CONF-960306--30

A PERSPECTIVE ON THERMAL ANNEALING OF REACTOR PRESSURE VESSEL MATERIALS FROM THE VIEWPOINT OF EXPERIMENTAL RESULTS*

Shafik K. Iskander, Mikhail A. Sokolov,†
and Randy K. Nanstad

Metals and Ceramics Division
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37831-6151

---

*Research sponsored sponsored by the Office of Nuclear Regulatory Research, Division of Engineering Technology, U.S. Nuclear Regulatory Commission, under Interagency Agreement DOE 1886-8109-8L with the U.S. Department of Energy under contract DE-AC05-96OR22464 with Lockheed Martin Energy Research Corp.

†Postdoctoral Researcher.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

The submitted manuscript has been authored by a contractor of the U.S. Government under contract No. DE-AC05-96OR22464. 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.

MASTER

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.

A PERSPECTIVE ON THERMAL ANNEALING OF REACTOR PRESSURE VESSEL MATERIALS FROM THE VIEWPOINT OF EXPERIMENTAL RESULTS

Shafik K. Iskander, Mikhail A. Sokolov,
and Randy K. Nanstad

Metals and Ceramics Division
Oak Ridge National Laboratory
Oak Ridge, Tennessee

ABSTRACT

It is believed that in the next decade or so, several nuclear reactor pressure vessels (RPVs) may exceed the reference temperature limits set by the pressurized thermal shock screening criteria. One of the options to mitigate the effects of irradiation on RPVs is to thermally anneal them to restore the toughness properties that have been degraded by neutron irradiation. This paper summarizes recent experimental results from work performed at the Oak Ridge National Laboratory to study the annealing response, or "recovery" of several irradiated RPV steels. The fracture toughness is one of the important properties used in the evaluation of the integrity of RPVs. Optimally, the fracture toughness is measured directly by fracture toughness specimens, such as compact tension or precracked Charpy specimens, but is often inferred from the results of Charpy V-notch impact specimens. The experimental results are compared to the predictions of models for embrittlement recovery which have been developed by Eason et al. Some of the issues in annealing that still need to be resolved are discussed.

INTRODUCTION

Some early nuclear reactor pressure vessels (RPVs) fabricated from certain types of steels may not meet the regulatory requirements for fracture toughness as they near their end of life. These regulatory requirements are promulgated in Appendix G of "Title 10," Part 50 of the *Code of Federal Regulations* (10CFR50). It is believed that in the next decade or so, several vessels may exceed the limits set by the pressurized thermal shock reference temperature (10CFR50.61). In that case, thermal annealing of the RPV may mitigate the effects of neutron embrittlement on fracture toughness. A dozen or so RPVs have already been thermally annealed in Eastern Europe (Rogov and Morozov, 1994) and a U.S. utility is contemplating annealing an RPV.

Proposed Rules issued by the U.S. Nuclear Regulatory Commission (NRC) in October 1994 to amend 10CFR50 include the "Thermal Annealing Rule," which provides new requirements for thermal annealing an RPV to mitigate the effects of neutron irradiation (10CFR50.66). The rule states that "two items of particular importance to the overall annealing are the recovery of fracture toughness and the rate of reembrittlement of the RPV beltline materials." These two items form the principal objectives of research performed at the Oak Ridge National Laboratory (ORNL). This research is performed within the NRC-sponsored Heavy Section Steel Irradiation (HSSI) Program. Several RPV materials which are most likely to be annealed are being investigated, and their fracture toughness recovery and the reembrittlement rate of the fracture toughness will be correlated to the corresponding rates of the Charpy V-notch (CVN) specimen recovery and reembrittlement. The rate of reembrittlement is an important consideration since it will determine how long the plant may be safely operated after it is annealed.

Historically, the toughness of RPVs has been monitored through surveillance programs in which predominantly CVN specimens are placed in capsules, withdrawn and tested periodically. The degradation of fracture toughness is estimated from both the radiation-induced shift of the CVN 41-J (30-ft-lb) transition temperature (ΔTT_i) as well as the decrease in the upper-shelf energy (USE). The fracture toughnesses of irradiated RPV material are estimated from the American Society of Mechanical Engineers (ASME) *Boiler and Pressure Vessel Code* fracture toughness curves by shifting them upward in temperature by ΔTT_i, (which is also referred to as the shift in the reference temperature, RT_{NDT}). The value of the unirradiated RT_{NDT} is based on both the drop-weight nil-ductility transition temperature and results of testing Charpy specimens. However, the shift of the fracture toughness curves is based solely on the Charpy ΔTT_i. Recent advances in fracture mechanics may allow the direct determination of the fracture toughness and shift in the transition region of thick-section RPV steels from relatively small fracture toughness specimens, but, for some of the earlier RPVs, the use of CVN-based surveillance data and specimens will probably play a key role in the judgement of the efficacy of the anneal. This paper discusses the effect of annealing on the CVN impact energy and fracture toughness of several irradiated RPV materials; a few general conclusions are drawn.

DESCRIPTION OF MATERIAL USED

The commercially fabricated submerged arc-welds and plate used in this study are commonly used in RPVs. These materials have been extensively characterized in their unirradiated and irradiated conditions (Nanstad et al., 1990, 1992), (Stelzman et al., 1985). The chemical composition and mechanical properties of the materials investigated have been summarized in Tables 1 and 2, respectively. Large variations in the copper content (from 0.21 to 0.46%) have been observed in welds fabricated using weld wire with copper coating (Nanstad et al., 1992). To avoid these large variations, the 73W weld wire was fabricated with copper added to the melt; consequently this weld has a very small standard deviation in copper content of 0.010%.

The "undersize" 73W CVN specimens used in part of this study were slightly smaller in one cross-sectional dimension than standard full-size CVN specimens. The dimension normal to the notch of the "undersize" CVN specimens is 95% of the full-size specimens and, for comparison to the full-size specimens the results have been normalized as described below. This slightly smaller dimension of the specimens was dictated by the space available in the HSSI Fifth Irradiation Series capsules (Miller et al., 1988). The difference in the unirradiated CVN 41-J (30-ft-lb) transition temperatures between the full-size and subsize specimens is insignificant, but the USE of the subsize specimen is 87% of that of the full-size specimen (see Table 2). The subsize 73W CVN specimens were irradiated to average exposures of 1.8×10^{19} neutrons/cm^2 (> 1 MeV), 1.1×10^{20} neutrons/cm^2 (> 0.1 MeV), and 0.040 displacements per atom. The irradiation was performed in the Oak Ridge Research Reactor for 1450 h at an average flux of 3×10^{12} neutrons/(cm^2-s) (> 1 MeV) (Miller et al., 1988). The rest of the materials were irradiated for 3596 h at an average flux of 8×10^{11} neutrons/(cm^2-s) (> 1 MeV) to an average fluence of 1×10^{19} neutrons/cm^2 (> 1 MeV) in the Ford Nuclear Reactor at the University of Michigan. For the range of fluences and fluxes of this study, the influence of fluence and flux on the percent recovery of CVN properties is probably of secondary importance compared to the effect of material chemistry, annealing temperature, and time. The nominal irradiation temperature for all materials was 288°C.

ANNEALING TEMPERATURE AND TIMES INVESTIGATED

The irradiated specimens were annealed at 343 and 454°C (650 and 850°F). These two temperatures have been often investigated as approximate lower and upper bounds of probable annealing temperatures (Major and Lott, 1989). The 343°C temperature could be used for a wet anneal. This is considerably simpler to perform than a dry anneal at 454°C, since the reactor internals would not have to be removed. One annealing time of 168 h was investigated at the 343°C temperature. In the case of the HSSI 73W weld, four annealing times varying from 1 day to 2 weeks (336 h) were investigated at a temperature of 454°C. The rest of the materials were annealed at the two temperatures mentioned for 168 h.

RESULTS AND DISCUSSION

The recovery of CVN impact properties as a result of annealing is typically measured by the changes in values of the Charpy USE and the 41-J transition temperature, TT, and are defined below. The values of the USE and TT were calculated from a nonlinear regression fit of a hyperbolic tangent equation to the CVN impact energy results. The hyperbolic tangent equation is of the form:

$$E = \frac{USE + LSE}{2} + \frac{USE - LSE}{2} \operatorname{Tanh}\left(\frac{T - MTT}{TZW/2}\right), \qquad (1)$$

where

E = impact energy
USE and LSE = upper- and lower-shelf energy values, respectively,
T = test temperature,
MTT = mid-transition temperature,
TZW = transition zone width.

The LSE was prescribed to be 2.7 J, the average value obtained from tests of five CVN specimens from a submerged-arc weld at liquid nitrogen temperature of −196°C (Nanstad et al., 1992). The USE, MTT, and TZW are fitting parameters.

The percent recovery of the ΔTT_i and USE are referenced to the shift or drop, respectively, due to neutron irradiation. A 100% recovery would indicate that the values of TT_i and USE after annealing have fully recovered their unirradiated values. The percent recovery of the TT_i is defined as the ratio of the residual transition temperature shift after annealing to the shift due to irradiation, $\Delta TT_i = TT_i - TT_{unirr}$, or:

$$\%\ \text{Recovery}\ TT_{ia} = \frac{TT_i - TT_a}{TT_i - TT_{unirr}} \cdot 100\,, \qquad (2)$$

where TT is the transition temperature at the 41-J energy level for the condition indicated by outer subscript.* The percent recovery of the USE is defined in an analogous manner to Eq. (2):

$$\%\ \text{Recovery}\ USE_{ia} = \frac{USE_a - USE_i}{USE_{unirr} - USE_i} \cdot 100\,. \qquad (3)$$

A representative test result from testing the undersize HSSI weld 73W Charpy specimens is shown in Fig. 1, in which the impact energy is shown as a function of temperature. The symbols are the experimental results for each specimen tested, and the three curves shown are the least squares mean fits of Eq. (1) to the experimental results. Also shown are the drops in USE and ΔTT_i, as well as the recoveries computed from Eqs. (2) and (3). The values used in either equation are those calculated from the mean curves. More details of the results of testing the undersize specimens from HSSI weld 73W may be found elsewhere (Iskander et al., 1996).

---

*Irradiated = i, annealed = a, unirradiated = unirr, and irradiated and annealed = ia.

Table 1. Average chemical composition of materials used in the annealing studies

Material	Composition (wt %)									
	C	Mn	P	S	Si	Cr	Ni	Mo	Cu	V
HSSI weld 73W	0.098	1.56	0.005	0.005	0.45	0.25	0.60	0.58	0.31	0.003
Midland beltline weld	0.084	1.61	0.017	0.007	0.62	0.10	0.57	0.41	0.21-0.34	0.004
Midland nozzle weld	0.088	1.57	0.015	0.010	0.56	0.11	0.58	0.39	0.37-0.46	0.008
HSST Plate 02	0.23	1.55	0.009	0.014	0.20	0.04	0.67	0.53	0.14	0.003

Table 2. Mechanical properties of materials used

Material	CVN impact USE (J)	CVN 41-J transition temperature (°C)	Room temperature tensile strength (MPa)	
			Yield	Ultimate
HSSI weld 73W (undersize)	118	−38	495	603
HSSI weld 73W (full size)	135	−40	495	603
Midland beltline weld	89	−9	407	586
Midland nozzle weld	88	−1	505	655
HSST Plate 02	164	−16	471	619

One of the results of this investigation is that annealing "*overrecovered*" or increased the USE to values greater than the unirradiated specimens. This was not unexpected since other investigators have also noted such an effect. Annealing, tempering and aging effects are diffusion processes where temperature is the dominant parameter and time is of secondary influence. As part of the original fabrication procedure, the HSSI 73W weld was postweld heat-treated at a temperature of 607°C (1125°F) for 40 h, and thus further exposure at the lower temperature of 454°C for 168 h would not be expected to have any effect. To determine whether this increase in USE was due to irradiation, unirradiated specimens were also aged at 460 and 490°C for 168 h, and the USE increased 117%. The reasons for this phenomenon are being investigated.

In the case of toughness testing in the transition temperature range, the following relationship between the median fracture toughness in the transition region, $K_{Jc(med)}$, and temperature is used:

$$K_{Jc(med)} = 30 + 70 \exp\left[0.019(T - T_0)\right] , \qquad (4)$$

where T_0 is a parameter, which together with $K_{Jc(med)}$, are obtained using procedures that are in the process of being developed into an ASTM standard* (Wallin, 1989; McCabe et al., 1994). The differences between the respective T_0s are used as measures of the effect of annealing. A typical result from such testing is shown in Fig. 2, which shows three $K_{Jc(med)}$ curves for each of the unirradiated, irradiated, and annealed conditions. Detailed results have or will be published (Sokolov et al., 1995; Sokolov et al., 1996).

The TT and USE of the various materials and for the conditions investigated are given in Tables 3 and 4, respectively. The ΔTT_i, and the percent recovery of the ΔTT_i have been plotted in Figs. 3 and 4. The figures show that in general, the values of TT_i and the percent recovery depend strongly on the annealing temperature, and to a lesser degree on annealing time. This trend is illustrated by the annealing behavior of the specimens from HSSI weld 73W that has a recovery of TT_i that is insignificant for annealing at 343°C for 168 h, but is over 90% when annealed at 454°C for the same length of time. Increasing the annealing times from 96 to 168 to 336 h did not cause an appreciable gain in recovery. However, the degree of recovery of the Midland weld (MW) and Heavy-Section Steel Technology (HSST) Plate 02 materials due to annealing at 343°C for 168 h was approximately 49 and 36%, respectively, which is substantially greater than the 10% of the specimens from HSSI weld 73W. Thus this could be a viable annealing temperature for such materials.

The response of the USE to annealing, Figs. 5 and 6, is different than that of the TT_i in the following aspects. The percent recovery of the USE is substantial for all conditions investigated, and, in many cases, the USE overrecovers to values greater than the unirradiated value. Even for the 343°C/168-h anneal, the materials that experienced a substantial recovery in TT_i also recovered over 100% of the drop in USE due to irradiation. Although the mechanisms involved in the recovery of the USE and TT_i may be different, such a response suggests that there may be a relationship between them.

Figures 5 and 6 also show that using the definition of the percent recovery of USE given by Eq. 3 (analogous to the definition of the percent recovery of the TT_{41J}) can lead to values of recovery ranging from 200 to 300%, which can be misleading unless Eq. 3 is kept in mind. An alternate definition of the fractional recovery is one that compares the value of the USE to the unirradiated value as follows:

$$\%\ \text{Recovery USE}' = \frac{\text{USE}'}{\text{USE}_{\text{unirr}}} \cdot 100 , \qquad (5)$$

where USE′ is the USE for the condition studied. Note that since it is not based on irradiated values, it can be used to compare changes in USE due to aging as well as to changes due to irradiation and annealing. However, if an irradiated USE does not recover, it still indicates a misleading "recovery," equal in value to the decrease in USE due to irradiation. Thus, each of these definitions has advantages and disadvantages. Besides yielding values such as those mentioned above, Eq. (3) is based on the drop in USE. The drop in USE due to irradiation for the Midland beltline weld is approximately 6 J, which is of the same order of magnitude as the scatter. Relatively small gains in USE could lead to USE recovery values of 300%. One advantage of the definition given by Eq. (3) is that it is analogous to that for the recovery of the transition temperature, and thus the corresponding recoveries can be compared. The advantage of Eq. (5) is that the recovery of the USE mentioned above, instead of being reported as 300%, would be indicated as 120%.

Preliminary fracture toughness results from testing compact and precracked Charpy specimens of irradiated RPV steels annealed at 454°C for 168 h show similar trends as those obtained in testing Charpy impact specimens (Sokolov et al., 1995, 1996). Recovery depends strongly upon annealing temperature and the measure of fracture toughness. The recovery of the cleavage fracture toughness in the transition region as indicated by the T_0 temperature is partial, but the tearing modulus and the ductile fracture toughness as indicated by J_{Ic} have either fully recovered or overrecovered. The investigation of the relationship of recovery of the fracture toughness to that of the Charpy properties is still under investigation.

PREDICTION OF RECOVERY

Models developed by Eason et al., 1995, give the following relationship for the recovery of the transition temperature:

$$TT_{ia} = TT_i - \Delta TT_i \left[0.5 + 0.5 \tanh\left(\frac{a_1 T_a - a_2}{95.7}\right)\right] , \qquad (6)$$

where TT is the transition temperature, in °F, for the condition indicated by the subscript, irradiated, i, irradiated and annealed, ia, and ΔTT_i is the shift due to irradiation, all temperatures are in °F, and

---

**Determination of Reference Temperature, T_0, for Ferritic Steels in the Transition Range*, Draft 11, Task Group E08.08.03 on Ductile-Brittle Transition, American Society for Testing and Materials, 1995.

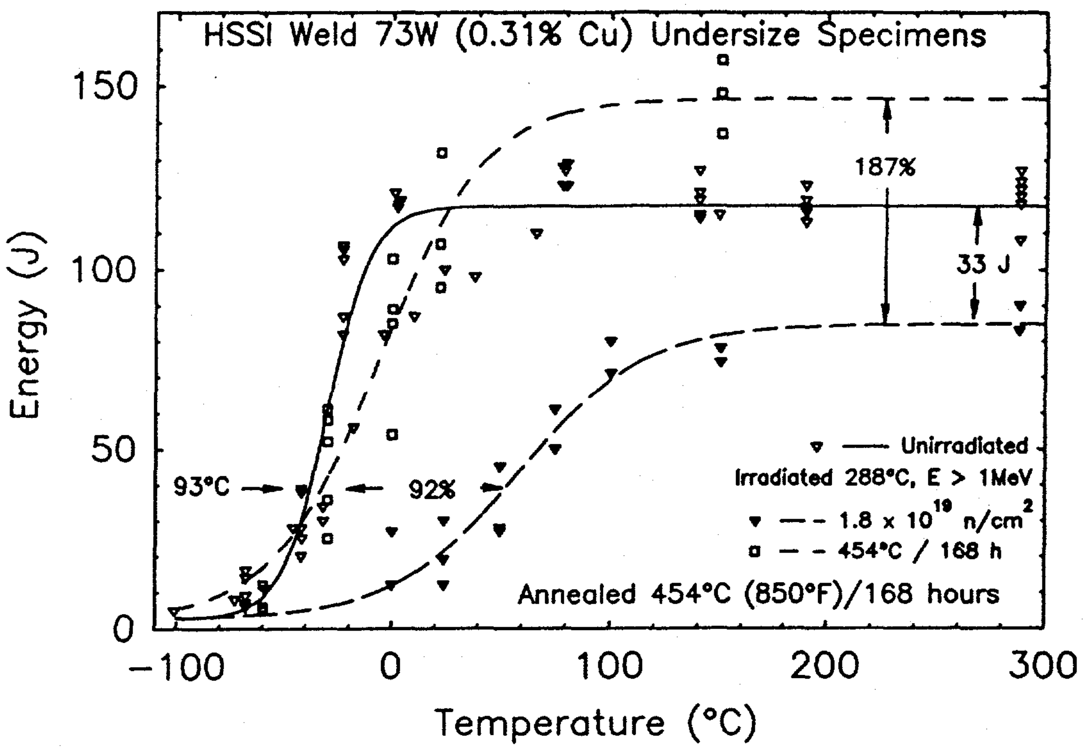

Fig. 1. Charpy energy of HSSI weld 73W in the unirradiated, irradiated, and annealed conditions. The irradiated specimens were annealed at 454°C for 168 h.

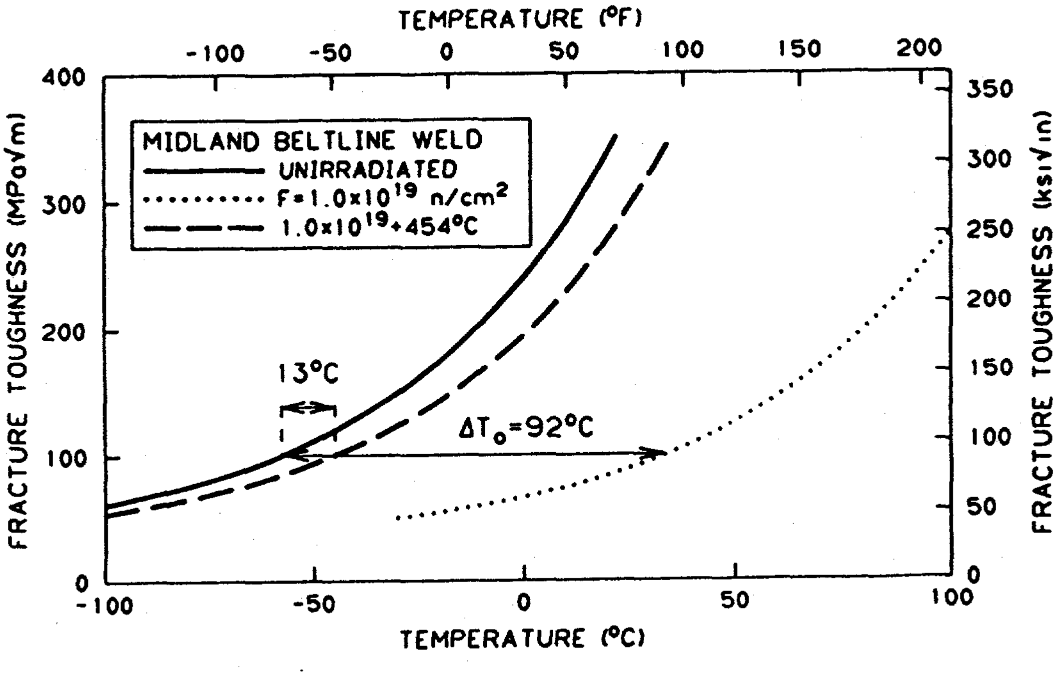

Fig. 2. Median fracture toughness of Midland beltline weld in the unirradiated, irradiated, and irradiated/annealed conditions. The irradiated specimens were annealed at 454°C for 168 h.

Table 3. Transition temperature of materials investigated in the unirradiated, irradiated, and irradiated/annealed conditions

Material condition	Annealing temperature (°C)	Annealing time (h)	Experimental $TT_{41\text{-}J}$ (°C)	Predicted[a] [Eqs. (6)-(9)] (°C)	Difference (predicted − experimental[a]) (°C)
73W undersize, 0.31% Cu, irradiated 1.8 × 10^{19} n/cm^2 at a flux of 3 × 10^{12} n/(cm^2·s) (> 1 MeV)					
Unirradiated			−38		
Irradiated			55		
Irradiated/annealed	343	168	46	36	−10
Irradiated/annealed	454	24	−7	−9	−2
Irradiated/annealed	454	96	−25	−16	9
Irradiated/annealed	454	168	−31	−18	13
Irradiated/annealed	454	336	−34	−21	13
73W full size, 0.31% Cu, irradiated 1× 10^{19} n/cm^2 at a flux of 8 × 10^{11} n/(cm^2·s) (> 1 MeV)					
Unirradiated			−40		
Irradiated			40		
Irradiated/annealed	343	168	26	29	3
Midland beltline weld, 0.21-0.34% Cu, irradiated 1 × 10^{19} n/cm^2 at a flux of 8 × 10^{11} n/(cm^2·s) (> 1 MeV)					
Unirradiated			−9		
Irradiated			95		
Irradiated/annealed	343	168	44	74 to 81	30 to 37
Irradiated/annealed	454	168	15	3 to 13	−12 to −2
Midland nozzle weld, 0.37-0.46% Cu, irradiated 1 × 10^{19} n/cm^2 at a flux of 8 × 10^{11} n/(cm^2·s) (> 1 MeV)					
Unirradiated			−1		
Irradiated			90		
Irradiated/annealed	454	168	31	18	−13
HSST Plate 02, 0.14% Cu, irradiated 1 × 10^{19} n/cm^2 at a flux of 6.43 × 10^{11} n/(cm^2·s) (> 1 MeV)					
Unirradiated, L-T			−16		
Irradiated, estimated			39		
Irradiated/annealed, L-T	343	168	19	25	6
Irradiated/annealed, L-T	454	168	−10	−12	−2

[a] The range of values corresponds to the range of copper content.

Table 4. Upper-shelf energy of materials investigated in the unirradiated, irradiated, and irradiated/annealed conditions

Material condition	Annealing temperature (°C)	Annealing time (h)	Experimental upper-shelf value (J)	Predicted[a] [Eq. (10)] (J)	Difference (predicted – experimental[a]) (J)
73W undersize, 0.31% Cu, irradiated 1.8×10^{19} n/cm^2 at a flux of 3×10^{12} n/(cm^2·s) (> 1 MeV)					
Unirradiated			118		
Irradiated			85		
Irradiated/annealed	343	168	99	103	4
Irradiated/annealed	454	24	128	119	–10
Irradiated/annealed	454	96	130	124	–6
Irradiated/annealed	454	168	147	124	–23
Irradiated/annealed	454	336	154	124	–30
73W full size, 0.31% Cu, irradiated 1×10^{19} n/cm^2 at a flux of 8×10^{11} n/(cm^2·s) (> 1 MeV)					
Unirradiated			135		
Irradiated			99		
Irradiated/annealed	343	168	124	119	–5
Midland beltline weld, 0.21-0.34% Cu, irradiated 1×10^{19} n/cm^2 at a flux of 8×10^{11} n/(cm^2·s) (> 1 MeV)					
Unirradiated			89		
Irradiated			80		
Irradiated/annealed	343	168	92	88 to 84	–3 to –8
Irradiated/annealed	454	168	106	105	–1
Midland nozzle weld, 0.37-0.46% Cu, irradiated 1×10^{19} n/cm^2 at a flux of 8×10^{11} n/(cm^2·s) (> 1 MeV)					
Unirradiated			88		
Irradiated			68		
Irradiated/annealed	454	168	105	103	–2
HSST Plate 02, 0.14% Cu, irradiated 1×10^{19} n/cm^2 at a flux of 8×10^{11} n/(cm^2·s) (> 1 MeV)					
Unirradiated, L-T			164		
Irradiated, estimated			140		
Irradiated/annealed, L-T	343	168	166	159	–7
Irradiated/annealed, L-T	454	168	190	174	–16

[a] The range of values corresponds to the range of copper content.

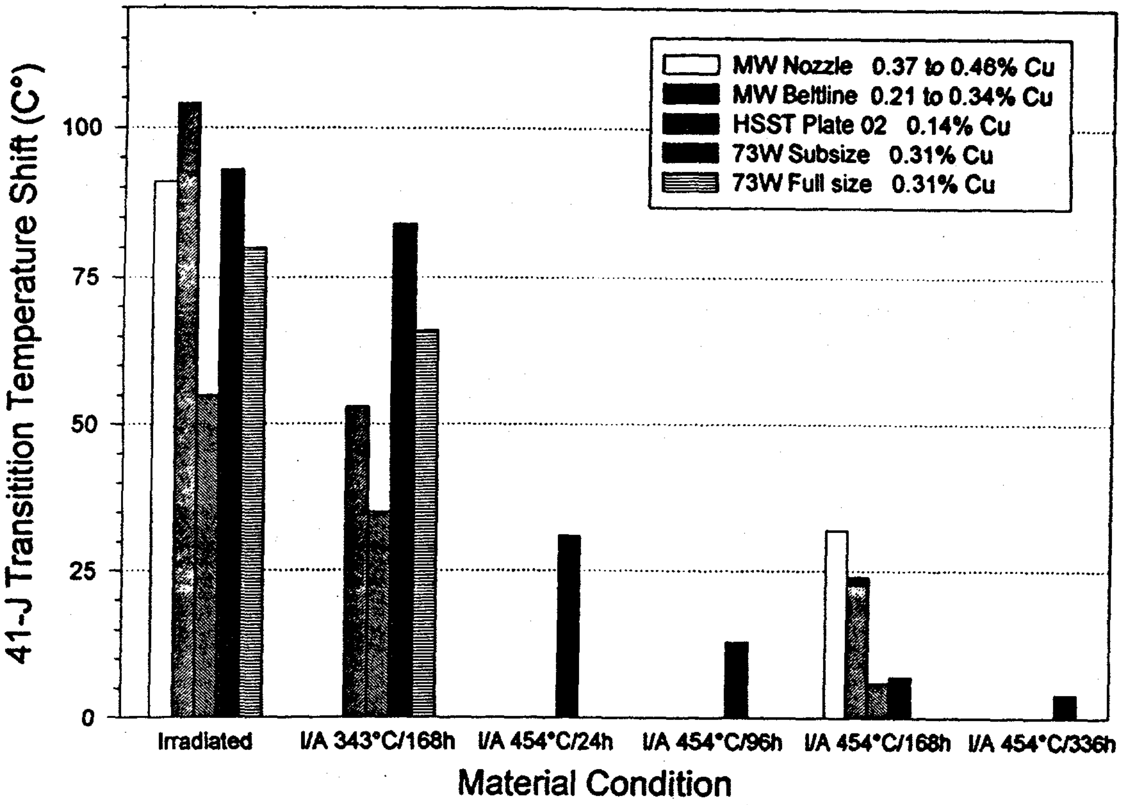

Fig. 3. The Charpy 41-J transition temperature shift for the various materials tested in the unirradiated, irradiated, and irradiated/annealed conditions.

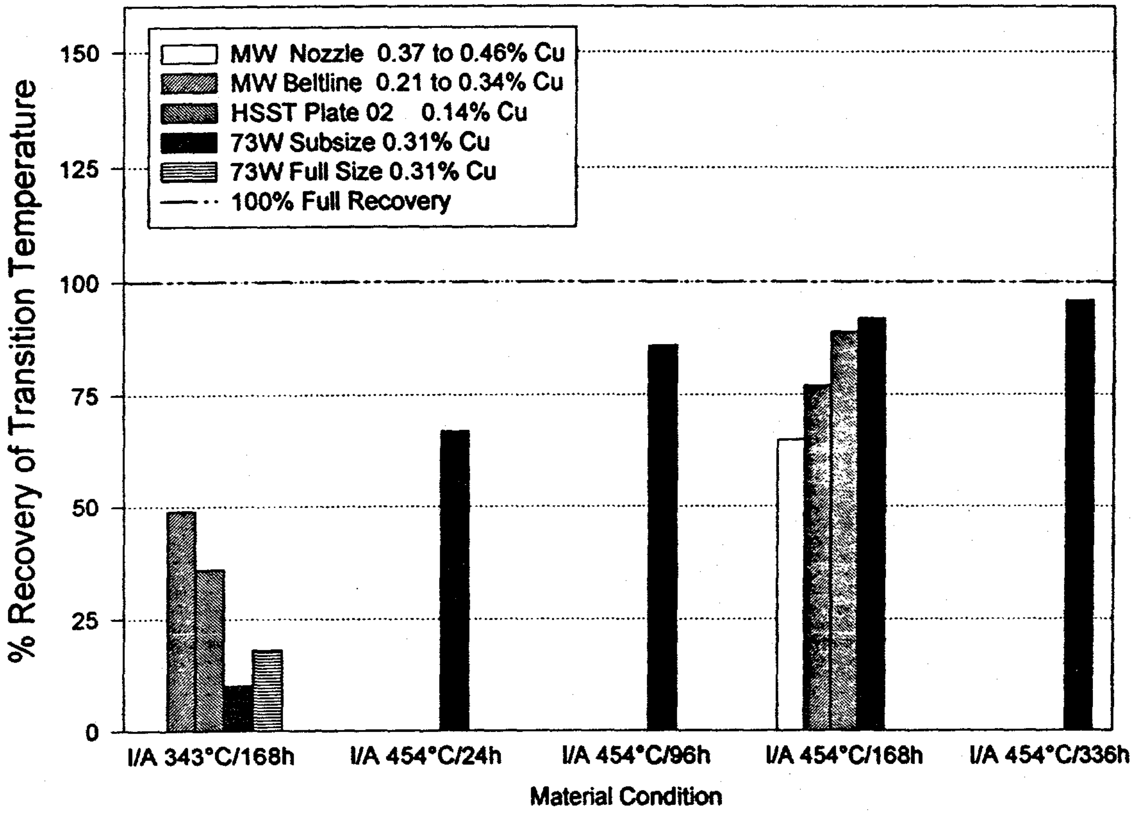

Fig. 4. Percent recovery of the Charpy transition temperature shift due to annealing.

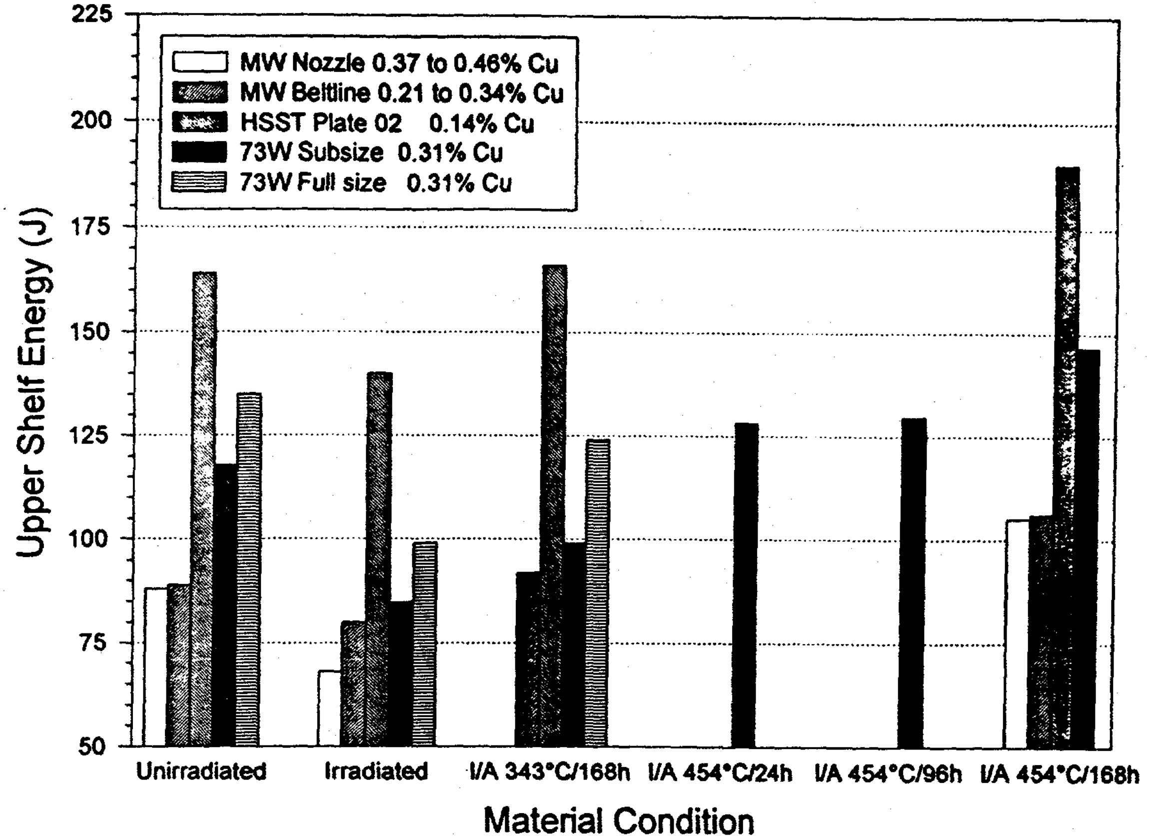

Fig. 5. The Charpy upper-shelf energy for the various materials tested in the unirradiated, irradiated, and irradiated/annealed conditions.

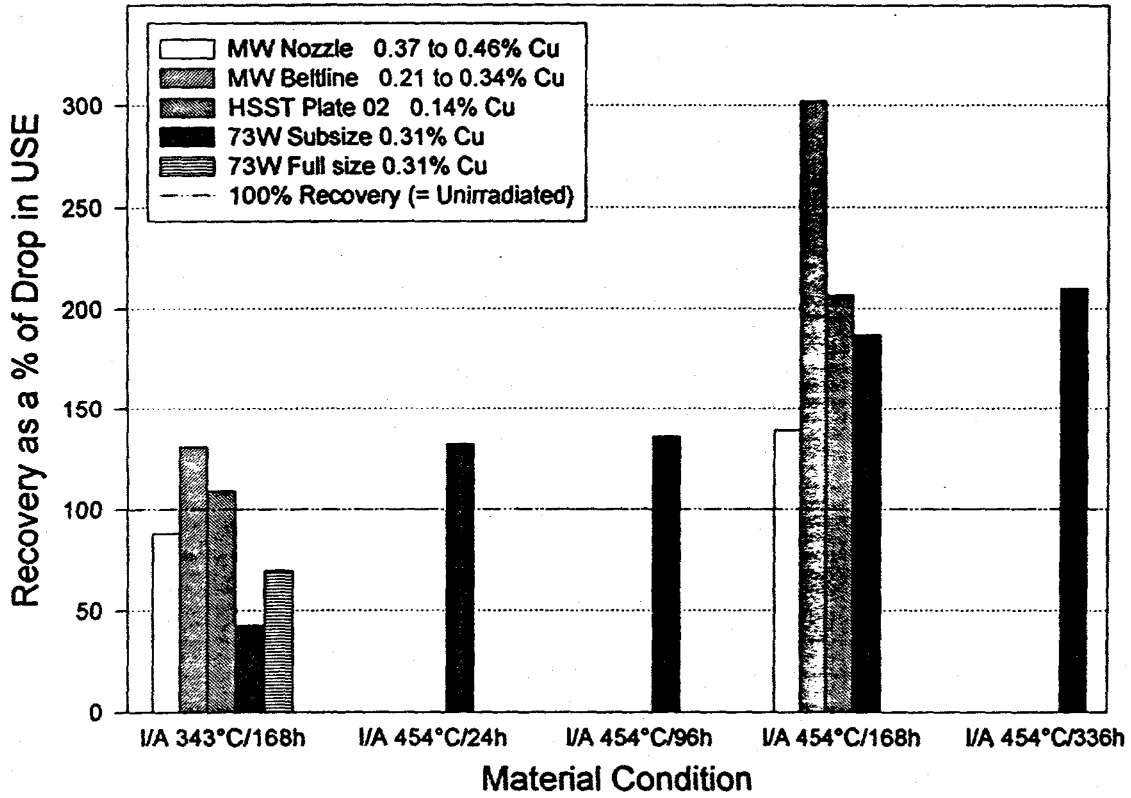

Fig. 6. Recovery as a percentage of Charpy drop in upper-shelf energy for the various materials tested in the unirradiated, irradiated, and irradiated/annealed conditions.

$$a_1 = 1 + 0.0151\ln(t_a) - 0.424\mathrm{Cu}'^{(3.28 - 0.00306T_a)} , \qquad (7)$$

where t_a and T_a are the annealing time and temperature in hours and °F , respectively, and Cu′, in wt %, is the lesser of the measured copper content and 0.30%, and

$$a_2 = 0.584T_i - 15.5\ln(\phi) + 833, \quad T_a \le 750°\mathrm{F} , \qquad (8)$$

or

$$a_2 = 0.584(T_i + 637), \quad T_a \ge 850°\mathrm{F} , \qquad (9)$$

in which ϕ, the flux, is in units of $n/(\mathrm{cm}^2\text{-s})$, and T_i is the irradiation temperature in °F. The standard error is approximately 9.4°C. The values predicted by Eqs. (6) through (9) are given in Table 3, together with the difference between the predicted and experimental values. Both latter values have been plotted in Figs. 7 and 8. It may be noted that, due to the variation in copper content in the Midland weld, a range of values was calculated corresponding to the range in measured copper content. The range of predicted values has also been indicated in Figs. 7 and 8. It may be seen that the values predicted by the model all fall within ± 2 standard errors, except for the MW material annealed 343°C for 168 h, which is over predicted.

The Eason et al. model to predict the recovery of the USE is

$$\mathrm{USE}_{ia} = \mathrm{USE}_i + \left[1 - 0.586\exp\left(\frac{-t_a}{15.9}\right)\right] \times \left[0.570\,\Delta\mathrm{USE}_i + (0.120T_a - 104)\mathrm{Cu} + 0.0389T_a - 17.6\right] , \qquad (10)$$

where the USE is in ft-lb, the subscripts and the remaining parameters are as defined previously. It should be noted that the copper in Eq. (10) is the measured copper content in wt %. The standard error for Eq. (10) is 6.9 J. The predicted USE_{ia}, together with the difference between the predicted and measured values, are given in Table 4. These values have also been plotted in Figs. 9 and 10. The predicted values are generally within ± 2 standard errors, except for HSSI weld 73W annealed at 454°C for 168 and 336 h, which Eq. (10) underpredicted the recovery of the USE.

The rate of toughness degradation of irradiated and annealed RPV steels upon reirradiation is the present focus of investigations at ORNL. This is a major consideration in determining how long an RPV could be operated safely after it is annealed. It is possible that for some of the older RPVs for which annealing will be considered no archival material will be available, and the surveillance data from CVN specimens are the only data available that describe the rate of embrittlement. Thus, relating the rate of toughness degradation due to reirradiation to the rate of transition temperature shift of CVN specimens (the so-called "trend curve") from the unirradiated state becomes important.

CONCLUSIONS

Specimens from irradiated submerged-arc welds and a plate material were annealed at two temperatures for various lengths of time. The following conclusions could be deduced from the results:

1. Annealing has resulted in various degrees of recovery of the transition temperature and USE that depend strongly upon the annealing temperature and to a somewhat lesser degree upon the annealing time.

2. Recovery at the lower annealing temperature investigated, 343°C and for the 168 h annealing time has resulted in recovering most of the USE, but the recovery of the $\mathrm{TT}_{41\text{-}J}$ varied from insignificant to substantial, depending upon the material.

3. For the materials investigated, there appears to be a relationship between the recovery of the $\mathrm{TT}_{41\text{-}J}$ and the recovery of the USE, in that the materials that recovered a substantial portion of the $\mathrm{TT}_{41\text{-}J}$ also recovered the USE to a significant degree. Thus it appears that if the transition temperature recovers, this indicates a high likelihood that the USE will also recover to a significant degree.

4. The percentage recovery of the USE was always greater than the percentage recovery of the Charpy TT.

Research performed to date used previously irradiated material. More studies are needed to determine the fracture toughness behavior and its relationship to the Charpy TT and USE during reirradiation after annealing at several temperatures and for different lengths of time. With regard to the potential use of 343°C as an annealing temperature, the results from the materials investigated show that, in some cases, the recovery of the TT_i was insignificant, but in others it was approximately 50%. It is believed that the subsequent *reembrittlement* rate should be investigated, as it is possible that it may be small enough that further embrittlement will be significantly retarded. Such a low annealing temperature could then be used for vessels that have not yet reached the screening criteria.

ACKNOWLEDGMENTS

This research was sponsored by the Office of Nuclear Regulatory Research, Division of Engineering Technology, U.S. Nuclear Regulatory Commission, under Interagency Agreement DOE 1886-8109-8L with the U.S. Department of Energy under contract DE-AC05-96OR22464 with Lockheed Martin Energy Research Corp. The authors gratefully acknowledge the financial support and encouragement provided by the U.S. Nuclear Regulatory Commission, particularly Alfred Taboada and Michael G. Vassilaros, the previous and present Heavy-Section Steel Irradiation Program Monitors, respectively. The authors also wish to thank Ernie D. Eason and J. E. Wright for their assistance; thanks are also due to Donald E. McCabe, David J. Alexander, and the ASME reviewers for their helpful comments, and Julia L. Bishop for preparation of the camera-ready manuscript.

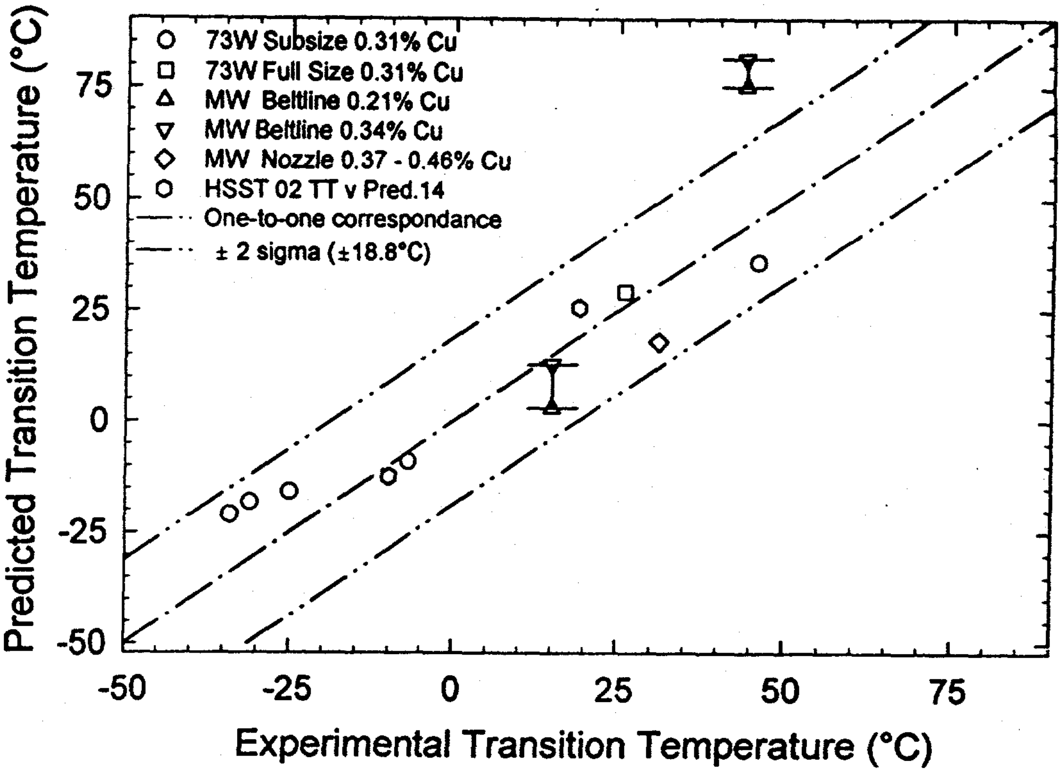

Fig. 7. Comparison of the predicted to the experimental Charpy transition temperature for the various materials tested in the unirradiated, irradiated, and irradiated/annealed conditions.

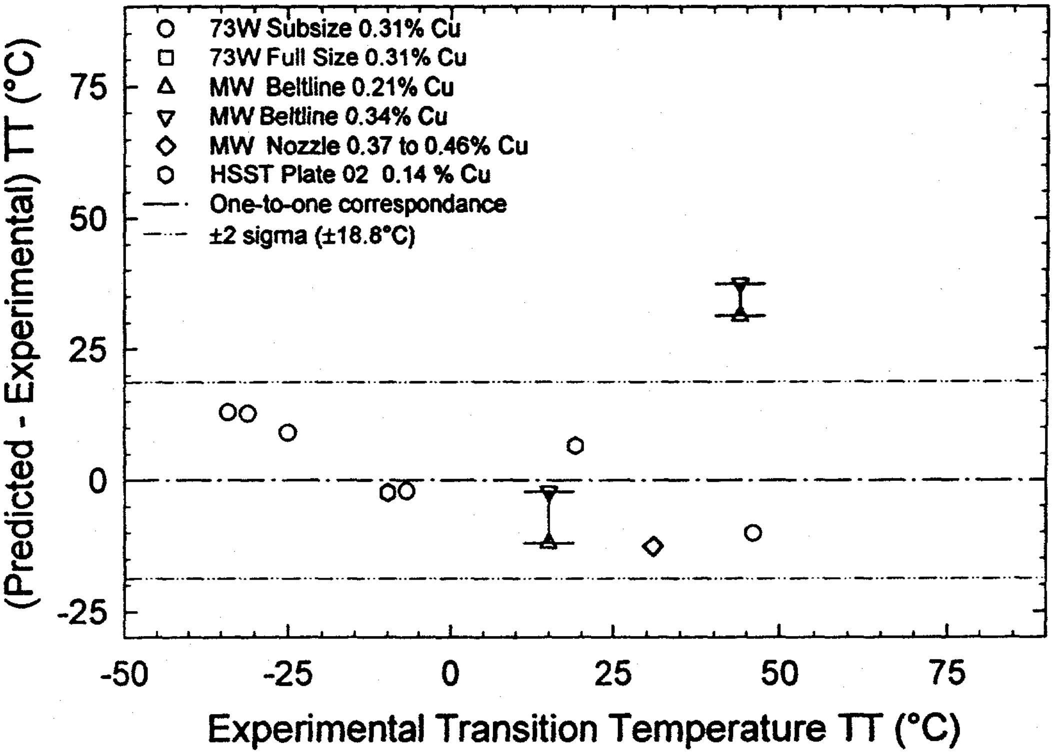

Fig. 8. Residuals of the predicted minus the experimental Charpy transition temperature for the various materials tested in the unirradiated, irradiated, and irradiated/annealed conditions.

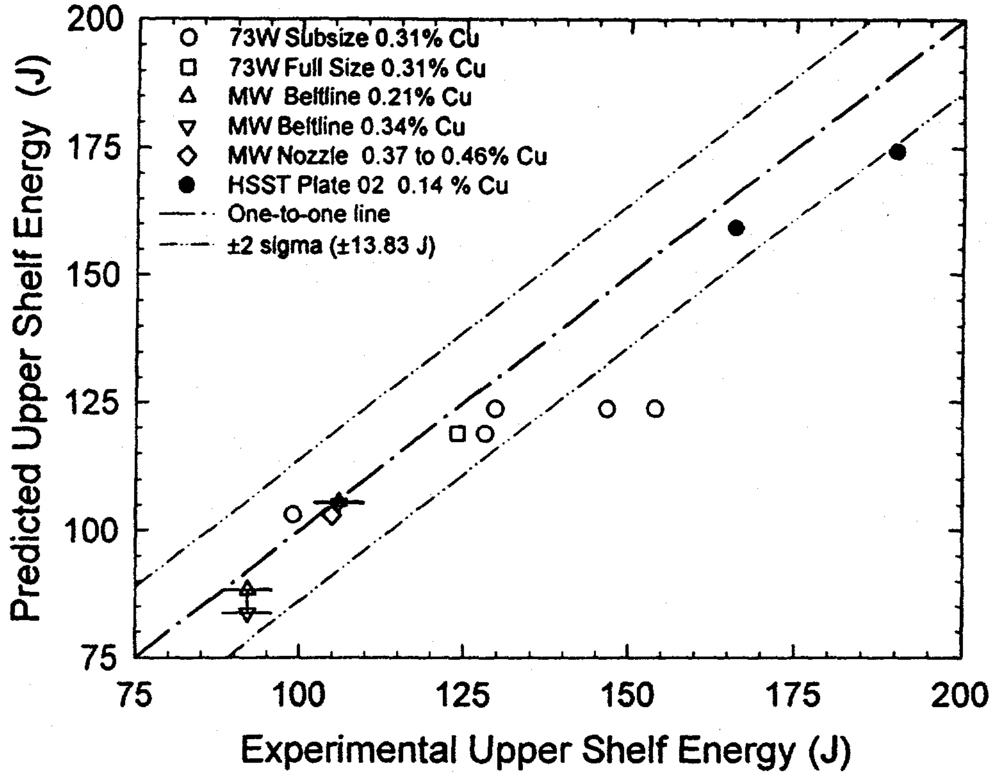

Fig. 9. Comparison of the predicted to the experimental Charpy upper-shelf energy for the various materials tested in the unirradiated, irradiated, and irradiated/annealed conditions.

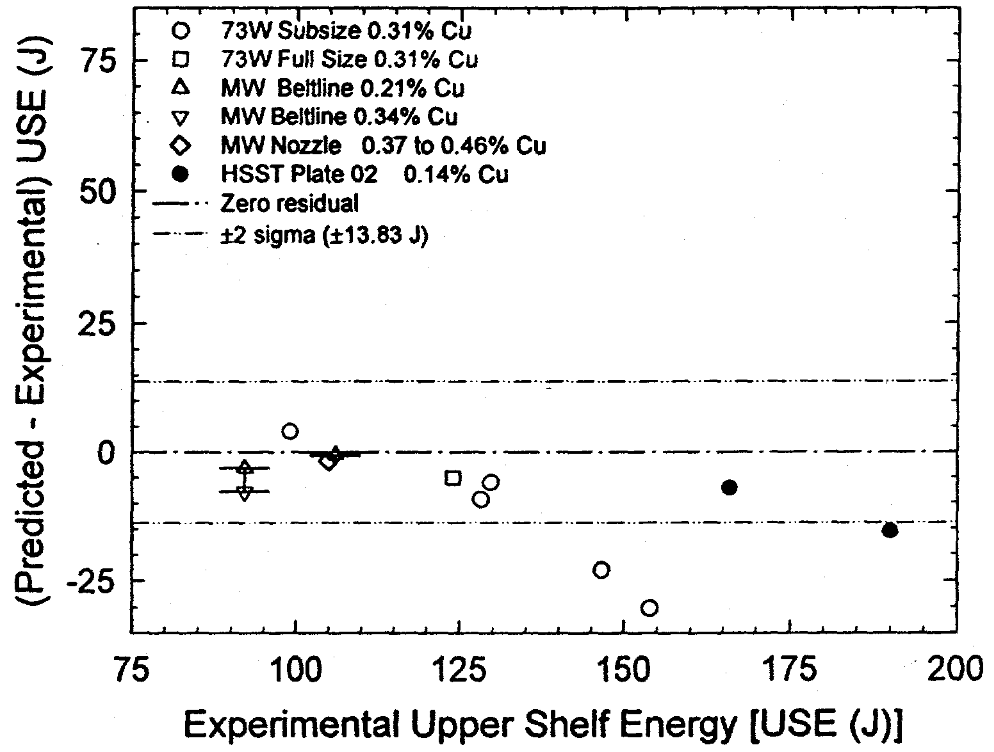

Fig. 10. Residuals of the predicted minus the experimental Charpy upper-shelf energy for the various materials tested in the unirradiated, irradiated, and irradiated/annealed conditions.

REFERENCES

10CFR50, "Title 10," *Code of Federal Regulations*, Part 50, U.S. Government Printing Office, Washington, D.C., published yearly.

10CFR50.66, "Thermal Annealing Rule," *Federal Register*, Vol. 59, No. 191, October 4, 1994.

ASME Boiler and Pressure Code, An American National Standard, 1992 Addenda, Section XI, Article A-4000, American Society of Mechanical Engineers, New York, December 31, 1992.

Eason, E. D., Wright, J. E., Nelson, E. E., Odette, G. R., and Mader, E. V., Modeling and Computing Services Boulder, Colo., *Models for Embrittlement Recovery Due to Annealing of Reactor Pressure Vessel Steels*, USNRC Report NUREG/CR-6327 (MCS 950302), May 1995.

Iskander, S. K., Sokolov, M. A., and Nanstad, R. K., "Effects of Annealing Time on the Recovery of Charpy V-Notch Properties of Irradiated High-Copper Weld Metal," *Effects of Radiation on Materials: 17th Volume, STP 1270*, David S. Gelles, Randy K. Nanstad, Arvind S. Kumar, and Edward A. Little, Editors, American Society for Testing and Materials, Philadelphia, 1996.

Major, T. R., and Lott, R. G., *Thermal Annealing of an Embrittled Reactor Pressure Vessel*, EPRI NP-6113-M, Electric Power Research Institute, Palo Alto, Calif., January 1989.

McCabe, D. E., Nanstad, R. K., Iskander, S. K., and Swain, R. L., Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., *Unirradiated Material Properties of Midland Weld* WF-70, USNRC Report NUREG/CR-6249 (ORNL/TM-12777), October 1994.

Miller, L. F., Baldwin, C. A., Stallman, F. W., Stallmann, and Kam, F. B. K., Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., *Neutron Exposure Parameters for the Metallurgical Test Specimens in the Fifth Heavy-Section Steel Irradiation Series Capsules*, USNRC Report NUREG/CR-5019 (ORNL/TM-10582), March 1988.

Nanstad, R. K., McCabe, D. E., Menke, B. H., Iskander, S. K. Iskander, and Haggag, F. M., "Effects of Irradiation on K_{Ic} Curves for High-Copper Welds," pp. 214-233 in *Effects of Radiation on Materials, 14th International Symposium, (Volume II), ASTM STP 1046*, N. H. Packan, R. E. Stoller, and A. S. Kumar, Editors, American Society for Testing and Materials, Philadelphia, 1990.

Nanstad, R. K. McCabe, D. E., Swain, R. L., and Miller, M. K., Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., *Chemical Composition and RT_{NDT} Determinations for Midland Weld WF-70*, USNRC Report NUREG/CR-5914 (ORNL-6740), December 1992.

Rogov, M., and Morozov, S., "Annealing Application Experience to Extend Reactor Vessel Life," pp. 13-113 to 13-127 in *Proceedings of the DOE/SNL/EPRI Sponsored Reactor Pressure Vessel Thermal Annealing Workshop*, Vol. 2, SAND94-1515/2, Sandia National Laboratories, Albuquerque, New Mexico, 1994.

Stelzman, W. J., Berggren, R. G., and Jones, Jr., T. N., Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., *ORNL Characterization of Heavy-Section Steel Technology Program Plates 01, 02, 03*, USNRC Report NUREG/CR-4092 (ORNL/TM-9491), April 1985.

Sokolov, M. A., McCabe, D. E., Nanstad, R. K and Iskander, S. K., "Comparison of Fracture Toughness and Charpy Impact Properties Recovery by Thermal Annealing of Irradiated Reactor Pressure Vessel Steels," pp. 771-782 in *Proceedings of the Seventh International Symposium on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors*, Geoffrey Airey et al, Editors, Breckenridge, Colorado, August 1995.

Sokolov, M. A., Nanstad, R. K and Iskander, S. K., "The Effect of Thermal Annealing on the Fracture Toughness of Low Upper-Shelf Welds," *Effects of Radiation on Materials: 17th Volume, STP 1270*, David S. Gelles, Randy K. Nanstad, Arvind S. Kumar, and Edward A. Little, Editors, American Society for Testing and Materials, Philadelphia, 1996.

Wallin, K., "Recommendations for the Application of Fracture Toughness Data for Structural Integrity Assessments," pp. 465-495 in *Proceedings of the Joint IAEA/CSNI Specialists' meeting on Fracture Mechanics Verification by Large-Scale Testing*, NUREG/CP-0131 (ORNL/TM-12413), October 1993.