Results of Charpy V-Notch Impact Testing of Structural Steel Specimens Irradiated at $\sim 30^{\circ}\text{C}$ to 1×10^{16} neutrons/cm² in a Commercial Reactor Cavity

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Abstract

A capsule containing Charpy V-notch (CVN) and mini-tensile specimens was irradiated at $\sim 30^{\circ}\text{C}$ ($\sim 85^{\circ}\text{F}$) in the cavity of a commercial nuclear power plant to a fluence of 1×10^{16} neutrons/cm² (> 1 MeV). The capsule included six CVN impact specimens of archival High Flux Isotope Reactor A212 grade B ferritic steel and five CVN impact specimens of a well-studied A36 structural steel. This irradiation was part of the ongoing study of neutron-induced damage effects at the low temperature and flux experienced by reactor supports. The plant operators shut down the plant before the planned exposure was reached. The exposure of these specimens produced no significant irradiation-induced embrittlement. Of interest were the data on unirradiated specimens in the L-T orientation machined from a *single* plate of A36 structural steel, which is the same specification for the structural steel used in some reactor supports. The average CVN energy of five unirradiated specimens obtained from one region of the plate and tested at room temperature was ~ 99 J, while the energy of 11 unirradiated specimens from other locations of the same plate was 45 J, a difference of $\sim 220\%$. The CVN impact energies for all 18 specimens ranged from a low of 32 J to a high of 111 J. Moreover, it appears that the University of Kansas CVN impact energy data of the unirradiated specimens at the 100-J level are shifted toward higher temperatures by about 20 K. The results were an example of the extent of scatter possible in CVN impact testing. Generic values for the CVN impact energy of A36 should be used with caution in critical applications.

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Previous Reports in Series

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This report is designated HSSI Report 15. Reports in this series are listed below:

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Results of Charpy V-Notch Impact Testing of Structural Steel Specimens Irradiated at $\sim 30^{\circ}\text{C}$ to 1×10^{16} neutrons/cm² in a Commercial Reactor Cavity*

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Introduction

Results from Charpy V-notch (CVN) surveillance testing for the High Flux Isotope Reactor (HFIR) performed in 1986 indicated a greater embrittlement of structural steel than was expected.^{1,2} The HFIR surveillance specimens were irradiated at a relatively low temperature and flux, namely $\sim 50^{\circ}\text{C}$ (120°F)[†] and $\sim 10^9$ neutrons-cm⁻²·s⁻¹ (> 1 MeV), respectively. Prototypical reactor pressure vessel (RPV) supports and other structures are sometimes fabricated from A36 steel and subjected to approximately the same low temperature and flux as the HFIR specimens.³ At the time, this raised concerns about the embrittlement of these supports.⁴ As part of the Heavy-Section Steel Irradiation (HSSI) Program investigations on the effects of low-temperature irradiation on structural materials, in early 1990, a capsule containing relevant materials was inserted in the cavity of the commercial Trojan Nuclear Power Plant reactor. Recent data⁵ appear to have resolved the issue of low-temperature, low-flux embrittlement of RPV supports by identifying the anomalously high fast gamma-to-neutron ratio at the HFIR pressure vessel.[‡]

Description of Materials

The capsule contained six A212B ferritic steel and five A36 structural steel CVN specimens, and 44 mini-tensile specimens from these two materials, as well as a 3.5 wt % Ni forging steel conforming to American Society for Testing and Materials (ASTM) A350LF3.[¶] Because of dimensional limitations placed on the capsule, the CVN specimens were made slightly shorter [52.71 mm (2.075 in.)] than the "standard" specimens generally machined [55 mm (2.165 in.)] at Oak Ridge National Laboratory (ORNL). However, the specimen dimensions were still within the tolerances permitted by the *ASTM Recommended Method for Notched Bar Impact Testing of Metallic Materials* (E 23-86) for this specimen, $+0, -2.5$ mm ($+0, -0.100$ in.). Both the A212B plate material and the A350LF3 forging material were from HFIR archival materials and were included as reference materials to correlate the results with previous studies performed on these materials. The A36 structural steel was from the same plate of material characterized in other investigations to be referred to below. The A212B specimens were machined from the HFIR HB2 nozzle dropout archival material that conforms to the *ASTM Specification for High Tensile Strength Carbon-Silicon Steel Plates for Boilers and Other Pressure Vessels* (A 212-54 Grade B).^{††}

The specimen complement placed in the Trojan capsule is given in Table 1, and the chemical compositions of the materials are shown in Table 2. The external dimensions of the mini-tensile specimen holder were the same as

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† Data were generated in English units, and SI values were obtained by conversions; because of round-off, they may not be the exact equivalents.

‡ R. E. Johnson and R. E. Lipinski, *Radiation Effects on Reactor Pressure Vessel Supports*, NUREG-1509 (GSI-15), August 1994 (draft).

¶ *ASTM Standard Specification for Forgings, Carbon, and Low-Alloy, Required Notch Toughness Testing for Piping Components* (A350), in effect at the time of the HFIR construction.

†† Discontinued and replaced by ASTM A 515 and A 516.

Table 1. Specimen complement enclosed in a capsule for placement in the Trojan reactor cavity

Charpy V-notch		Mini-tensile*		
A 36	A 212B	A 36	A 350-3	A 212B
A364	2CO3	601	001	201
A365	2CO4	602	002	202
A366	2CO5	606	003	203
A367	2CO6	607	004	204
A368	2CO7	608	005	205
	2CO8	609	006	206
		610	008	207
		611	009	208
		612	010	209
		615	011	210
		617	012	211
		618	013	212
		619	015	213
		620	017	214
			018	215

*A single Charpy-size holder containing 44 mini-tensiles.

Table 2. Chemical composition of materials irradiated in Trojan reactor cavity capsule

Element	Composition (wt %)		
	A 212B	A 350 LF3	A 36
C	0.26	0.18	0.21
Al	0.07	0.08	0.003
Co	0.015	0.03	0.007
Cr	0.075	0.090	0.04
Cu	0.15	0.11	0.05
Mn	0.85	0.55	1.10
Mo	0.02	0.03	0.03
Nb	< 0.001	< 0.001	0.002
Ni	0.09	3.3	0.07
Si	0.29	0.29	0.03
Sn	0.02	0.02	0.002
Ti	0.01	< 0.001	< 0.001
V	0.0005	0.001	0.001
W	< 0.005	< 0.005	< 0.01
Zr	< 0.001	< 0.001	< 0.001
P	0.006	0.01	0.009
S	0.04	0.02	0.026
As	0.007	0.01	0.007
B	< 0.0005	< 0.0005	< 0.001
N	0.0060	0.0090	?
O	0.0024	0.0027	?

those of the CVN specimens. The holder was designed to be easily disassembled in the hot cell by cutting the stainless steel straps with a knife. The holder, before and after assembly, together with a mini-tensile specimen, is shown in Figure 1. The CVN and tensile specimen drawings are shown in Figures 2 and 3, respectively. The orientation of the CVN specimens from both the A212B and A36 was L-T,* and the main axis of the tensile specimen was oriented along the major rolling direction of the plates or forging (longitudinal). The location and orientation of the CVN specimens with respect to the block of material from which they were machined are given in Appendix A. The thickness, width, and length of the mini-tensiles are $0.76 \times 5 \times 25$ mm, respectively.

The irradiation of the "ambient temperature" capsule was discontinued when the utility operating the reactor decided to shut it down before the planned exposure was attained. The capsule contents were exposed to a flux and fluence estimated to be $\sim 3 \times 10^8$ neutrons/(cm-s) and 1×10^{16} neutrons/cm² (> 1 MeV), respectively. The capsule location was very close to four thermoelements from which the temperatures were recorded for about 1 year (see Appendix B). Although the temperature measurements were made in the 1982 operating period, it is believed that they are still relevant, and a reasonable average irradiation temperature is $\sim 30^\circ\text{C}$ ($\sim 85^\circ\text{F}$).

The capsule was returned to ORNL, disassembled, and all 11 irradiated CVN specimens were tested. The details of the results from the CVN testing are given below. The exposure of the CVN specimens at the abovementioned conditions produced no significant irradiation-induced embrittlement. Consequently, no testing was performed on the tensile specimens. The unirradiated (and, similarly, the irradiated specimens, since no embrittlement was observed) CVN impact energies of A36 specimens were significantly higher than the energies published⁶ for specimens from the same plate of A36 and for the same orientation. The detailed results are also given below.

CVN Impact Test Results for A212B

The CVN impact energies of L-T orientation specimens machined from the HFIR A212B archival material and irradiated at 30°C to a fluence of 1×10^{16} neutrons/cm² (> 1 MeV) are shown in Figure 4. The detailed CVN test results of the A212B Trojan irradiation are given in Table 3. It is notable that the Trojan irradiation has not resulted in any significant embrittlement. For purposes of comparison, the results of testing performed on HFIR archival specimens that were supplied by ORNL to Sandia National Laboratories (SNL), and irradiated by them, are included, and details of their CVN impact test results are given in Table 4. The details of the unirradiated control data are given in Table 5. The data from the 1986 HFIR surveillance testing of specimens irradiated at 50°C (120°F) to a fluence of 1.4×10^{17} neutrons-cm⁻² (> 1 MeV) are given in Table 6. Although the SNL irradiation appears to have resulted in a smaller temperature shift at the 20-J (15-ft-lb) energy level than in the surveillance data, recent research has indicated that the contribution of gamma damage to the surveillance data is significant, as discussed below.

Solely as an aid to the presentation of the data, the three curves in Figure 4 were drawn by fitting the following "tanh" expression to the data:

$$E = \frac{USE + LSE}{2} + \frac{USE - LSE}{2} \text{TANH} \left(\frac{T - MTT}{TZW/2} \right), \quad (1)$$

where

E = energy (J or ft-lb),
 USE, LSE = upper- and lower-shelf energy values, respectively (J or ft-lb)
 TZW = transition zone width, K or F.[†]

*L-T designates the orientation of a CVN specimen where the main axis lies parallel to the major rolling direction (L) with the crack running in the direction that is transverse to the major rolling direction (T). The thickness direction is designated (S) for short.

[†]In referring to temperature intervals, the symbols for Kelvin (K) or Fahrenheit (F) are used without the degree symbol.

Figure 1. Holder for 44 mini-tensile specimens with approximate external dimensions of a full-size Charpy V-notch specimen before and after assembly.

Specimens are made according to dimensions of ASTM E 23-86.

- Base length is somewhat shorter than E 23 base length (but still within standard's tolerances) to fit into capsule for exposure in Trojan Reactor cavity.
- Tolerances are somewhat tighter.

Notes:

- 1) Specimen Orientation, all L - T.
- 2) Specimen IDs are listed on attached sheet.
- 3) Machined surface finish shall not exceed $32\sqrt{}$

Title:	Trojan Charpy Impact Specimen
L - T	(Irradiation grade)
Drawing Number:	T-CVN033090-1
File name:	Trojan Charpy w/notch
Drawn:	E. T. Manneschildt
Date:	April 17, 1990

Approved:

Figure 2. Charpy V-notch specimen machined from A212B and A36 material and used in the Trojan capsule. The specimens were all in the L-T orientation.

Figure 3. Tensile specimen used in the Trojan capsule. The main axis of the specimen was oriented along the major rolling direction of the material from which it was machined.

Figure 4. Charpy V-notch impact energy of L-T orientation specimens machined from High Flux Isotope Reactor archival material and irradiated at 30°C and 1×10^{16} neutrons/cm² (> 1 MeV) in the cavity of the Trojan reactor.

Table 3. Charpy V-notch impact test results on specimens (L-T orientation) of A212 High Flux Isotope Reactor archival material irradiated in the Trojan reactor cavity at ~ 30°C to ~ 1×10^{16} neutrons·cm⁻² (> 1 MeV)

Specimen	Test temperature		Energy		Shear (%)
	(°C)	(°F)	(J)	(ft-lb)	
2C07	-7	20	40	29.3	40
2C04	-7	20	36	26.5	25
2C08	-7	20	36	26.6	20
2C06	32	90	117	86.0	99
2C05	32	90	91	67.4	85
2C03	32	90	89	65.3	80

Table 4. Results of Charpy V-notch impact tests performed by Sandia National Laboratories on irradiated A212B High Flux Isotope Reactor archival specimens (L-T orientation) supplied by Oak Ridge National Laboratory

Specimen	Test temperature		Energy		Lateral expansion		Shear (%)
	(°C)	(°F)	(J)	(ft-lb)	(mm)	(mils)	
18	-7	20	20	14.5	0.381	15	1
11	4	40	19	14.0	0.406	16	10
15	16	60	35	26.0	0.711	28	10
19	16	60	40	29.5	0.914	36	35
23	27	80	58	43.0	1.041	41	40
14	27	80	68	50.5	1.168	46	50
20	49	120	87	64.0	1.549	61	80
13	77	170	99	73.0	1.524	60	97
21	110	230	95	70.0	1.626	64	100
10	110	230	100	74.0	1.626	64	100

Source: J. R. Hawthorne and S. T. Rosinski, Accelerated 54 °C Irradiated Test of Shippingport Neutron Shield Tank and HFIR Vessel Materials, SAND92-2420, Sandia National Laboratories, Albuquerque, N.M., January 1993.

Table 5. Charpy V-notch impact test results from unirradiated High Flux Isotope Reactor A212B specimens (L-T orientation)

Specimen	Temperature		Energy		Lateral expansion		Shear (%)
	(°C)	(°F)	(J)	(ft-lb)	(mm)	(mils)	
A-21	-29	-20	7	5.5	0.229	9.0	20.0
A-22	-29	-20	14	10.0	NA	NA	16.8
A-17	-29	-20	16	11.5	NA	NA	NA
A-64	-23	-10	12	9.0	0.254	10.0	10.0
A-75	-23	-10	13	9.5	0.302	11.9	20.7
A-70	-23	-10	33	24.5	0.699	27.5	10.0
A-63	-18	0	15	11.0	0.361	14.2	20.0
A-56	-18	0	18	13.5	0.445	17.5	27.8
A-49	-18	0	29	21.5	0.607	23.9	5.0
A-35	-12	10	24	17.5	0.462	18.2	28.3
A-46	-12	10	24	17.5	0.495	19.5	10.0
A-34	-12	10	28	21.0	0.559	22.0	21.2
A-24	-7	20	26	19.5	0.559	22.0	32.9
ND-2C	-7	20	28	20.4	0.66	26.0	34.0
ND-2D	-7	20	35	26.1	0.711	28.0	39.0
A-29	-7	20	36	26.5	0.665	26.2	31.7
ND-6C	-7	20	36	26.5	0.711	28.0	25.0
A-26	-7	20	39	28.5	0.792	31.2	29.5
A-83	16	60	54	39.5	1.024	40.3	42.6
D94-L	16	60	55	40.8	1.016	40.0	38.0
D94-E	16	60	57	41.8	1.092	43.0	41.0
ND-6B	16	60	59	43.8	1.016	40.0	45.0
D94-F	32	90	83	60.9	1.397	55.0	45.0
D94-A	32	90	86	63.6	1.473	58.0	51.0
D94-K	32	90	89	65.5	1.473	58.0	49.0
D94-J	32	90	99	72.8	1.549	61.0	57.0
A-80	38	100	97	71.5	1.676	66.0	94.0
A-53	49	120	105	77.5	1.638	64.5	99.0
A-14	49	120	106	78.2	1.676	66.0	100.0
ND-2B	49	120	110	81.3	1.651	65.0	99.0

Source: R. D. Cheverton, J. G. Merkle, and R. K. Nanstad, eds., *Evaluation of HFIR Pressure Vessel Integrity Considering Radiation Embrittlement*, ORNL/TM-10444, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., Oak Ridge, Tenn., April 1988.

Table 6. Results of Charpy V-notch impact testing of 1986 High Flux Isotope Reactor A212B surveillance specimens (L-T orientation) irradiated at 48.9°C (120°F) at an average flux of 2.44×10^{18} neutrons·cm⁻²·s⁻¹ and an average fluence of 1.35×10^{17} neutrons·cm⁻² (> 1 MeV)

Specimen	Flux (10^8 neutrons·cm ⁻² ·s ⁻¹)	Fluence (10^{17} neutrons·cm ⁻²)	Temperature		Energy		Lateral expansion		Shear (%)
			(°C)	(°F)	(J)	(ft-lb)	(mm)	(mils)	
A136	2.40	1.33	13	55	10	7.6	0.010	0.4	30
A145	2.21	1.22	13	55	20	14.9	0.018	0.7	20
A96	2.76	1.53	18	65	8	6.2	0.000	0.0	20
A141	2.21	1.22	18	65	12	8.5	0.000	0.0	25
A140	2.40	1.33	18	65	15	10.9	0.008	0.3	30
A120	2.37	1.31	18	65	25	18.6	0.127	5.0	35
A161	2.37	1.31	29	85	27	20.1	0.183	7.2	30
A99	2.76	1.53	29	85	32	23.5	0.198	7.8	35
A97	2.76	1.53	29	85	50	36.7	0.445	17.5	45
A135	2.40	1.33	49	120	50	37.1	0.478	18.8	65
A124	2.37	1.31	49	120	52	38.0	0.620	24.4	65
A142	2.21	1.22	66	150	96	70.6	1.006	39.6	90

Source: R. D. Cheverton, J. G. Merkle, and R. K. Nanstad, eds., *Evaluation of HFIR Pressure Vessel Integrity Considering Radiation Embrittlement*, ORNL/TM-10444, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., Oak Ridge, Tenn., April 1988.

The nil-ductility-transition temperatures (NDTs) for A212B in the unirradiated and irradiated conditions are given in Table 7. The NDT values and their corresponding shifts were obtained from either Table D.5 of ref. 1 or from curve-fit parameters given in ref. 7. At the time that the NDTs in ref. 1 were determined, it was decided to use engineering judgment for all the materials, since the only interest was in the determination of the NDTs. In many cases, there were not enough data for a regression fit over the whole range of the CVN impact energy curve. This was attempted for the A212B unirradiated temperature versus energy control data and required the use of prescribed values for both the lower- and upper-shelf energy (USE).^{*} The results were slightly different from those published in ref. 1 and were not used to avoid confusion.

Recent Results Regarding Contribution of Gamma Rays to HFIR Embrittlement

Since the decision to shut down the Trojan reactor terminated this irradiation at such a low fluence, it is not surprising that no embrittlement was observed in either the A212B or the A36 steel. This experiment was initiated at a time when data from the HFIR surveillance program suggested that low-flux irradiation at temperatures near 50°C could lead to unexpected levels of embrittlement. When initially compared with the test reactor data that were used in the design of the HFIR, the data from the HFIR surveillance program appeared to show significantly accelerated embrittlement. However, the exposure conditions of the HFIR pressure vessel surveillance capsules were subsequently determined to be quite different from those found in most other test reactors and either commercial RPVs or support structures. These conditions occurred primarily because the HFIR pressure vessel is separated from the core by a relatively thick (0.6-m) region of water. This long water path very effectively attenuates high-energy neutrons but has little effect on the high-energy gamma rays that also originate in the core. In addition, the HFIR core is surrounded by a 0.3-m-thick Be reflector. This further attenuates the fast neutron flux while increasing the flux of high-energy gamma rays via neutron capture reactions. As a result, the HFIR pressure vessel is exposed to a fast gamma flux that is about 10^4 higher than the fast neutron flux. Energetic gamma rays create high-energy electrons via Compton scattering and electron-positron pair production. These electrons can displace atoms by elastic collisions if the electron energy exceeds about 0.5 MeV. For conditions typical of commercial reactors and most test reactor irradiations, the ratio of electron-induced (gamma ray) displacements to neutron-induced displacements is less than a few percent. However, the anomalously high fast gamma-to-neutron ratio at the HFIR pressure vessel leads to essentially equivalent atomic displacement rates from the gamma rays and neutrons. When the HFIR data and other test reactor data are correlated based on the total number of atomic displacements per atom (dpa), the additional gamma-induced displacements bring the HFIR surveillance data into compliance with the balance of the design data.⁵ This explanation has mitigated concerns about a low neutron flux leading to unexpected embrittlement of commercial reactor support structures since the dpa contribution from gamma ray-induced displacements is insignificant for the spectrum in current commercial power reactors.

CVN Impact Test Results for the A36 Steel

The CVN impact energies of the A36 specimens irradiated in the Trojan reactor are shown in Figure 5 and Table 8. The capsule contents were exposed to a flux and fluence estimated to be $\sim 3 \times 10^8$ neutrons·cm⁻²·s⁻¹ and 1×10^{16} neutrons/cm² (> 1 MeV), respectively. The irradiation temperature was about 30°C. A straight line has been regression fit through the irradiated data points. The irradiated impact energy values are significantly higher than the unirradiated ones. The differences observed may be metallurgical variations in the A36 plate, although both the unirradiated and irradiated specimens were machined from the same plate.

As mentioned above, the impact energies of irradiated specimens are significantly higher than the unirradiated values at the same temperature. This apparent anomaly was investigated by performing a limited number of tests on unirradiated material. Originally, ORNL did not plan on testing unirradiated control specimens but intended to use published values from tests on specimens machined from the same plate and in the same orientation. Moreover, the exposure of these irradiated specimens is so low that no significant difference between the CVN

^{*}The tanh fit is sensitive to the choice of a prescribed value for the USE.

Table 7. Nil-ductility-transition temperature for Charpy V-notch specimens (L-T orientation) machined from archival High Flux Isotope Reactor A212B steel

Material condition	Irradiation temperature		Flux [neutrons·cm ⁻² ·s ⁻¹ (> 1 MeV)]	Fluence [10 ¹⁷ neutrons·cm ⁻² (> 1 MeV)]	NDT temperature ^a		Shift	
	(°C)	(°F)			(°C)	(°F)	(°C)	(°F)
Unirradiated					-20.56	-5 ^b		
Trojan irradiation	30	86	3 × 10 ⁸	0.1				
1986 Surveillance	48.9	120	2.5 × 10 ⁸	1.4	21.11	70	41.67	75 ^b
Sandia irradiation	54.4	130	5.3 × 10 ¹¹	5.1	1.3 ^c	34.3	18.6 ^c	33.5

^aNDT index level of 20.3 J (15 ft-lb). Source: R. D. Cheverton, J. G. Merkle, and R. K. Nanstad, eds., *Evaluation of HFIR Pressure Vessel Integrity Considering Radiation Embrittlement*, ORNL/TM-10444, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., Oak Ridge, Tenn., April 1988, p. 88.

^bValue reported in ORNL/TM-10444, Table D.5, evaluated using engineering judgment.

^cNot enough data to evaluate.

^dNondetectable.

^eValue calculated from the tanh fit parameters. Source: J. R. Hawthorne and S. T. Rosinski, *Accelerated 54 °C Irradiated Test of Shippingport Neutron Shield Tank and HFIR Vessel Materials*, SAND92-2420, Sandia National Laboratories, Albuquerque, N.M., January 1993. The value of the unirradiated NDT given in this report is slightly different than ORNL/TM-10444 because of the different approaches used in determination.

Figure 5. Charpy V-notch impact energy of the L-T orientation specimens machined from A36 material and irradiated in the Trojan reactor.

Table 8. Results of Oak Ridge National Laboratory tests on A36 Charpy V-notch specimens (L-T orientation)

Sequence number	Specimen	Test temperature		Energy		Lateral expansion*		Shear (%)
		(°C)	(°F)	(J)	(ft-lb)	(mm)	(mils)	
Unirradiated								
1	A361	22	72	104	77	1.52	60	60
2	A362	22	72	104	77	1.52	60	65
3	A3611	23	73	111	82	1.7	67	70
4	A3610	23	73	80	59.3	1.37	54	55
5	A3609	23	73	94	69.1	1.6	63	60
Irradiated in Trojan reactor at 65 °C to 1×10^{16} neutrons/cm² (> 1 MeV)								
1	A366	22	72	121	89			70
2	A364	22	72	110	81			50
3	A367	0	32	84	62			35
4	A365	-18	0	32	23.4			10
5	A368	-18	0	19	14.2			10

*Lateral expansion of specimens irradiated in the Trojan reactor was not measured.

impact energy values of the unirradiated and irradiated specimens was expected. All ORNL specimens, both unirradiated and irradiated, were machined from a single block of A36 (marked 6B24), as shown in Appendix A, which was obtained from the University of Kansas (UK).^{*} This block is from the same 32-mm-thick (1.25-in.) plate of A36 that was used in an investigation by Sorem et al.⁶ Tabular values of the results of the CVN impact testing of unirradiated specimens of A36 in the L-T orientation, and shown in Figure 2 of ref. 6, were obtained from the UK and are given in Tables 9 and 10. They have been labeled in the same manner as obtained, namely, "results of tests by Sorem" and "results of tests by Hollomb," in Tables 9 and 10, respectively. The CVN impact energy values from these two sets of results have been included in Figure 5 and are labeled "Unirradiated, U. of Kansas."

The values obtained by ORNL in testing unirradiated specimens, also in the L-T orientation, are given in Table 8 and Figure 5. The first two unirradiated specimens tested were left over from those fabricated for irradiation in the Trojan capsule and were thus from the same region of the plate. When these two specimens also gave values that were higher than those of the UK, some concern was raised about orientation, and it was decided to machine three more specimens, with particular attention to orientation.

The standard procedure for machining of CVN specimens calls for the machine shop to lay out the specimens on the material block from which they are to be machined. Identification marks are then engraved on the block to a depth that would allow the specimen identification marks to be easily legible after the remaining machining operations are performed. The location of the identification marks with respect to the specimen is used as a means of determining the orientation of the specimen after it is parted from the parent material. In this case, before the specimens were parted from the block, the layout was inspected at the machine shop by the principal author.

The results of these three specimens were also higher than the UK results. The average unirradiated CVN impact energy value of all five specimens tested at room temperature from a single location was approximately 99 J, with values ranging from 80 to 111 J. The average value of 11 UK specimens, also tested at room temperature *but from other locations in the same plate*, was 45 J, with values ranging from 32 to 69 J. The CVN impact energies of all the UK and ORNL tests (18 specimens) at room temperature and in the L-T orientation range from a low of 32 J to a high of 111 J. Moreover, it appears that the UK CVN impact energy of the unirradiated specimens at the 100-J level is shifted toward higher temperatures by about 20 K.[†]

In general, CVN impact properties, both irradiated and unirradiated, show considerable scatter in the results. For example, in a study conducted by U.S. Steel in 1964 on unirradiated A212 grade B steel, a structural material similar to A36, two sets of three specimens each were taken at the quarter-thickness of a 4-in.-thick plate.[‡] They were machined from different sized slabs cut from the same plate, but each slab was given the same heat treatment. They were all tested at -23°C (-10°F), and the average CVN impact energy of each set was 40 and 52 J (28 and 38 ft-lb), respectively, a difference of $\sim 36\%$. However, the difference between average CVN impact energy of the UK and ORNL A36 values is $\sim 220\%$.

In efforts to shed some light on the cause of the difference between the UK results and those of ORNL, the CVN impact energy was plotted as a function of the lateral expansion (LE) and is shown in Figure 6(a). Similar plots for a plate material and a weldment are given in Figures 6(b) through (d). Since the relationship between CVN impact energy and LE depends on the yield strength,⁸ the latter is given for the materials of Figure 6. Except for the A36, the slope of the impact energy versus LE is either a constant or increases smoothly over the range of values represented. The values shown in Figures 6(b) through (d) all seem to fall within a single population. For the A36, however, this is not the case. For the UK CVN results, the ratio of the average room-temperature CVN impact energy to the average of the corresponding LEs is 46.5 J/mm, which is in reasonable agreement with the 43.6 J/mm obtained over the whole test temperature range. As expected, the corresponding ratio for ORNL results is

^{*}Courtesy of S. T. Rolfe.

[†]Figure 5 was transmitted to S. T. Rolfe of the UK. In telephone discussions on October 4 and November 18, 1993, metallurgical variations in the plate were discussed as a possible cause for the differences between the UK and ORNL results.

[‡]J. V. Alger and L. F. Porter, *Evaluation of Reference Pressure-Vessel Steels for Neutron-Irradiation Studies*, Technical Report, Project No. 40.002-066 (4), Applied Research Laboratory, U.S. Steel, Monroeville, Pa., June 18, 1964.

Table 9. University of Kansas test results of unirradiated A36 Charpy V-notch specimens (L-T orientation)

Sequence number	Test temperature		Energy	
	(°C)	(°F)	(J)	(ft-lb)
1	-67	-89	3.4	3
2	-67	-89	3.4	3
3	-34	-29	4.8	4
4	-34	-29	4.1	3
5	-34	-29	7.5	6
6	-34	-29	4.8	4
7	-12	10	10.2	8
8	-12	10	10.2	8
9	-12	10	12	9
10	-12	10	10.2	8
11	0	32	13.6	10
12	0	32	17	13
13	4	39	22	16
14	4	39	38	28
15	4	39	45	33
16	4	39	20	15
17	4	39	20	15
18	4	39	14	10
19	10	50	27	20
20	10	50	29	21
21	21	70	50	37
22	21	70	55.5	41
23	21	70	35	26
24	22	72	50	37
25	22	72	69	51
26	22	72	32	24
27	32	90	70.5	52
28	32	90	61	45
29	43	109	118	87
30	43	109	103	76
31	60	140	142	105
32	60	140	239	176
33	82	180	171	126
34	82	180	138	102

Source: Personal communication, S. T. Rolfe, University of Kansas, to S. K. Iskander, Oak Ridge National Laboratory, June 6, 1993.

Table 10. University of Kansas test results of unirradiated A36 Charpy V-notch specimens (L-T orientation)

Sequence number	Specimen	Test temperature		Energy		Lateral expansion	
		(°C)	(°F)	(J)	(ft-lb)	(mm)	(mils)
1	1	23	74	41	30.0	0.91	36.0
2	2	23	74	42	31.0	0.94	37.0
3	3	23	74	45	33.0	0.80	31.5
4	4	23	74	34	25.0	0.85	33.5
5	5	23	74	43	32.0	0.91	36.0
6	6	-18	0	13	9.5	0.20	8.0
7	7	-18	0	6	4.5	0.17	6.5
8	8	-18	0	6	4.5	0.10	4.0
9	9	-18	0	10	7.5	0.28	11.0
10	10	-18	0	11	8.0	0.17	6.5
11	11	-76	-105	3	2.0	0.14	5.5
12	12	-76	-105	3	2.0	0.00	0.0
13	13	-76	-105	3	2.0	0.04	1.5
14	14	-76	-105	2	1.5	0.01	0.5
15	15	-76	-105	2	1.5	0.03	1.0
16	16	0	32	22	16.5	0.51	20.0
17	17	0	32	26	19.5	0.62	24.5
18	18	0	32	27	20.0	0.60	23.5
19	19	0	32	14	10.0	0.60	23.5
20	21	0	32	26	19.0	0.65	25.5
21	22	0	32	22	16.5	0.55	21.5
22	26	-43	-45	4	3.0	0.08	3.0
23	27	-43	-45	4	3.0	0.19	7.5
24	28	-43	-45	5	3.5	0.03	1.0
25	29	-43	-45	4	3.0	0.15	6.0
26	30	-43	-45	3	2.5	0.04	1.5

Source: Personal communication, S. T. Rolfe, University of Kansas, to S. K. Iskander, Oak Ridge National Laboratory, June 6, 1993.

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Figure 6(b) . Relationship between Charpy V-notch (CVN) impact energy and lateral expansion: A533 grade B class 1 steel.

Figure 6(c). Relationship between Charpy V-notch (CVN) impact energy and lateral expansion: Heavy-Section Steel Irradiation weld 73W.

Figure 6(d). Relationship between Charpy V-notch (CVN) impact energy and lateral expansion: Heavy-Section Steel Irradiation weld 73W, undersize CVN specimen.

63.9 J/mm, compared to 64.0 J/mm obtained by a linear regression on the same data. The ratio of the impact energy to LE of the ORNL results is ~ 37% higher than the UK ratio. The precise cause of the difference between the UK and ORNL results is still unknown. There is a possibility that differences observed are due to metallurgical variations and the nature of the CVN impact test. Consequently, "generic" values of CVN impact energy for A36 should be used with caution until a statistical analysis of a sufficient number of results is made to define the uncertainty involved.

Summary and Conclusions

CVN and mini-tensile specimens were irradiated at ~ 30°C (~ 85°F) in the cavity of a commercial nuclear power plant to a fluence of 1×10^{16} neutrons/cm² (> 1 MeV). The capsule included six CVN impact specimens fabricated from archival HFIR A212B ferritic steel and five from a well-studied A36 structural steel. This irradiation was part of the ongoing studies of neutron-induced damage effects at the low temperature and flux experienced by reactor supports. The plant operators shut down the plant before the planned exposure was reached. The exposure of these specimens in the reactor cavity of a commercial reactor at the conditions mentioned above produced no significant irradiation-induced embrittlement. Of interest were the data on unirradiated specimens in the L-T orientation machined from a *single* plate of A36 structural steel that is the same specification for the structural steel used in some reactor supports. The average CVN impact energy of five unirradiated specimens obtained from one region of the plate and tested at room temperature was approximately 99 J, while that of 11 unirradiated specimens from other locations of the same plate was 45 J, a difference of ~ 220%. The CVN impact energies for all 18 specimens range from a low of 32 J to a high of 111 J. Moreover, it appears that the UK CVN impact energy of the unirradiated specimens at the 100-J level is shifted toward higher temperatures by about 20 K. The results were an example of the extent of scatter possible in CVN impact testing. Generic values for the CVN impact energy of A36 should be used with caution in critical applications.

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*Available for purchase from National Technical Information Service, Springfield, VA 22161.

†Available in public technical libraries.

Appendix A

Location and Orientation of Specimens

Appendix A

Location and Orientation of Specimens

The location and orientation of the specimens with respect to the blocks of material from which they were machined are shown in Figures A1 and A2.

Figure A1 shows the location of the Charpy V-notch (CVN) specimens with respect to the archival High Flux Isotope Reactor (HFIR) HB2 nozzle dropout of A212B material. The specimens were machined with the top surface about 6.4 mm (0.25 in.) below the clad inner surfaces.

Figure A2 gives the location of the CVN specimens machined from the block of A36, designated 6B24, from the University of Kansas (UK).^{*} It originated from a 32-mm-thick (1.25-in.) plate that was used extensively by the UK in their studies that are referenced in the main body of this report. Eight specimens were originally machined for this purpose. Six were irradiated in the Trojan capsule. The remaining two were left unirradiated and subsequently tested when a large difference of CVN impact energy was observed between the ORNL and UK results. When the same difference was observed in these two specimens, doubts about the orientation arose. Three more specimens, shown as a single bottom row in Figure A2 below the previous eight, were machined and tested with the same difference (see main body of report for details).

^{*} Courtesy of S. T. Rolfe.

Figure A1. Location of the L-T orientation Charpy V-notch specimens with respect to the archival High Flux Isotope Reactor HB2 nozzle dropout of A212B material.

Figure A2. Location of the original eight L-T orientation Charpy V-notch specimens machined from the block of A36, designated 6B24, and obtained from the University of Kansas. The three confirmatory L-T orientation Charpy V-notch specimens are shown in the single bottom row below the first eight specimens machined.

Appendix B

Records of Temperatures from Four Temperature Elements Close to Capsule

Appendix B

Records of Temperatures from Four Temperature Elements Close to Capsule*

Figure B1 gives the variations of temperature recorded by the four temperature elements shown in Figure B2 for the 1982 operating period, indicated in Figure B3. The capsule location was very close to the four temperature elements mentioned. Although the temperature measurements were made in the 1982 operating period, it is believed that they are still relevant, and a reasonable average irradiation temperature is $\sim 30^{\circ}\text{C}$ ($\sim 85^{\circ}\text{F}$). The range of temperature dropped for short periods, as low as 17°C (62°F) and as high as 44°C (112°F). It should be noted that the temperature is approximately $\sim 30^{\circ}\text{C}$ ($\sim 85^{\circ}\text{F}$) and varies about $\pm 6^{\circ}\text{C}$ ($\pm 10^{\circ}\text{F}$). Temperature variations in this range are not expected to affect the embrittlement response of steel.

*Information provided by T. E. Bushnell, Portland General Electric, Trojan Nuclear Plant, TCB-2, Rainier, Oregon, June 30, 1995.

TROJAN NUCLEAR PLANT

TEMPERATURE RANGE
TENT-TE10136

FOR OPERATING TIME 1982

Figure B1(a). Temperature in the reactor cavity close to the Trojan capsule location for temperature element TE10136.

TROJAN NUCLEAR PLANT

TEMPERATURE RANGE
ITEM 1-TE10137

FOR OPERATING TIME 1982

Figure B1(b). Temperature in the reactor cavity close to the Trojan capsule location for temperature element TE10137.

Figure B1(c). Temperature in the reactor cavity close to the Trojan capsule location for temperature elements TE10138.

TROJAN NUCLEAR PLANT

TEMPERATURE RANGE
ITEM-TE10139

FOR OPERATING TIME 1982

Figure B1(d). Temperature in the reactor cavity close to the Trojan capsule location for temperature element TE10139.

REVISION NOTES:

1. PUMP-1 SAMPLE SYSTEM REMOVED & REFERENCE MARK
2. NEW VALVE NUMBERS ADDED TO TEST VENTILS & CO
3. ADDED TSC COMPUTER INPUTS & NOTE 9 PER ELEC
4. HYDROGEN VENT SYSTEM DOWNGRADE TO S.C.II. REVI

Figure B2. Locations of the four temperature elements in the reactor pressure vessel cavity.

TROJAN NET ELECTRIC GENERATION

Figure B3. Record of the 1982 operating period "net electric power generation" for the Trojan plant.

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M. G. Vassilaros, NRC Project Manager

11. ABSTRACT (200 words or less)

A capsule containing Charpy V-notch (CVN) and mini-tensile specimens was irradiated at ~ 30°C (~ 85°F) in the cavity of a commercial nuclear power plant to a fluence of 1×10^{16} neutrons/cm² (> 1 MeV). The capsule included six CVN impact specimens of archival High Flux Isotope Reactor A212 grade B ferritic steel and five CVN impact specimens of a well-studied A36 structural steel. This irradiation was part of the ongoing study of neutron-induced damage effects at the low temperature and flux experienced by reactor supports. The plant operators shut down the plant before the planned exposure was reached. The exposure of these specimens produced no significant irradiation-induced embrittlement.

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