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APPLICATION OF SMALL SPECIMENS TO FRACTURE MECHANICS CHARACTERIZATION OF IRRADIATED PRESSURE VESSEL STEELS

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APPLICATION OF SMALL SPECIMENS TO FRACTURE MECHANICS CHARACTERIZATION OF IRRADIATED PRESSURE VESSEL STEELS

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ABSTRACT: In this study, precracked Charpy V-notch (PCVN) specimens were used to characterize the fracture toughness of unirradiated and irradiated reactor pressure vessel steels in the transition region by means of three-point static bending. Fracture toughness at cleavage instability was calculated in terms of elastic-plastic K_{Jc} values. A statistical size correction based upon weakest-link theory was performed. The concept of a master curve was applied to analyze fracture toughness properties. Initially, size-corrected PCVN data from A 533 grade B steel, designated HSST Plate 02, were used to position the master curve and a 5% tolerance bound for K_{Jc} data. By converting PCVN data to 1T compact specimen equivalent K_{Jc} data, the same master curve and 5% tolerance bound curve were plotted against the Electric Power Research Institute valid linear-elastic K_{Ic} database and the ASME lower bound K_{Ic} curve. Comparison shows that the master curve positioned by testing several PCVN specimens describes very well the massive fracture toughness database of large specimens. These results give strong support to the validity of K_{Jc} with respect to K_{Ic} in general and to the applicability of PCVN specimens to measure fracture toughness of reactor vessel steels in particular. Finally, irradiated PCVN specimens of other materials were tested, and the results are compared to compact specimen data. The current results show that PCVNs demonstrate very good capacity for fracture toughness characterization of reactor pressure vessel steels. It provides an opportunity for direct measurement of fracture toughness of irradiated materials by means of precracking and testing Charpy specimens from surveillance

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capsules. However, size limits based on constraint theory restrict the operational test temperature range for K_{Jc} data from PCVN specimens.

KEYWORDS: precracked Charpy, fracture toughness, master curve, reconstitution, reactor pressure vessel

INTRODUCTION

The American Society of Mechanical Engineers (ASME) K_{Ic} curve is based upon data acquired by testing large specimens of unirradiated reactor pressure vessel (RPV) steels and weld metals that satisfy the validity requirements of the American Society for Testing and Materials (ASTM) Standard Test Method for Plane-Strain Fracture Toughness of Metallic Materials (E 399-90). Currently, the provisions for determination of the upward temperature shift of the ASME K_{Ic} curve due to irradiation of reactor pressure vessel steels are based on the Charpy 41-J shift, and the shape of the fracture toughness curve is assumed not to change as a consequence of irradiation. The main reason for such assumptions was that it is not practicable to accumulate the equivalent linear-elastic K_{Ic} data base for irradiated material in the transition region. In fact, the maximum size of compact specimens for irradiation studies is limited to 4T (101.6 mm) simply due to through-thickness fluence gradients. With testing of small specimens in the transition region, some amount of local crack tip plasticity is unavoidable and fracture toughness up to cleavage instability is calculated in terms of size-dependent elastic-plastic K_{Jc} values. Therefore, for a ductile-to-brittle transition region a statistical size correction based upon weakest-link theory has been proposed [1].

In this study, precracked Charpy V-notch (PCVN) specimens were used to characterize fracture toughness of unirradiated and irradiated reactor pressure vessel steels in the transition region by means of three-point slow bending. The PCVN specimens were fatigue precracked to a/W ratio of about 0.5. A method employing Weibull statistics was applied to model fracture toughness data distributions in the transition region and a master curve concept was used to describe the temperature dependence of fracture toughness. The PCVN specimen has exceptional application for reactor pressure vessels. The Charpy V-notch specimen is the most commonly used specimen geometry in surveillance programs. Precracking and testing of irradiated Charpy surveillance specimens would allow one to determine and monitor directly actual fracture toughness of an irradiated vessel instead of indirect evaluations using correlations established with impact data.

How well PCVN K_{Jc} data compare to compact specimen K_{Jc} data and how well a PCVN specimen generated master curve lower tolerance bound compares to the ASME lower-bound K_{Ic} curve, will be examined in this paper.

ANALYSIS PROCEDURE

The fracture toughness data were analyzed by a procedure based on earlier work described in Ref. [2] and developed in a proposed ASTM draft standard, [3], by applying the statistical model of Weibull [4]. The analysis procedure is based on fitting replicated fracture toughness data to a three-parameter Weibull cumulative distribution function at the test temperature. It was determined in Ref. [2], at least for reactor pressure vessel steels, that among these three parameters, the shape parameter (Weibull slope) is equal to 4 and the location parameter, K_{min}, is about 20 MPa√m. Fixing the slope b = 4 and K_{min} = 20 gives the Weibull cumulative probability distribution function as:

$$P_f = 1 - \exp\left[-\left(\frac{K_{Jc}-20}{K_o-20}\right)^4\right], \tag{1}$$

where P_f is the cumulative fracture probability for $K \le K_{Jc}$ and K_o is a specimen thickness and temperature-dependent scale parameter. Thus, only the scale parameter, K_o, needs to be determined. As a consequence, only a few replicate tests are needed to obtain this parameter with good accuracy. The proposed ASTM practice, Ref. [3], requires at least six replicated tests. The procedure employs the maximum likelihood concept regarded as the most accurate method of obtaining K_o:

$$K_o = \left[\frac{\sum_{i=1}^{N}(K_{Jc(i)}-20)^4}{N-1+\ln 2}\right]^{1/4} + 20,\ MPa\sqrt{m} \tag{2}$$

where $K_{Jc(i)}$ represents each datum obtained at the given test temperature. The term N is the total number of replicate data at that test temperature. Occasionally with the testing of small specimens, a data set may contain an invalid K_{Jc} value, and, in such cases, Eq. (2) i modified to handle censored (invalid) data. This procedure is described in Ref. [3] and requires at least six valid data to proceed. Additionally, weakest-link theory is used [1] to explain statistical specimen size effects so that data, for example, equivalent to that for a 1T size specimen, $K_{Jc(1T)}$, can be calculated from data measured with specimens of different sizes, $K_{Jc(xT)}$:

$$K_{Jc(1T)} = 20 + [K_{Jc(xT)}-20]\left[\frac{B_{(xT)}}{B_{(1T)}}\right]^{1/4},\ MPa\sqrt{m} \tag{3}$$

where $B_{(xT)}$ and $B_{(1T)}$ are the test specimen and 1T size specimen thicknesses, respectively. Statistical size correction is based on the fact that the cleavage fracture in the transition range is initiated by small microstructural defects that are always present in commercially produced reactor pressure vessel steels. Thus, the thicker the specimen being tested, the higher the probability of encountering the trigger point of a critical size on the crack tip front at a critical stress state and, as result, measuring lower fracture toughness than with a specimen of smaller thickness. Equation (3) is the mathematical expression for these statistical effects. Finally, knowing all of the parameters of the distribution allows one to determine the median K_{Jc} toughness for a specimen of chosen reference size, usually a 1T C(T), $K_{Jc(med)}$, at a given temperature; the K_{Jc} value at $P_f = 0.5$.

Thus, the current procedure provides a tool to describe the scatter of fracture toughness data in the transition region and to determine median K_{Jc} (1T) value by means of performing a few replicate tests. However, the application of this procedure to small specimens has some limitations. On the high-temperature side small specimens are limited by specimen capacity to maintain constraint. As the lower-shelf toughness at low temperatures is approached, the statistical size effects diminish since the fracture becomes more and more propagation controlled and Eq. (3) becomes inapplicable because the initiation criterion is no longer dominant. These mean that the test temperature range for small specimens is quite narrow in order to provide data acceptable for the current analysis procedure. Practically, PCVN specimens provide reliable data at $K_{Jc(med)}$ values equal to or slightly below 100 MPa√m.

For structural ferritic steels however, $K_{Jc(med)}$ values tend to form transition temperature curves of the same universal shape which is known now as the "master curve." The master curve of $K_{Jc(med)}$ for 1T size specimens in the transition region is described by:

$$K_{Jc(med)}^{\;1T} = 30 + 70\exp[0.019(T - T_{100})],\ MPa\sqrt{m} \tag{4}$$

where T_{100} is the reference temperature at which $K_{Jc(med)}^{1T}$ is 100 MPa√m. Thus, having the temperature dependence of fracture toughness fixed by Eq. (4) permits obtaining a reliable value of $K_{Jc(med)}$ from PCVN specimens at one temperature and then estimating the whole transition region curve by means of the master curve.

TEST OF HSST PLATE 02

Initial tests were performed on ASTM A 533 grade B class 1 plate, designated HSST Plate 02. PCVN specimens were tested in three-point slow bending. Load versus load-point displacement was measured. The 1T compact specimens of the same orientation (T-L) and location in the plate have been previously tested as a part of the Heavy-Section Steel Technology Program (HSST) performed at Oak Ridge National Laboratory (ORNL) [5]. Table 1 summarizes test and analysis results for this plate. Four test temperatures were selected based on 1T specimen data. The lowest test temperature was –50°C. Seven PCVN specimens were tested at this temperature and the parameter K_o is equal to 91.9 MPa√m, see Table 1. The median toughness value adjusted to 1T equivalence by Eq. (3) is reported in Table 1. Finally, the reference transition temperature, T_{100}, as determined by rearranging Eq. (4) was –23°C. Seven specimens were tested at –30°C and, although this test temperature was only 20° higher, one K_{Jc} value slightly exceeded the constraint limit currently set in Ref. [3] by the following:

$$K_{Jc(limit)} = \left(\frac{E b_o \sigma_y}{30}\right)^{1/2},\ MPa\sqrt{m} \tag{5}$$

where E is elastic modulus, b_o is the initial remaining ligament dimension, and σ_y is the yield strength. The yield strength for HSST Plate 02 was calculated by $\sigma_y = 492 - 0.842T + 0.00234T^2$ from Ref. [5]. According to the proposed ASTM draft standard [3], the invalid data point was censored and assigned the $K_{Jc(limit)}$ toughness value. Then, the K_o was determined by:

$$K_o = \left[\frac{\sum_{i=1}^{N} (K_{Jc(i)} - 20)^4}{r - 1 + \ln 2} \right]^{1/4} + 20, \ MPa\sqrt{m} \tag{6}$$

where r is the number of valid data (six in this case) and N is the total number of valid and invalid K_{Jc} values. The reference fracture toughness temperature determined from this data set is –26°C. The difference between two estimates is only 3°C, which indicates that median toughness values determined by PCVNs fit very well to the shape of the master curve. The average of these two values, –25°C, is used as the reference fracture toughness temperature determined by testing of PCVN specimens in following evaluations of HSST Plate 02 properties. The third data set illustrates how narrow the operational test temperature range is for PCVN specimens based on the constraint limit set by Eq. (5). Although the test temperature was increased by 15°C only, all seven tests gave invalid K_{Jc} results. Finally, seven specimens were tested at 15°C and only six of them cleaved after some slow-stable crack extension. Results from the last two sets of data are included in Table 1 for information only.

Figure 1 reviews fracture toughness data for HSST Plate 02 derived by testing 1T compact [5] and precracked Charpy specimens. The PCVN data, both valid and invalid, are plotted after adjustment to 1T size. Dotted lines represent the upper-shelf validity limits by Eq. (5) for corresponding specimen sizes assuming $b_o = 0.5W$. The validity limit for PCVN specimens is also adjusted to 1T size. The master curve and 5 and 95% tolerance bounds evaluated from testing of PCVN specimens ($T_{100} = -25$°C) are presented on the same plot, see Fig. 1. Tolerance bounds are calculated using following [3]:

$$K_{Jc(0.95)} = 34.6 + 102.2\exp[0.019(T - T_{100})], \ MPa\sqrt{m} \tag{7}$$

$$K_{Jc(0.05)} = 25.4 + 37.8\exp[0.019(T - T_{100})]. \ MPa\sqrt{m} \tag{8}$$

Figure 1 shows that the analysis procedure described here provides a powerful tool to describe fracture toughness K_{Jc} properties in the transition region by testing limited numbers of PCVN specimens. Together with the advantages, these data also highlight the limitation on PCVN specimens due to the constraint limit imposed by Eq. (5). In other words, K_{Jc} values from PCVN specimens can be as good as those from larger compact

TABLE 1–Results of PCVN specimen data analysis of HSST Plate 02.

T_{test} (°C)	K_{Jc} (MPa√m)	b_o (mm)	$K_{Jc(limit)}$ (MPa√m)	K_o (MPa√m)	$K_{Jc(med)}^{1T\ adj}$ (MPa√m)	T_{100} (°C)
–50	79.23	4.94	136.66	91.90	72.17	–23
	82.21	4.69	133.16			
	85.77	4.76	134.15			
	92.99	4.84	135.27			
	93.44	4.13	124.96			
	94.56	5.14	139.40			
	101.67	4.78	134.43			
–30	96.20	4.86	132.58	122.88	94.65	–26
	101.83	4.52	127.86			
	109.37	5.01	134.61			
	121.46	5.14	136.34			
	121.66	5.20	137.14			
	126.57	4.75	131.07			
	147.63	4.77	131.35			
–15	141.85	4.48	125.28	N/A	N/A	N/A
	149.24	4.73	128.73			
	152.04	5.20	134.97			
	163.07	4.78	129.41			
	173.68	4.91	131.15			
	174.65	4.91	131.15			
	178.36	4.86	130.49			
15[a]	238.93	5.05	129.11	N/A	N/A	N/A
	242.79	5.43	133.88			
	268.93	5.39	133.38			
	280.91	5.46	134.25			
	281.00	5.35	132.89			
	300.30	5.05	129.11			
	304.29[b]	4.81	126.00			

[a] All specimens tested at this temperature were 20% side-grooved.

[b] End of test value; specimen did not cleave.

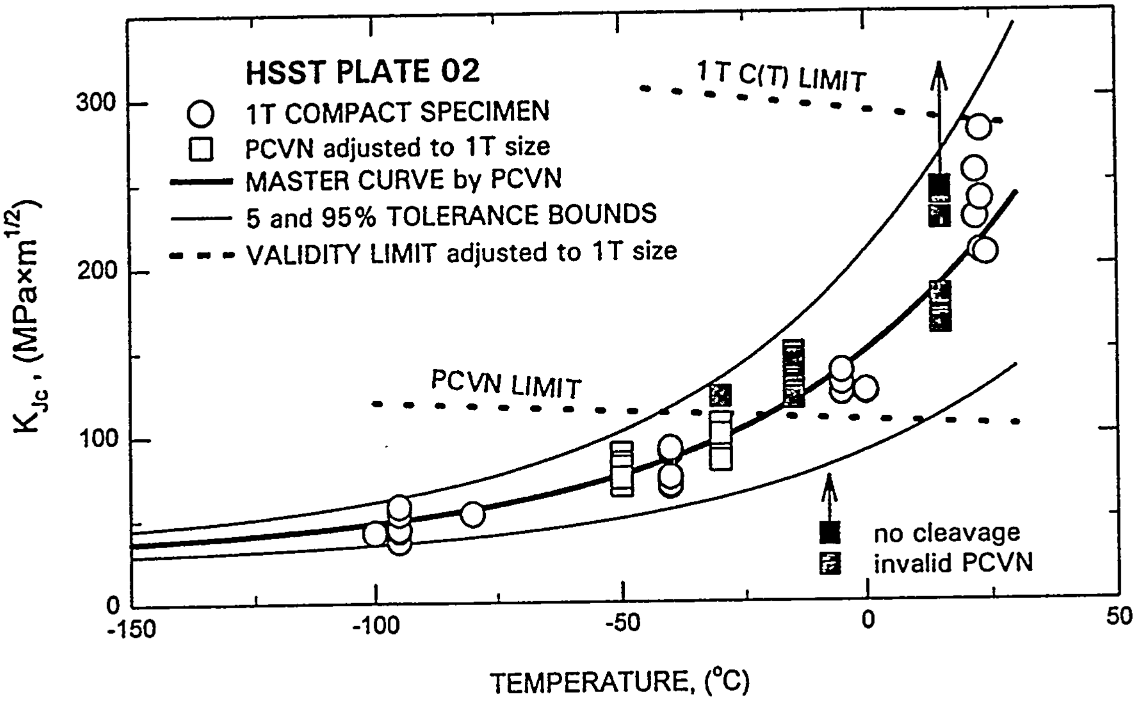

FIG. 1--Elastic-plastic fracture toughness, K_{Jc}, of A 533 grade B HSST Plate 02 determined by 1T compact and precracked Charpy specimens.

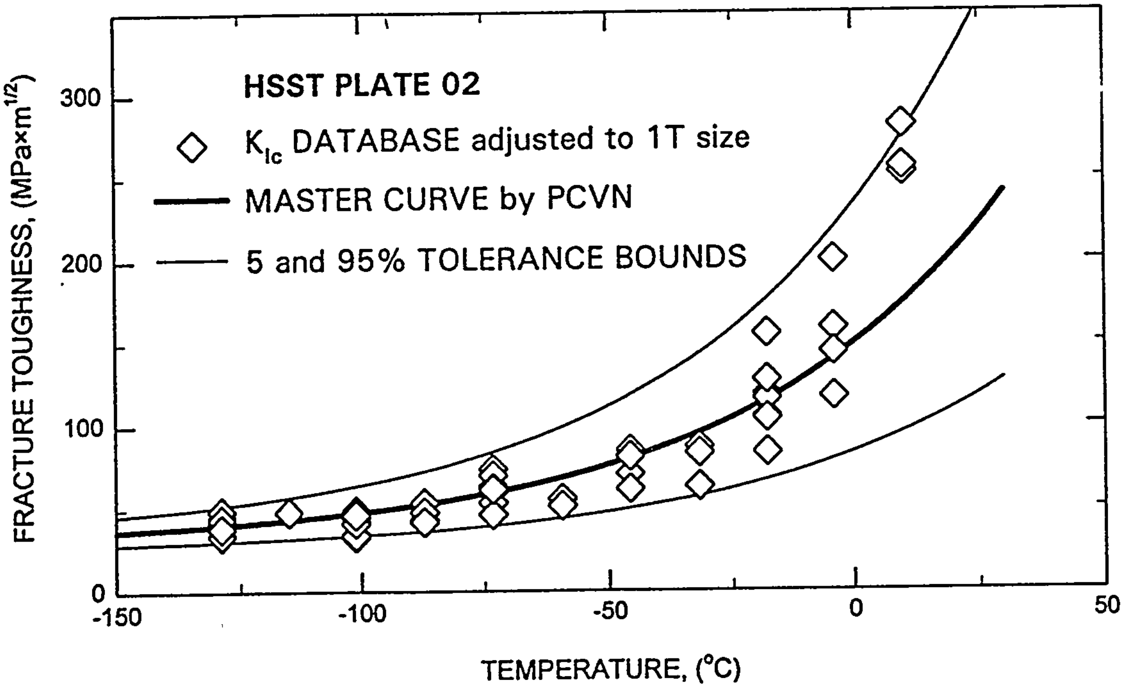

FIG. 2--Comparison of the HSST Plate 02 linear-elastic K_{Ic} database relative to the master curves with 5 and 95 % margin-adjusted tolerance bound curves derived by testing of several PCVN specimens.

specimens but caution needs to be applied in the selection of a test temperature in order to have valid K_{Ic} data.

RELEVANCE TO THE ASME K_{Ic} CURVE

The ASME K_{Ic} curve was constructed as a lower bound to its respective linear-elastic K_{Ic} database for reactor pressure vessel steels [6] plotted as a function of test temperature (T) normalized to a reference nil-ductility temperature, RT_{NDT}, namely, $T - RT_{NDT}$. The RT_{NDT} is derived from a combination of drop-weight and Charpy impact test results. The majority of the ASME database is represented by the HSST Plate 02.

Obviously none of the K_{Jc} values from PCVN specimens reported in Table 1 could satisfy the validity requirements for linear-elastic K_{Ic} stated in ASTM E 399-90. Lower bound fracture toughness has, for many years, been believed to be achievable only through valid K_{Ic} data. Therefore, a question remains regarding the relevance of properties evaluated by the "master curve" procedure to the ASME lower-bound K_{Ic} curve. We will approach this question in two steps. First, the same master curve evaluated by testing PCVN specimens will be compared to the linear-elastic K_{Ic} data of HSST Plate 02 from Ref. [6], see Fig. 2. These K_{Ic} data have been obtained by testing of seventy specimens of different sizes up to 11T thickness. The statistical size correction by Eq. (3) is applied to adjust the data to 1T size equivalence. In order to cover uncertainty in T_o due to testing only a few specimens, a margin, ΔT_{100}, is added to tolerance bounds. The margin is equal to:

$$\Delta T_{100} = \sigma(Z_{85}) \tag{9}$$

were σ is standard deviation and Z_{85} is the tabulated two-tail normal deviate for the specified probability (we used 85%). Standard deviation for estimates on T_{100} is approximated as $\sigma = 18°C/\sqrt{N}$, where N is the total number of specimens that were used to obtain T_{100}. In our case $N = 14$. Z_{85} is of 1.44. Thus, ΔT_{100} is equal to 7°C. Figure 2 shows that the master curve and the 5 and 95% margin-adjusted tolerance bounds derived from testing of several PCVN specimens represents very well the large K_{Ic} database accumulated by testing of massive specimens.

Having success in describing the K_{Ic} database by the master curve from PCVN specimens of the same material, the next step is the direct comparison between the ASME lower bound curve and the 5% margin-adjusted tolerance bound curve, see Fig. 3. All 174 K_{Ic} data from the EPRI database were re-examined and checked for accuracy in Ref. [7] and these data are also plotted on this figure. The top and right axes are in English units which is usual when relative temperature, $T - RT_{NDT}$, is expressed in °F. The first ASME curve was manually constructed as the lower boundary to all K_{Ic} values available at that time in a normalized temperature range, $T - RT_{NDT}$, from −100 to +100°F. More recently, such graphical representation has been replaced by the so-called EPRI equation which in SI units is as follows:

$$K_{Ic} = 36.5 + 3.083 \exp[0.036(T - RT_{NDT} + 55.6)].\ MPa\sqrt{m} \tag{10}$$

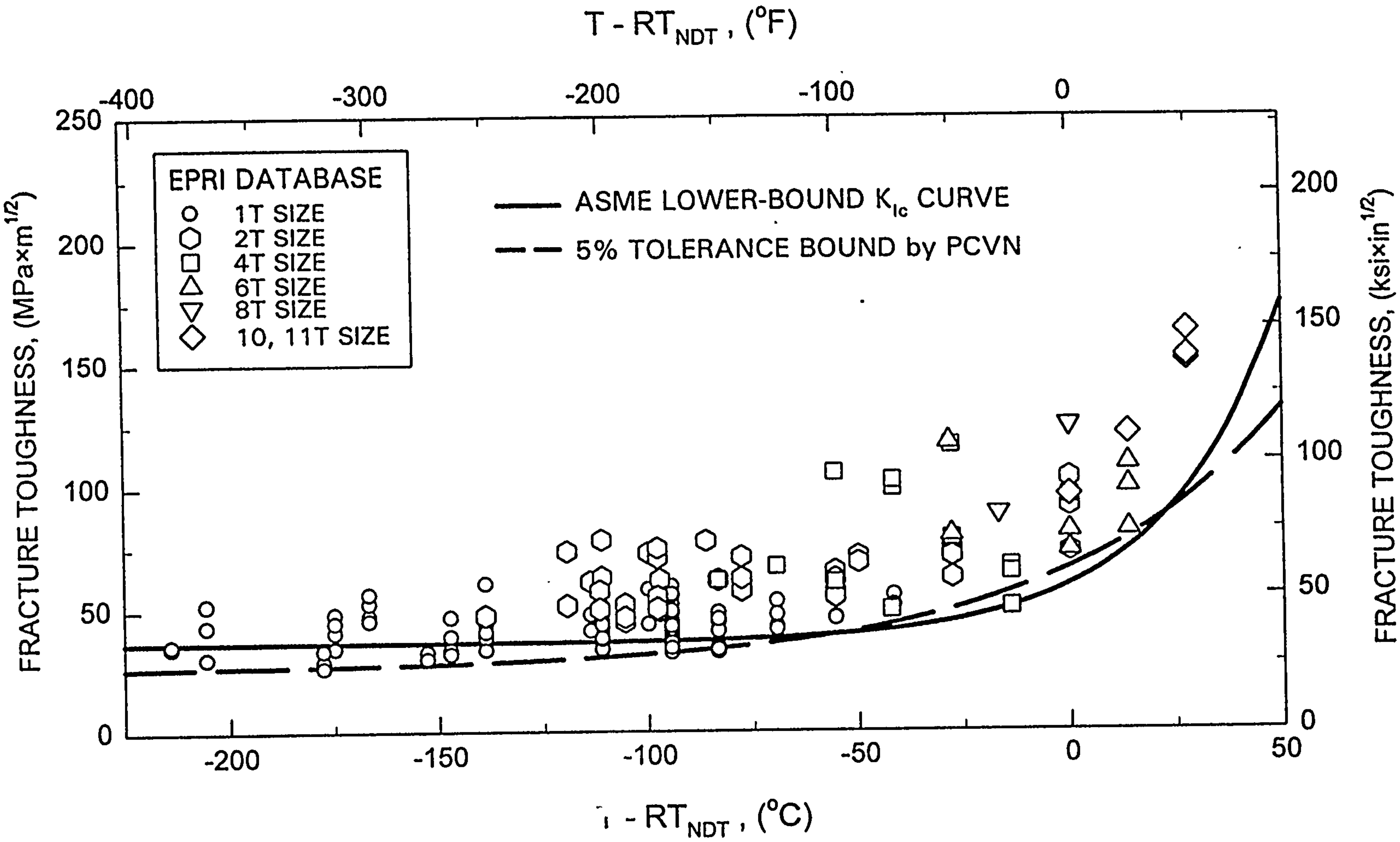

FIG. 3--Comparison of the K_{Ic} EPRI database and ASME lower-bound curve relative to the 5% margin-adjusted tolerance bound curve derived by testing of several PCVN specimens of HSST Plate 02.

For a comparison, the 5% margin-adjusted tolerance bound curve derived from testing of PCVN specimens of HSST Plate 02 in the temperature coordinate normalized to RT_{NDT},[3] including the effect of ΔT_{100}, is equal to:

$$K_{Jc(0.05)} = 25.4 + 37.8\exp[0.019(T - RT_{NDT})],\ MPa\sqrt{m} \tag{11}$$

In Fig. 3, Eqs. (10) and (11) are both plotted over the full temperature range of the K_{Ic} data. The first observation is that Eq. (10) is only a fitting function for the data in the temperature range –100°F to +100°F, hence it is not a true lower bound to all of the data. In fact, the 5% tolerance bound curve from the present study suits better as the lower-bound to the total EPRI database. In the transition region, the ASME K_{Ic} curve rises more rapidly than the tolerance bound to the master curve. The deviation starts at $T - RT_{NDT}$ above 25°C. On the other hand, this is the region where almost no K_{Ic} data are available. Thus, the shape of the ASME curve at $T - RT_{NDT}$ above 25°C reflects rather a postulated shape, while the master curve concept has been experimentally proven to describe the scatter of elastic-plastic-based fracture toughness values in the transition region. In this discussion however, the caution regarding the necessity for using only valid K_{Ic} data is relaxed by applying the master curve based on K_{Jc} data to describe the scatter of K_{Ic} data of the same material and also the total K_{Ic} database. The specific advantage of the present results is that the master curve was developed from PCVN specimens.

TEST OF RECONSTITUTED PCVN SPECIMENS

Recent progress in reconstitution by welding of Charpy-size specimens from previously broken surveillance specimen halves [8] opens a new area for the PCVN specimen application. Reconstituted surveillance PCVN specimens can be used for direct measurements of fracture toughness of reactor pressure vessels in the irradiated condition and/or, for example, for an evaluation of benefits from possible thermal annealing. Reconstituted PCVN specimens are also good candidates for a supplemental surveillance program. In the present study, PCVN specimens were reconstituted by a welding technique described in Ref. [9] from the broken halves of previously tested crack-arrest specimens of a RPV submerged-arc weld, designated as HSSI weld 73W.

The HSSI weld 73W has been well characterized as a part of the Heavy-Section Steel Irradiation (HSSI) Program Fifth Irradiation Series [10]. Seventy-eight compact specimens ranging in sizes from 1T to 8T were tested in the unirradiated condition at ORNL and Materials Engineering Associates to characterize the transition region. These data are compared to reconstituted PCVN specimen data from the present study in Fig. 4. The scatter of fracture toughness data is well described by the master curve with 5 and 95% margin-adjusted tolerance bounds obtained only from PCVN specimen data. Eleven PCVN specimens were tested over the temperature range. Utilizing the postulates already discussed [Eqs. (1) through (4)], each K_{Jc} value was used to calculate T_{100} from individual data points and then the maximum likelihood estimate of T_{100} for this set was determined

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[3] In this case, $T_{100} = -25$°C, $RT_{NDT} = -18$°C(0°F), and $\Delta T_{100} = 7$°C.

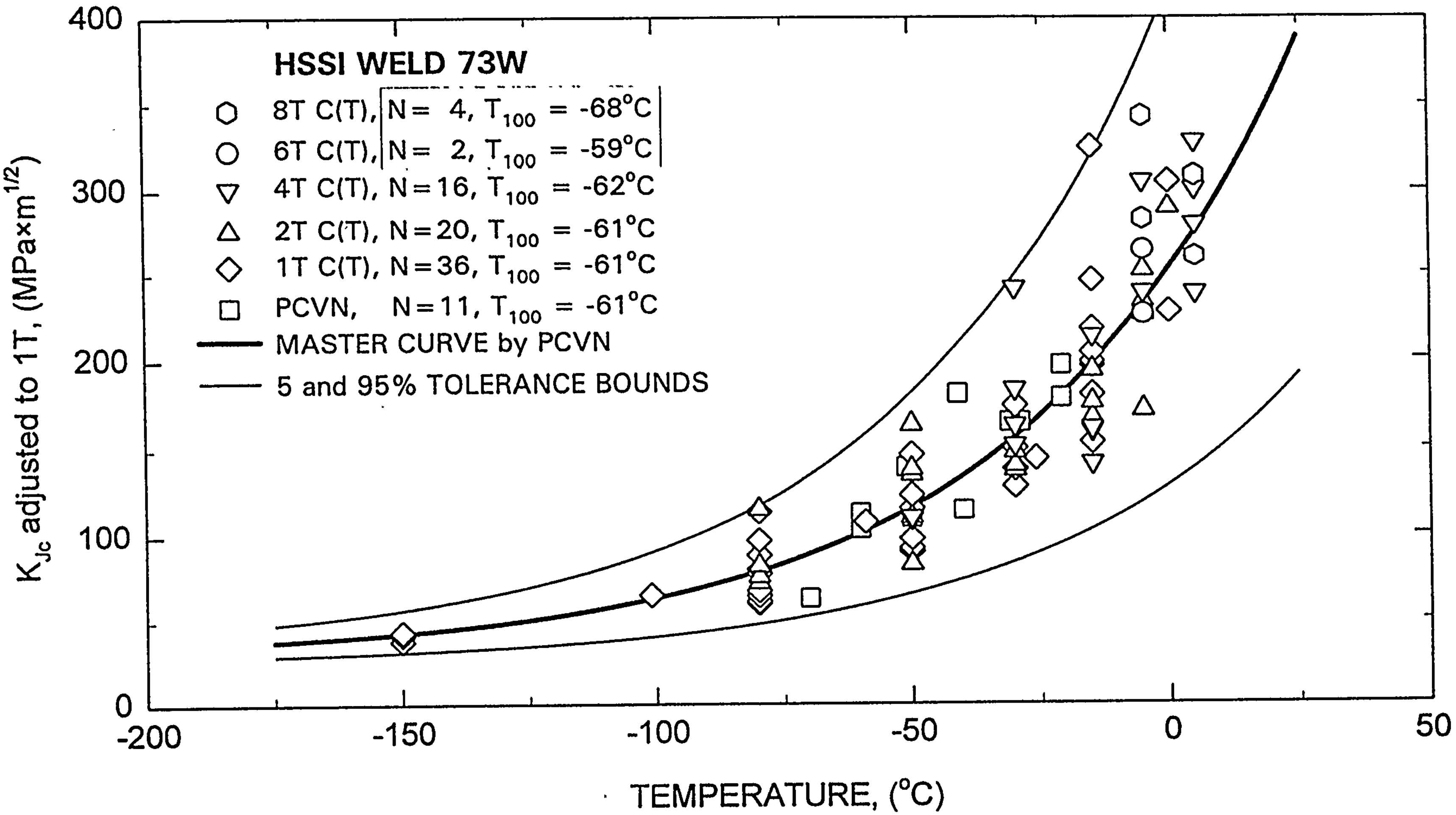

FIG. 4--Fracture toughness of HSSI weld 73W measured with different specimens relative to the master curve with 5 and 95% margin-adjusted bounds obtained only from tests of several reconstituted PCVN specimens.

by a procedure described in Ref. [11]. The constraint limit imposed by Eq. (5) was not applied to qualify data for this analysis. In order to perform the comparison, K_{Jc} data from specimens of each size were separately analyzed to determine T_{100}. The result of each analysis is also presented in Fig. 4. There were only two 6T C(T) and four 8T C(T) tested. Thus, T_{100} estimates from these two data sets are unreliable and are presented as supplementary information only.

The comparison of T_{100} values obtained from specimens of different sizes clearly proves the applicability of reconstituted PCVN specimens to characterize fracture toughness of RPV steels in the transition region. Some unresolved issues may remain regarding quality of welding reconstitution, minimum length of the inserts, etc., but such matters are outside of the scope of this paper.

CHARACTERIZATION OF IRRADIATED STEELS

PCVN specimens were used to characterize fracture toughness of an A 533 grade B plate and submerged-arc weld in both the unirradiated and irradiated conditions. The PCVN data are compared to compact specimens data.

An A533 grade B plate, designated JRQ, is the new International Atomic Energy Agency (IAEA) correlation monitor material. This plate was widely used in the IAEA Coordinated Research Programme Phase 3 (CRP-3). The analysis of K_{Jc} data from CRP-3 has revealed a T_{100} value gradient in the plate thickness direction [12]. Based on this observation, only specimens from about the same depth in the plate can be compared. PCVN specimens, 0.5T round compact (RCT) specimens, and 1T compact specimens of L-T orientation were tested in the unirradiated condition. PCVN and 0.5T RCT specimens were also studied after irradiation in the surveillance position of Loviisa Nuclear Power Plant to a neutron fluence of approximately 2×10^{19} n/cm^2 (>1 MeV) at 265°C.

Fracture toughness data from specimens of different sizes are summarized in Figs. 5 and 6 for the unirradiated and irradiated conditions, respectively. In both Figs. 5 and 6, the master curve with 5 and 95% tolerance bounds obtained only from testing of PCVN specimens are used to describe the scatter of all K_{Jc} data. The plate JRQ data show that the master curve with tolerance bounds from tests of only PCVN specimens adequately characterize the scatter of K_{Jc} data from compact specimens. As in the case with HSSI weld 73W, PCVN specimens from the JRQ plate were tested over the transition temperature range. Thus, estimation of the T_{100} values was performed by the procedure described in Ref. [11]. The constraint limit imposed by Eq. (5) was not applied. This issue will be addressed next.

The HSSI Program at ORNL has a task to characterize the properties, before and after irradiation, of the submerged-arc welds from the Midland Unit 1 pressurized water reactor vessel. This vessel was built for a nuclear unit to be operated by Consumers Power of Midland, Michigan, that was canceled prior to startup. The beltline weld from that vessel has the designation WF-70 which stands for a specific heat of copper-coated weld wire used with a specific lot of Linde 80 flux. A thorough characterization [13] has demonstrated that this weld is distinguished by inhomogeneity of fracture toughness, mechanical properties, and copper content within the weld. Therefore, this weld was

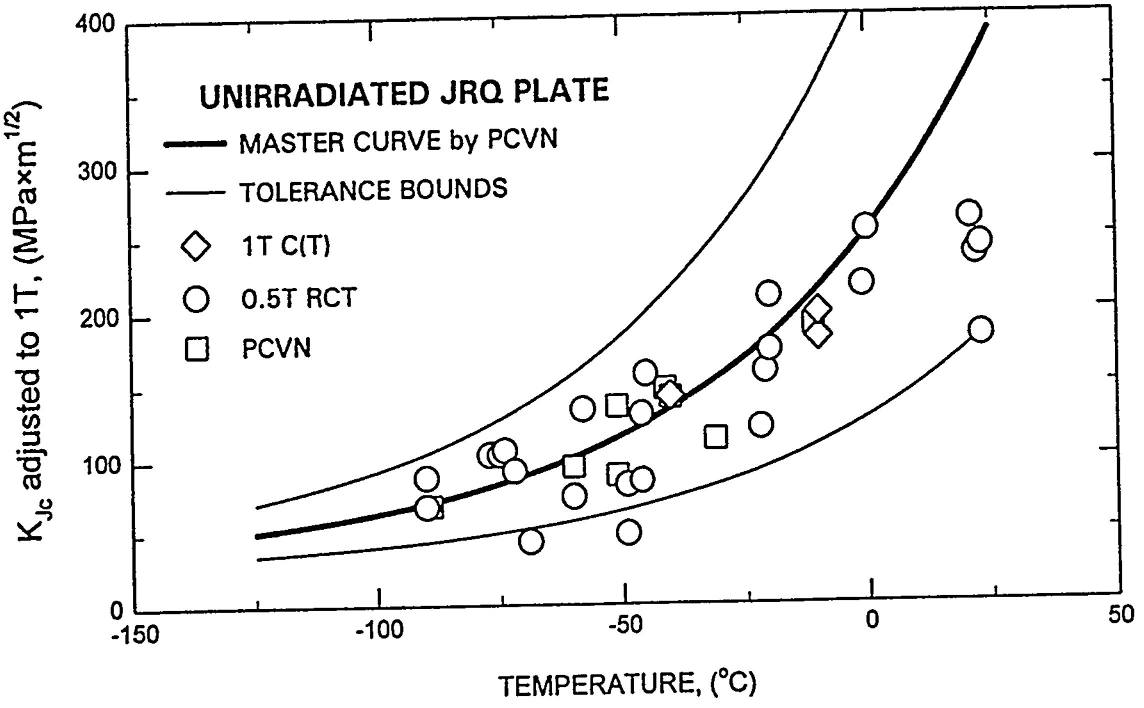

FIG. 5--Fracture toughness of A 533 grade B JRQ plate measured with different specimens relative to the master curve with 5 and 95% margin-adjusted bounds evaluated only from tests of several PCVN specimens.

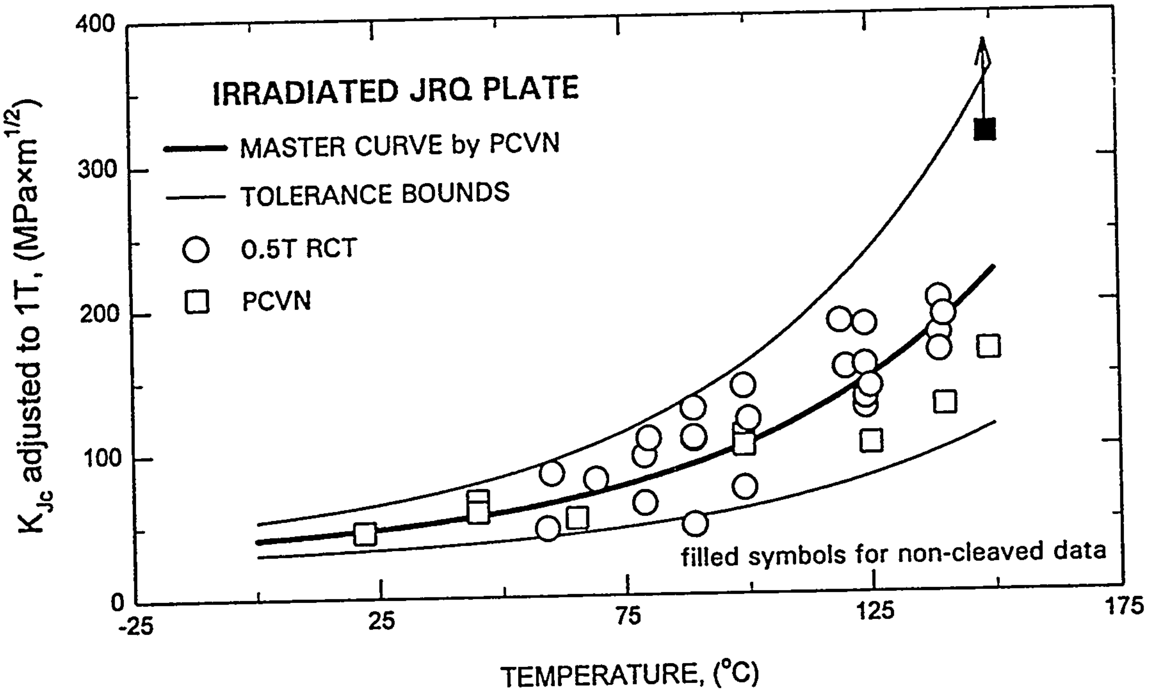

FIG. 6--Fracture toughness of JRQ plate after irradiation to 2×10^{19} n/cm^2 measured with different specimens relative to the master curve with 5 and 95% margin-adjusted bounds obtained only from tests of several PCVN specimens.

selected to be a good trial to study the ability of PCVN specimens to establish the transition region fracture toughness of an actual reactor pressure vessel weld both before and after irradiation. Irradiation of this weld was performed at 288°C to the target neutron fluence of 1×10^{19} n/cm^2 (>1 MeV) at the University of Michigan Ford Reactor.

The PCVN specimens were tested together with compact specimens before and after irradiation. The results were processed using the analysis procedure described in the present study. The master curves and 5/95% margin-adjusted tolerance bounds obtained from testing PCVN specimens were employed to predict compact specimen data in the transition region. Compact specimens ranging in size from 0.5T to 4T were tested in the unirradiated condition, while only 0.5T and 1T irradiated compact specimens were tested.

Figures 7 and 8 present K_{Jc} values of the beltline weld in the unirradiated and irradiated conditions, respectively. Irradiation-hardening results in an increase of the K_{Jc} validity limit, which is a critical aspect in an application of PCVN specimens. In general, master curves derived from PCVN specimens describe very well the wide scatter of fracture toughness of weld studied, as can be seen in Figs. 7 and 8.

The capacity of PCVN specimens to provide valid K_{Jc} before losing constraint is restricted by the extremely small remaining ligament, see Eq. (5). This penalizes the PCVN geometry more compared to, for example, the 0.5T compact specimen, although both are about the same thickness. In order to have valid PCVN data, the test temperature needs to be selected to be in the lower part of the transition region (below 100 MPa$\sqrt{m}$). Due to the exponential nature of the master curve as it approaches the lower shelf, median K_{Jc} must be determined with more accuracy than the median K_{Jc} determined at the T_{100} temperature. The accuracy of PCVN-derived K_{Jc} values on the lower part of transition region is also somewhat reduced because the statistical size effect implied by Eq. (3) is tending to vanish in this region. Thus, it may become necessary to recommend an increase in the number of PCVN specimens to be tested in the lower transition region. Ten to twelve PCVN specimens per curve may be necessary.

CONCLUSIONS

In this paper, the applicability of small specimens to characterize the fracture toughness of pressure vessel steels has been examined by the testing of precracked Charpy specimens. Weibull statistical concepts were applied to analyze K_{Jc} values and the master curve approach was used to describe the temperature dependence of fracture toughness in the transition region. Conclusions are summarized as follows:

1. The Weibull statistic/master curve approach provides a powerful tool to describe the fracture toughness properties in the transition region of unirradiated and irradiated reactor pressure vessel steels enabling the testing of limited numbers of PCVN specimens.

2. However, the "valid" test temperature range for PCVN specimens is very narrow. The capacity of PCVN specimens is restricted on the high-temperature side by constraint control requirements and on the lower-temperature side by accuracy of statistical effects.

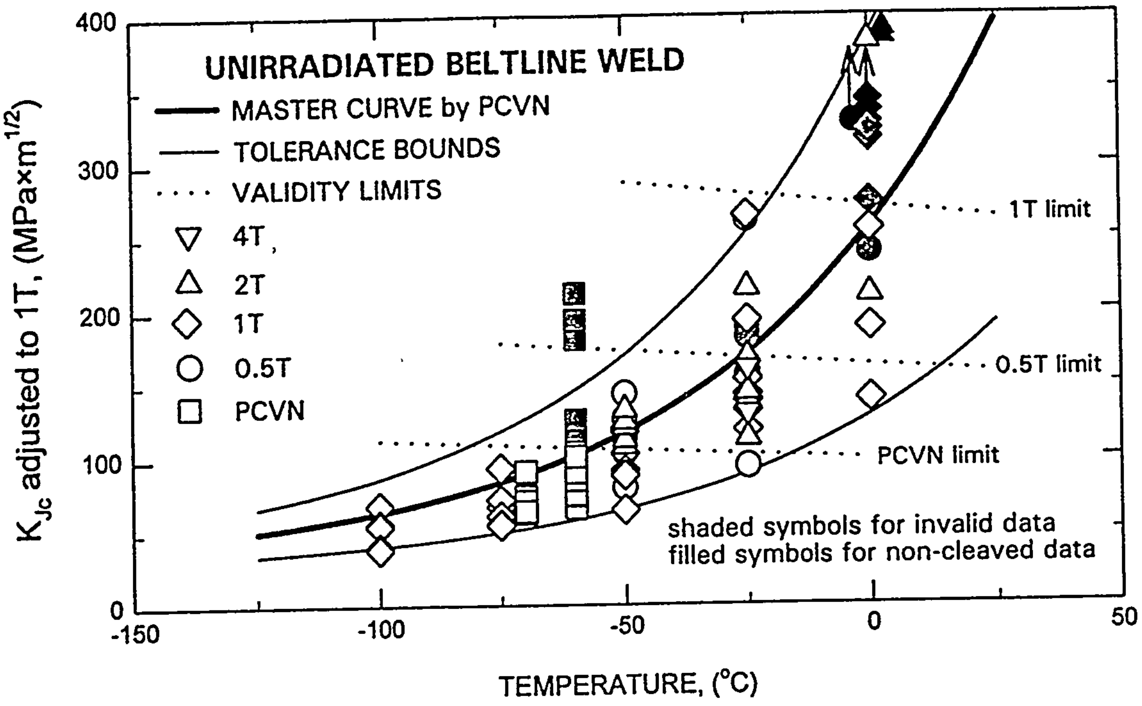

FIG. 7--Fracture toughness of Midland beltline weld measured with different specimens relative to the master curve with 5 and 95% margin-adjusted bounds obtained only from tests of several PCVN specimens.

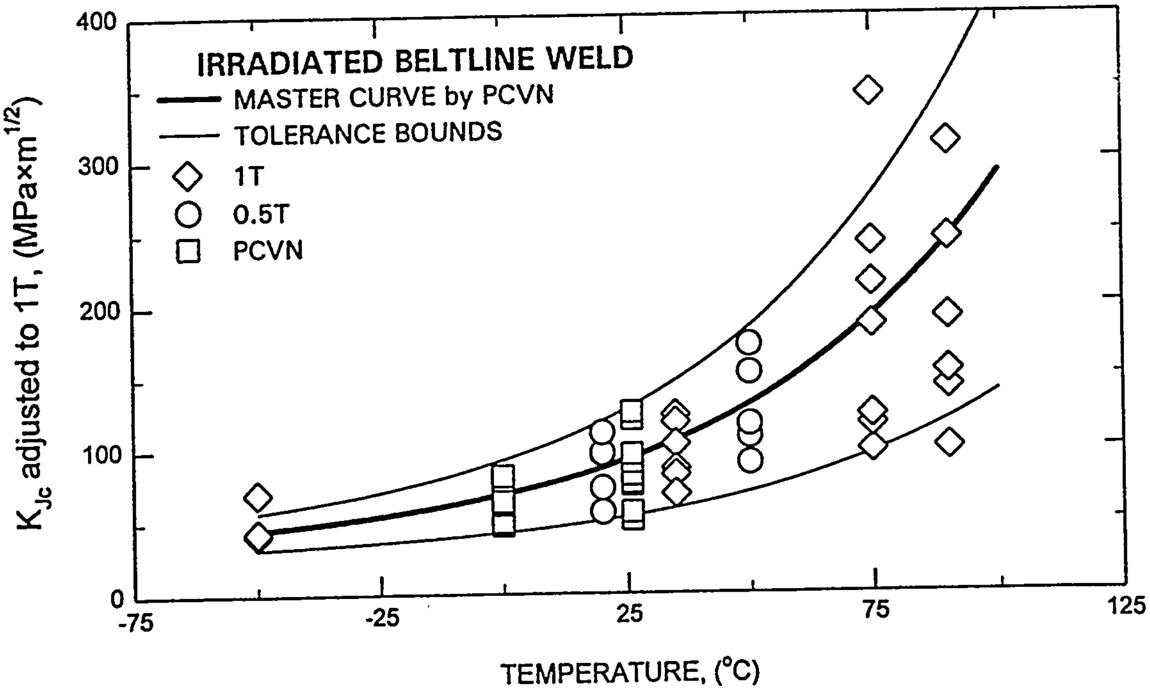

FIG. 8--Fracture toughness of Midland beltline weld after irradiation to 1×10^{19} n/cm^2 measured with different specimens relative to the master curve and 5 and 95% margin-adjusted tolerance bounds obtained only from tests of several PCVN specimens.

3. It is shown that the master curve derived from the testing of several PCVN specimens of HSST Plate 02 represents very well the large linear-elastic K_{Ic} database (adjusted to 1T C(T) size) accumulated by the testing of massive specimens needed for K_{Ic} validity. Also the 5 and 95% margin-adjusted tolerance bounds of the master curve describe successfully the scatter in K_{Ic} results of this same material.

4. The 5% margin-adjusted tolerance bound derived from the testing of several PCVN specimens of HSST Plate 02 was compared to the EPRI K_{Ic} database. It is shown that the 5% tolerance bound from the present work is more accurate as a lower bound curve to the K_{Ic} database than the ASME K_{Ic} curve itself.

5. PCVN specimens of HSSI weld 73W were manufactured by means of welding reconstitution from the broken halves of previously tested specimens. The master curve obtained from testing these reconstituted PCVN specimens fits perfectly within a large K_{Ic} database for compact specimens in sizes ranging from 1T to 8T.

6. The fracture toughnesses of Plate JRQ and the Midland reactor vessel weld, in both the unirradiated and irradiated conditions, were adequately characterized by PCVN specimens. The accuracy of characterization of fracture toughness in the transition region by PCVN specimens will probably have to be improved by increasing the number of specimens tested.

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