA-2028, U.S. Nuclear Regulatory Commission, Washington, D.C., April 1984.
- [13] J. A. Williams, *Tensile Properties of Irradiated and Unirradiated Welds of A 533 Steel Plate and A 508 Forgings*, NUREG/CR-1158, HEDL-TME 79-51, Hanford Engineering Development Lab., Richland, Washington, January 1980.
- [14] J. J. McGowan, *Tensile Properties of Irradiated Nuclear Grade Pressure Vessel Welds for the Third HSST Irradiation Series*, NUREG/CR-4086 (ORNL/TM-9477), Martin Marietta Energy Systems, Oak Ridge Natl. Lab., Oak Ridge, Tenn., March 1985.
- [15] "Standard Practice for Effects of High-Energy Neutron Radiation on the Mechanical Properties of Metallic Materials, E 706(1B)," E 184-79, in *1989 Annual Book of ASTM Standards*, Vol. 12.02, American Society for Testing and Materials, Philadelphia.
- [16] D. A. Canonico, W. J. Stelzman, R. G. Berggren, and R. K. Nanstad, "Use of Instrumented Charpy Tests to Determine Onset of Upper-Shelf Energy," *Welding Research Supplement*, 85-s-91-s (May 1981).
- [17] R. K. Nanstad, *Characterization of Four Prestressed Concrete Reactor Vessel Liner Steels*, ORNL/TM-7480, Union Carbide Corp. Nuclear Div., Oak Ridge Natl. Lab., Oak Ridge, Tenn., December 1980.
- [18] G. R. Odette and G. E. Lucas, "Irradiation Embrittlement of Reactor Pressure Vessel Steels: Mechanisms, Models, and Data Correlations," pp. 206-41 in *Radiation Embrittlement of Nuclear Reactor Pressure Vessel Steels: An International Review (Second Volume)*, ASTM STP 909, L. E. Steele, Ed., American Society for Testing and Materials, Philadelphia, 1986.
- [19] "Radiation Embrittlement of Reactor Vessel Materials," *Regulatory Guide 1.99*, Rev. 2, U.S. Nuclear Regulatory Commission, Washington, D.C., May 1988.
- [20] G. R. Odette and G. E. Lucas, *Irradiation Embrittlement of Light Water Reactor Pressure Vessel Steels*, EPRI NP-6114, Electric Power Research Institute, Palo Alto, January 1989.

- [21] G. R. Odette, P. M. Lombrozo, and R. A. Wullaert, "Relationship Between Irradiation Hardening and Embrittlement of Pressure Vessel Steels," pp. 840-60 in *Effects of Radiation on Materials: Twelfth International Symposium, ASTM STP 870*, F. A. Garner and J. S. Perrin, Eds., American Society for Testing and Materials, Philadelphia, 1985.
- [22] A. L. Lowe, Jr., "An Evaluation of Linde 80 Submerged-Arc Weld Metal Charpy Data Irradiated in the HSST Program," pp. 201-213 in *Effects of Radiation on Materials: 14th International Symposium, ASTM STP 1046*, Volume II, N. H. Packan, R. E. Stoller, and A. S. Kumar, Eds., American Society for Testing and Materials, Philadelphia, 1990.
- [23] R. G. Berggren and F. W. Stallman, "Statistical Analysis of Pressure Vessel Steel Embrittlement Data," *Trans. Am. Nucl. Soc.* 44, 225-27 (June 1983).
- [24] A. S. Heller and A. L. Lowe, Jr., *Correlations for Predicting the Effects of Neutron Radiation on Linde 80 Submerged-Arc Welds*, BAW-1803, Babcock and Wilcox Co., Lynchburg, Va., January 1984.
- [25] A. L. Lowe, Jr., "Review of B&W Reactor Vessel Irradiated Materials Data," pp. 15-1-15-20 in *15th MPA Seminar*, University of Stuttgart, Federal Republic of Germany, Oct. 5-6, 1989.
- [26] J. F. Perrin, R. A. Wullaert, G. R. Odette, and P. M. Lombrozo, *Physically Based Regression Correlations of Embrittlement Data From Reactor Pressure Vessel Surveillance Programs*, EPRI NP-3319, Electric Power Research Institute, Palo Alto, January 1984.
- [27] W. N. McElroy, R. Gold, R. L. Simons, and J. H. Roberts, "Trend Curve Data Development and Testing," pp. 505-34 in *Influence of Radiation on Material Properties: 13th International Symposium, ASTM STP 956*, F. A. Garner, C. H. Henager, Jr., and N. Igata, Eds., American Society for Testing and Materials, Philadelphia, 1987.

END

DATE
FILMED
10 / 6 / 93