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APPLICABILITY OF THE FRACTURE TOUGHNESS MASTER CURVE TO IRRADIATED REACTOR PRESSURE VESSEL STEELS

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SUMMARY

The current methodology for determination of fracture toughness of irradiated reactor pressure vessel (RPV) steels is based on the upward temperature shift of the American Society of Mechanical Engineers (ASME) K_{Ic} curve from either measurement of Charpy impact surveillance specimens or predictive calculations based on a database of Charpy impact tests from RPV surveillance programs. Currently, the provisions for determination of the upward temperature shift of the curve due to irradiation are based on the Charpy V-notch (CVN) 41-J shift, and the shape of the fracture toughness curve is assumed to not change as a consequence of irradiation. The ASME curve is a function of test temperature (T) normalized to a reference nil-ductility temperature, RT_{NDT}, namely, $T - RT_{NDT}$. That curve was constructed as the lower boundary to the available K_{Ic} database and, therefore, does not consider probability matters. Moreover, to achieve valid fracture toughness data in the temperature range where the rate of fracture toughness increase with temperature is rapidly increasing, very large test specimens were needed to maintain plain-strain, linear-elastic conditions. Such large specimens are impractical for fracture toughness testing of each RPV steel, but the evolution of elastic-plastic fracture mechanics has led to the use of relatively small test specimens to achieve acceptable cleavage fracture toughness measurements, K_{Jc}, in the transition temperature range. Accompanying this evolution is the employment of the Weibull distribution function to model the scatter of fracture toughness values in the transition range. Thus, a probabilistic-based bound for a given data population can be made. Further, it has been demonstrated by Wallin[1,2] that the probabilistic-based estimates of median fracture toughness of ferritic steels tend to form transition curves of the same shape, the so-called "master curve," normalized to one common specimen size, namely the 1T [i.e., 1.0-in.-thick (25-mm)] specimen. Thus, fracture toughness of the material can be described by a fracture toughness-based reference temperature rather than by a temperature derived from a combination of drop-weight and Charpy impact tests. A statistical size correction based upon weakest-link theory is used to adjust the measured fracture toughness to that expected from a 1T specimen.[1] Although the details of a consensus procedure is still under development, the basic procedure is widely used now to characterize elastic-plastic K_{Jc} values in the transition range. For application to commercial nuclear RPVs, however, various uncertainties are being investigated as part of the Heavy-Section Steel Irradiation (HSSI) Program managed by the Oak Ridge National Laboratory (ORNL) for the U.S. Nuclear Regulatory Commission. These include the use of relatively small specimens, e.g., precracked CVN (PCVN) and smaller size specimens, the applicability of the master curve to highly irradiated steels, and the effects of intergranular fracture.

In the HSSI Program studies, PCVN and smaller three-point bend specimens, as well as 0.2T compact specimens, were used to characterize the fracture toughness of RPV steel in the transition region.[3] The American Society for Testing and Materials (ASTM) A 533 grade B class 1 plate, designated Heavy-Section Steel Technology (HSST) Program Plate 02, was used because of the existence of an extensive fracture toughness database for Plate 02 accumulated from testing of various size specimens up to 11T thickness.[4,5] The testing and analysis procedures were conducted in accordance with Draft 12 of the Proposed ASTM Test Practice.[6] The procedure allows for the testing of a relatively small number of specimens tested at one temperature and employs the maximum likelihood concept regarded as the most accurate method of obtaining the scale parameter, K_o, in the Weibull cumulative probability distribution function. The procedure incorporates a constraint limit which defines the measurement capacity for a given specimen size and material. 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. The remaining ligament size is a critical parameter to satisfy the constraint limit specified in the proposed ASTM Test Practice. As the lower-shelf toughness at low temperatures is approached, the specimen size adjustment becomes inapplicable because the statistical size effects diminish and initiation criterion is not longer dominant; fracture becomes more propagation-controlled. This means that the test temperature range for small specimens is quite narrow in order to provide data acceptable for the current analysis procedure. Having determined the position of the master curve on the temperature scale, lower and upper tolerance bounds (0.05 and 0.95, respectively, are common) can be calculated. Four types of specimens have been tested in this study, three-point bend specimens with dimensions of 10 × 10 × 55 mm (PCVN specimen), 4.8 × 10 × 55 mm, and 4.8 × 4.8 × 27 mm, and 0.2T (5-mm-thick) compact specimens. The 0.2T compact specimen has a remaining ligament about the same as the 10 mm thick bend specimen. The PCVN tests were conducted at −30 and −50°C, while the smaller bend specimens were conducted at −50°C.

The results obtained to this time in the program have 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 size) accumulated by the testing of massive specimens needed for K_{Ic} validity. Also, the 5% margin-adjusted tolerance bound of the master curve describes successfully the lower bound of scatter in K_{Ic} of this same material. The 4.8-mm-thick specimens exhibited some disparities in results relative to the current weakest-link size adjustment predictions, indicating that the current mathematical expression for weakest-link theory size adjustment may need some evaluation for such small thicknesses. The current results suggest that ratio of width to thickness becomes a vital parameter in size adjustment modeling for specimens with small thickness. Further investigation is needed to develop a unique size adjustment model for small thicknesses.

Regarding the fracture toughness curve shift and shape as a consequence of irradiation, HSSI Program data and data from the literature have been assembled in a database for analysis. Only data for which the neutron fluence of the Charpy and fracture toughness specimens were similar were incorporated into the database. To assure that all the results were compared on a consistent basis, the raw Charpy impact data were fit with a hyperbolic tangent function and the raw fracture toughness data were analyzed with the master curve procedure. For Charpy 41-J shifts up to about

150°C, the following preliminary observations have been made: (1) for 40 sets of weld metals, on average the K_{Jc} shift at 100 MPa√m is the same as the CVN shift at 41 J, with 95% confidence limits of ±30°C; (2) for 50 sets of base metals, on average the K_{Jc} shift at 100 MPa√m is greater than the CVN shift at 41 J by 12°C, with 95% confidence limits of ±35°C; (3) correlations between the K_{Jc100} shift and other CVN energy criteria showed no improvement compared to that of the 41-J correlation; (4) correlations between fracture toughness shift and radiation hardening is the same for weld and base metals; and (5) a graphical comparison of all the irradiated fracture toughness data normalized to $T - T_{100}$ do not suggest a change in shape of the master curve due to irradiation.[7]

The current investigations of small specimen technology concentrates on specimen measuring capacity and size adjustment procedures; these are (1) further testing of precracked Charpy specimens of different materials; (2) further testing of small specimens of different geometries for comparison with larger specimens to validate size adjustment procedure; (3) analytical evaluation of small specimens with different geometries; and (4) investigation of master curve methodology to low-strength materials. The current investigations of curve shift methodology concentrate on determination of uncertainties; these are, (1) fracture toughness curve shape and shift for highly embrittled materials (i.e., $\Delta TT \approx 200°C$, $\Delta\sigma_y \approx 300$ MPa); (2) applicability of data sets with K data <<100 MPA√m for master curve analysis; and (3) evaluation of uncertainties associated with the use of Charpy surveillance specimens to determine T_{100}. Finally, the applicability of the master curve to fracture toughness data obtained from specimens which have significant amounts of intergranular fracture is a recent area of study, which is being pursued for materials in both the unirradiated and irradiated conditions.

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2. Wallin, K. "The Scatter in K_{Ic}-Results," *Engineering Fracture Mechanics*, Vol. 19, No. 6, pp. 1085-1093, 1985.

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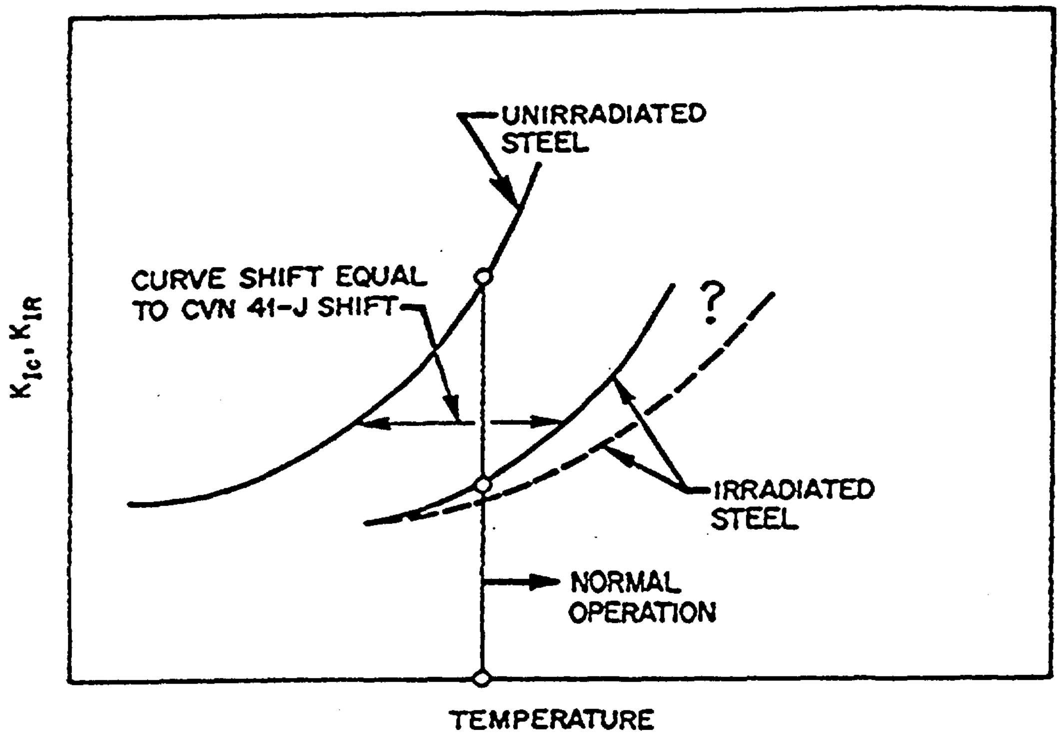
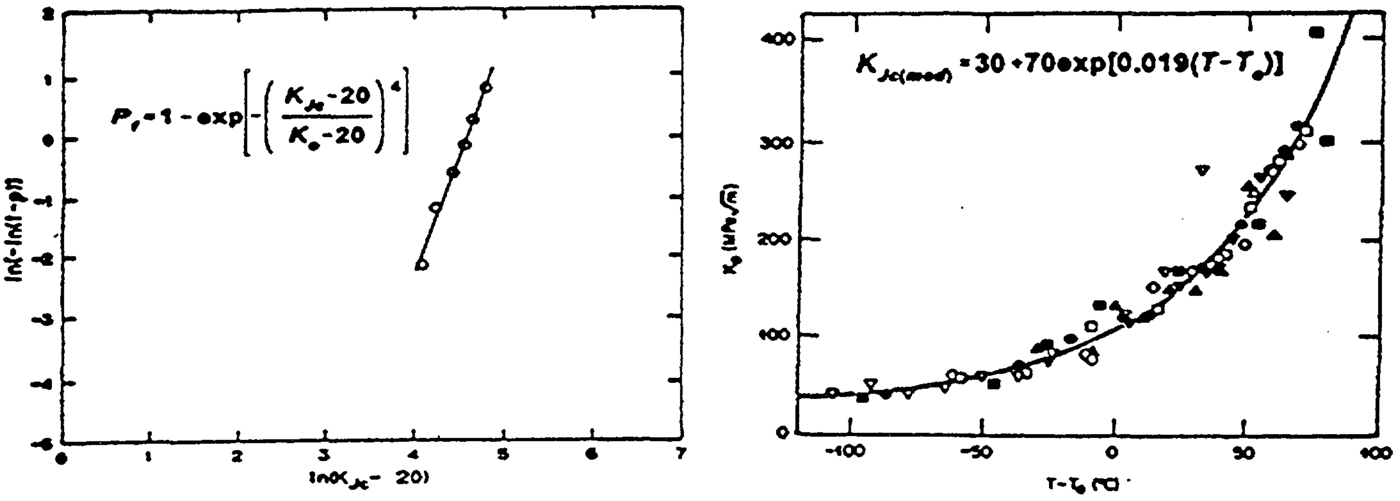
A MAJOR GOAL OF THE HSSI PROGRAM IS TO DETERMINE THE EFFECTS OF IRRADIATION ON SHIFT AND SHAPE OF THE K_{Ic} AND K_{Ia} CURVES



DATABASE ASSEMBLED FROM PUBLISHED SOURCES

- TWO GROUPS OF MATERIALS - BASE AND WELD METALS
- RAW DATA OR DIGITIZED FROM PLOTS
- K_{Jc} AND CVN PAIRS WITH COMPARABLE NEUTRON FLUENCE AND IRRADIATION TEMPERATURES
- CONSISTENT ANALYSIS OF DATA
  - MASTER CURVE APPROACH FOR FRACTURE TOUGHNESS
  - HYPERBOLIC TANGENT FIT FOR CHARPY WITH LOWER-SHELF ENERGY = 2.7 J
- LINEAR REGRESSION FOR SHIFT CORRELATION

WEIBULL STATISTIC/MASTER CURVE APPROACH WAS USED FOR K_{Jc} DATA (AFTER WALLIN)



THE MASTER CURVE ANALYSIS OF FRACTURE TOUGHNESS IN THE TRANSITION RANGE INCORPORATES STATISTICAL ANALYSIS AND SPECIMEN SIZE ADJUSTMENT

- WEIBULL FRACTURE PROBABILITY FORMS BASIS FOR DATA ANALYSIS

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

$$K_{Jc(med)} = \left[\frac{\sum_{i=1}^{N}(K_{Jc(i)} - 20)^4}{r - 0.3068}\right]^{1/4} \cdot [\ln(2)]^{1/4} + 20, \quad \mathrm{MPa}\sqrt{m} .$$

THE MASTER CURVE ANALYSIS OF FRACTURE TOUGHNESS IN THE TRANSITION RANGE INCORPORATES STATISTICAL ANALYSIS AND SPECIMEN SIZE ADJUSTMENT

(CONTINUED)

- WEAKEST-LINK SIZE ADJUSTMENT APPLIED TO MEASURED DATA

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

- MASTER CURVE OF FRACTURE TOUGHNESS VS TEMPERATURE APPLIED TO DETERMINE REFERENCE TEMPERATURE

$$K_{Jc(med)}{}^{1T} = 30 + 70 \exp\left[0.019(T - T_{100})\right] \text{, MPa}\sqrt{\text{m}} \text{ .}$$

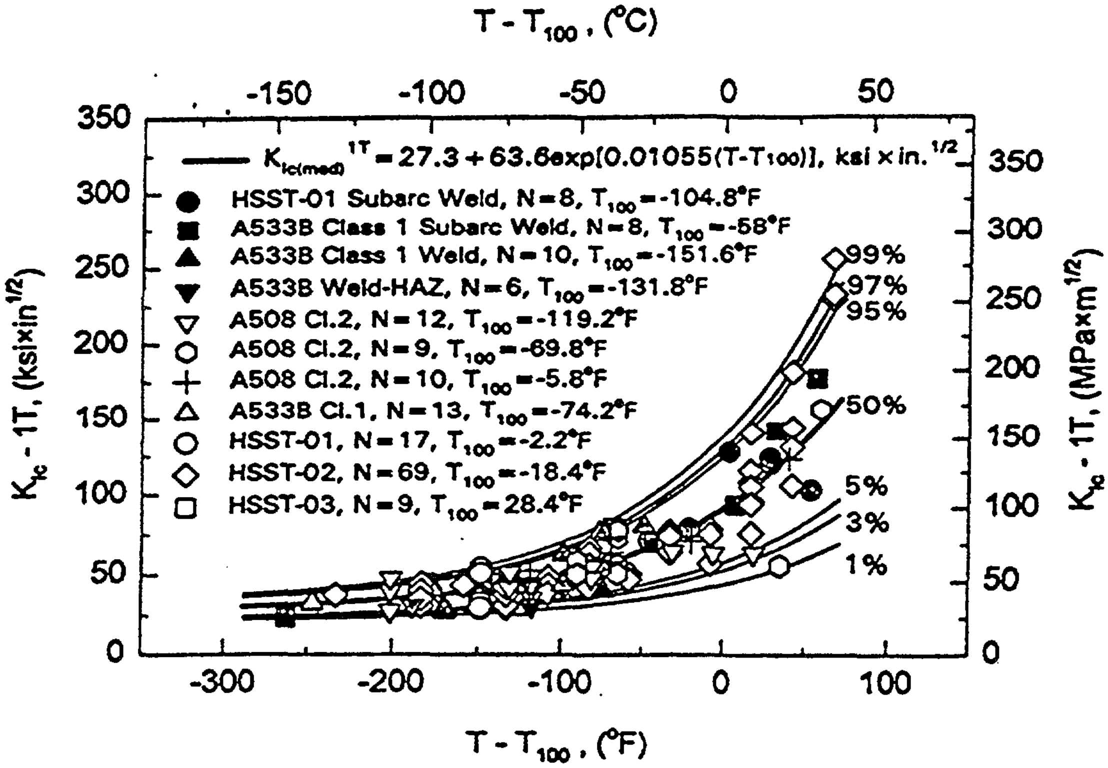
- T_{100} = REFERENCE FRACTURE TOUGHNESS TEMPERATURE,

$$T \text{ at } K_{Jc(med)}{}^{1T} = 100 \text{ MPa}\sqrt{\text{m}} \text{ .}$$

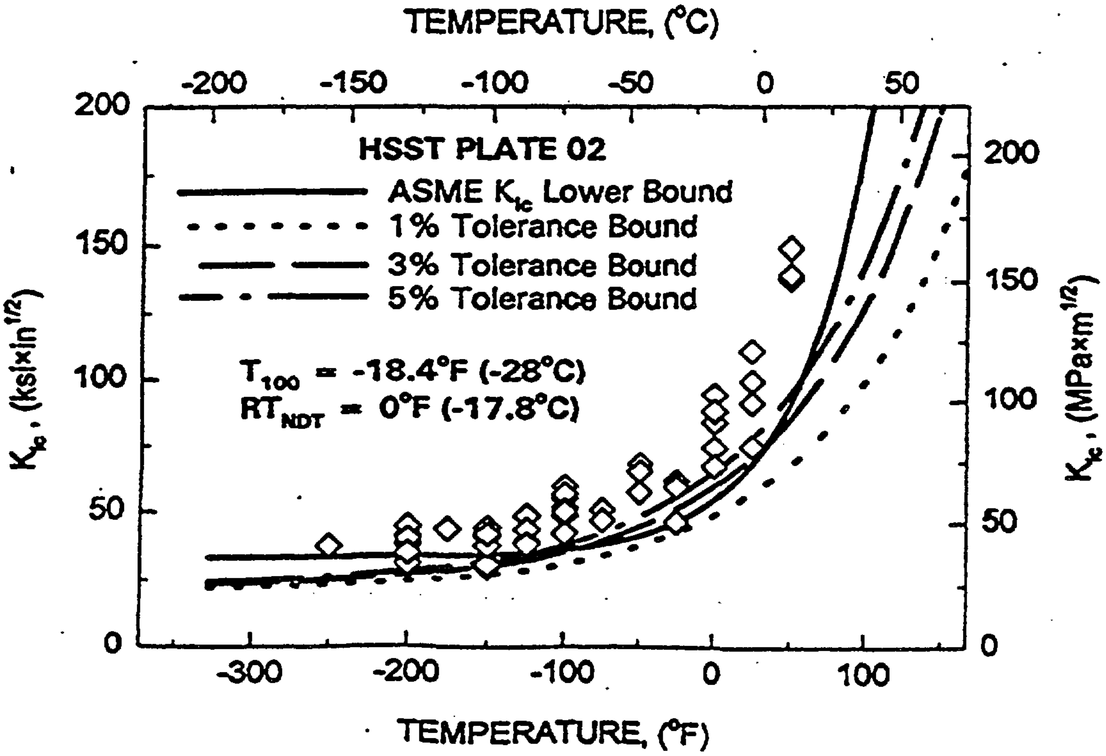
- PROCEDURES INCORPORATE CERTAIN CRITERIA REGARDING STATISTICAL VARIATIONS AND CONSTRAINTS
  - AT LEAST SIX REPLICATED TESTS AT A GIVEN TEST TEMPERATURE
  - REMAINING LIGAMENT SIZE,

$$b_o \geq 30 \frac{K_{Jc}{}^2}{E\sigma_{ys}} \text{ .}$$

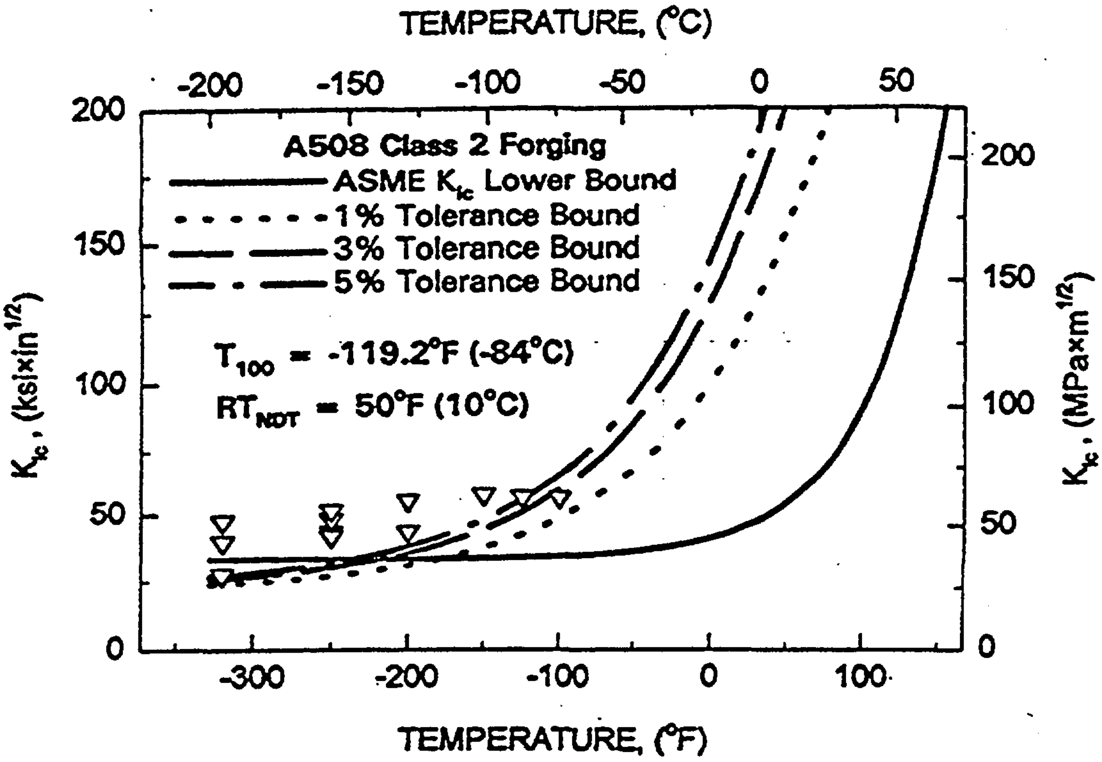
TOTAL EPRI/ASME DATABASE ANALYZED FOR MASTER CURVE (TEMPERATURE NORMALIZED BY T_{100}; ALL CONFORM TO MASTER CURVE TREND)



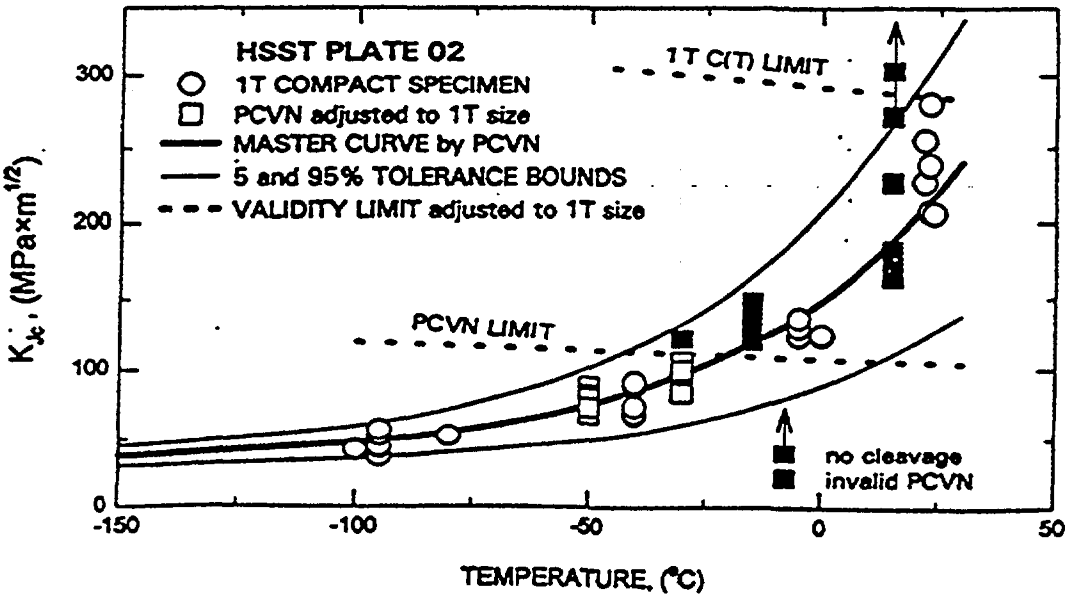
COMPARISON OF TOLERANCE BOUNDS AND K_{Ic} LOWER BOUND WHEN $T_{100} \cong RT_{NDT}$



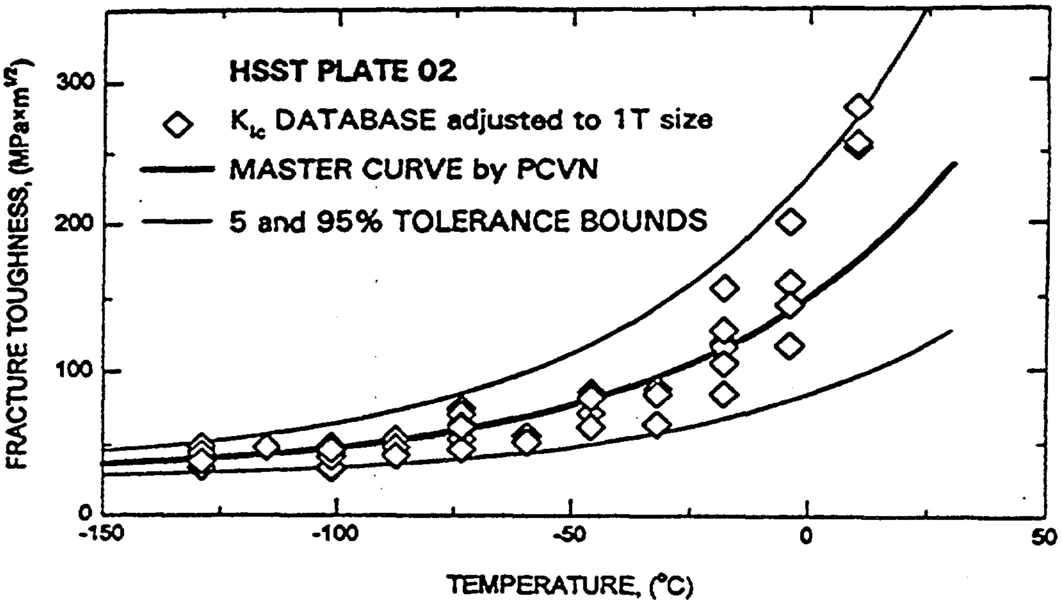
COMPARISON OF TOLERANCE BOUNDS AND K_{Ic} LOWER BOUND WHEN T_{100} << RT_{NDT}



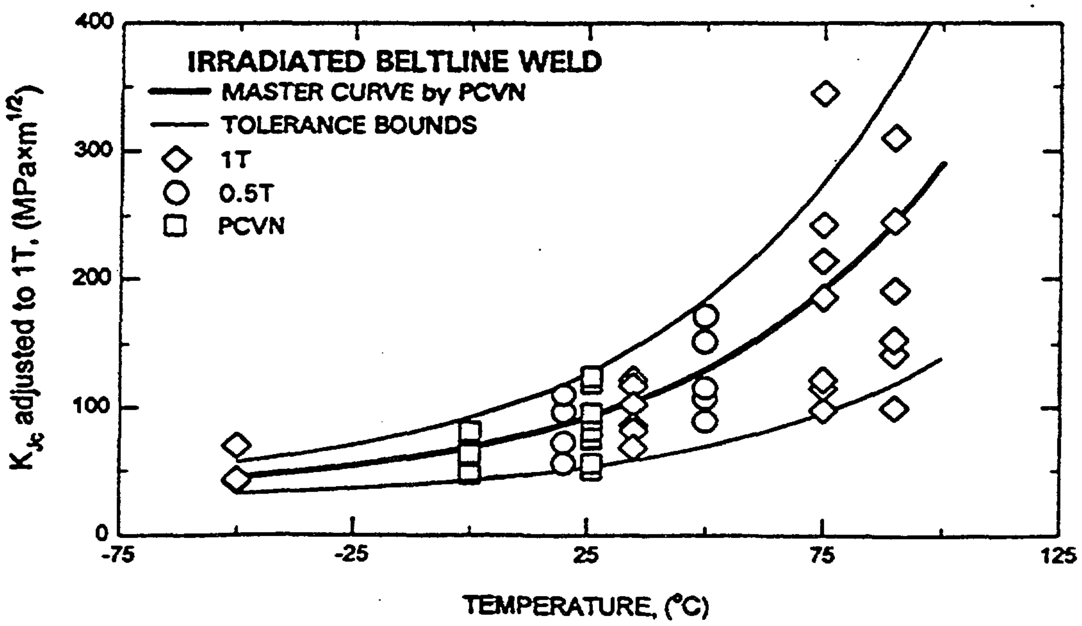
HSST PLATE 02, A 533 GRADE B STEEL PLATE



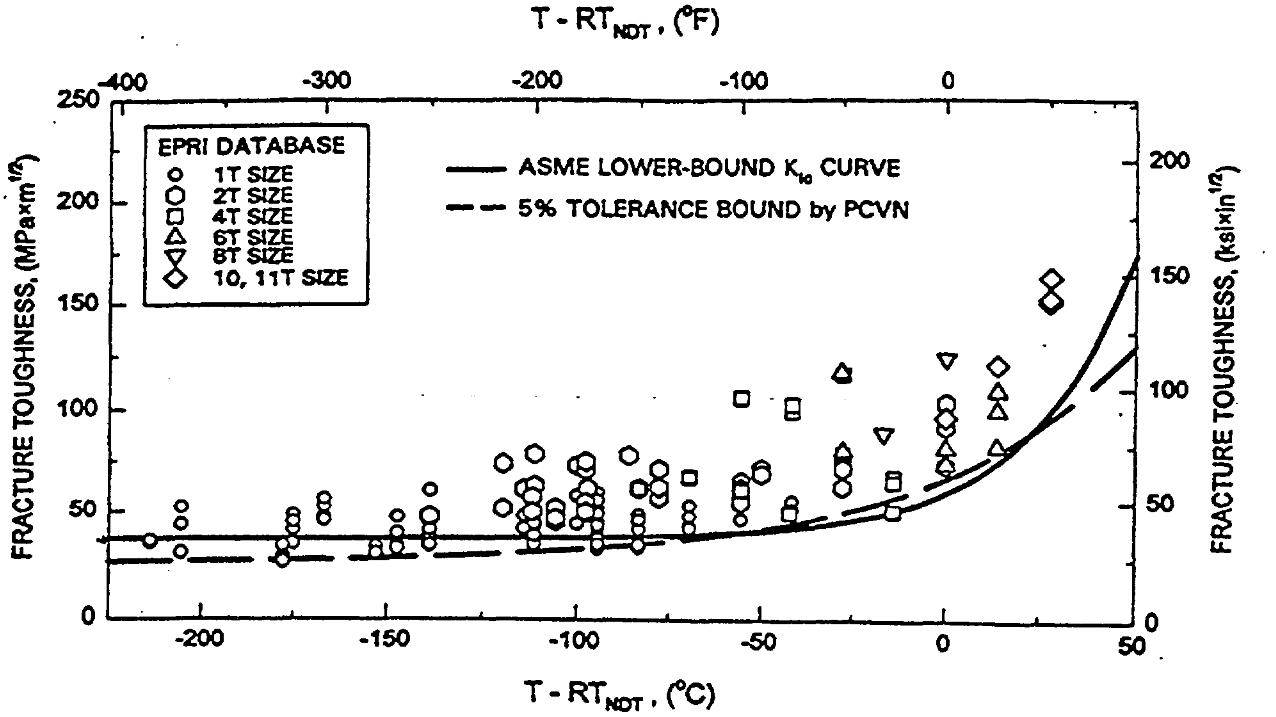
HSST PLATE 02
(SOURCE: ASME/EPRI DATABASE ON K_{Ic} VALUES)



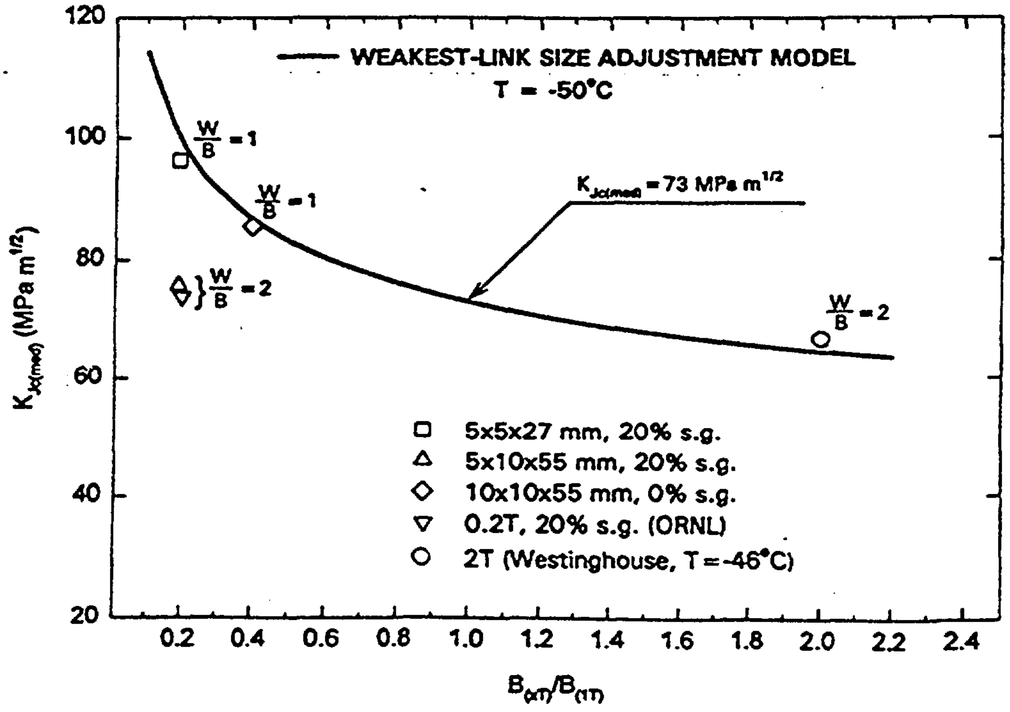
IRRADIATED BELTLINE WELD METAL FROM THE MIDLAND REACTOR, MIDLAND, MICHIGAN



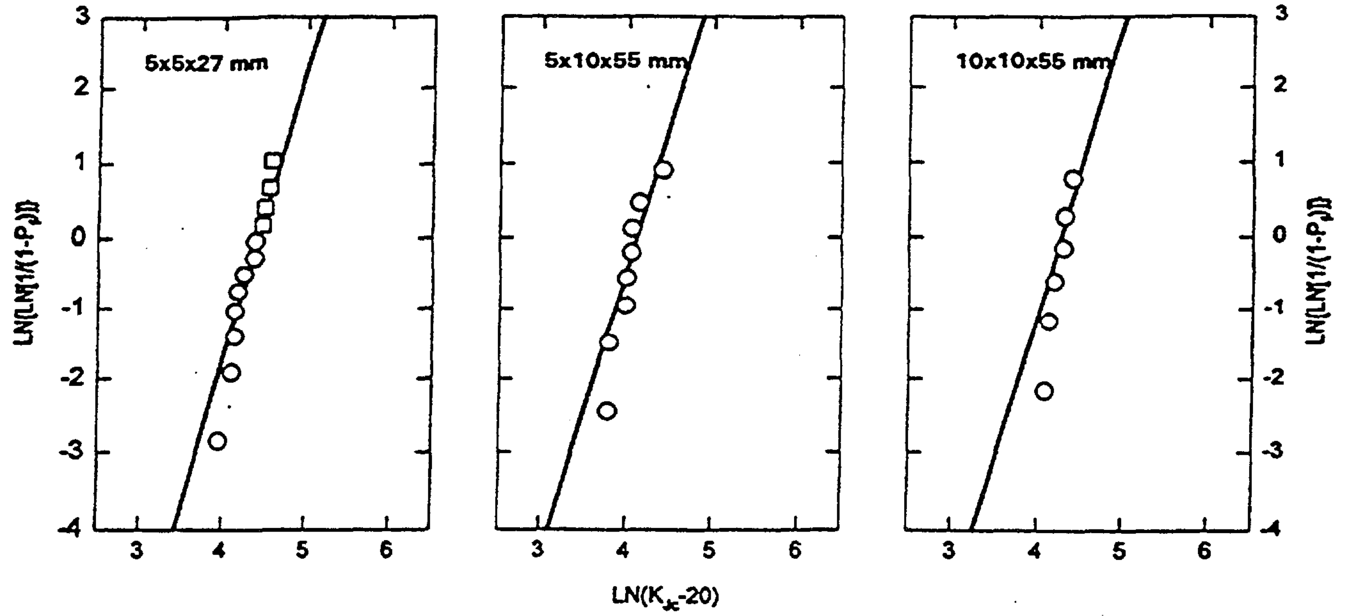
COMPARISON OF TWO LOWER-BOUND METHODS



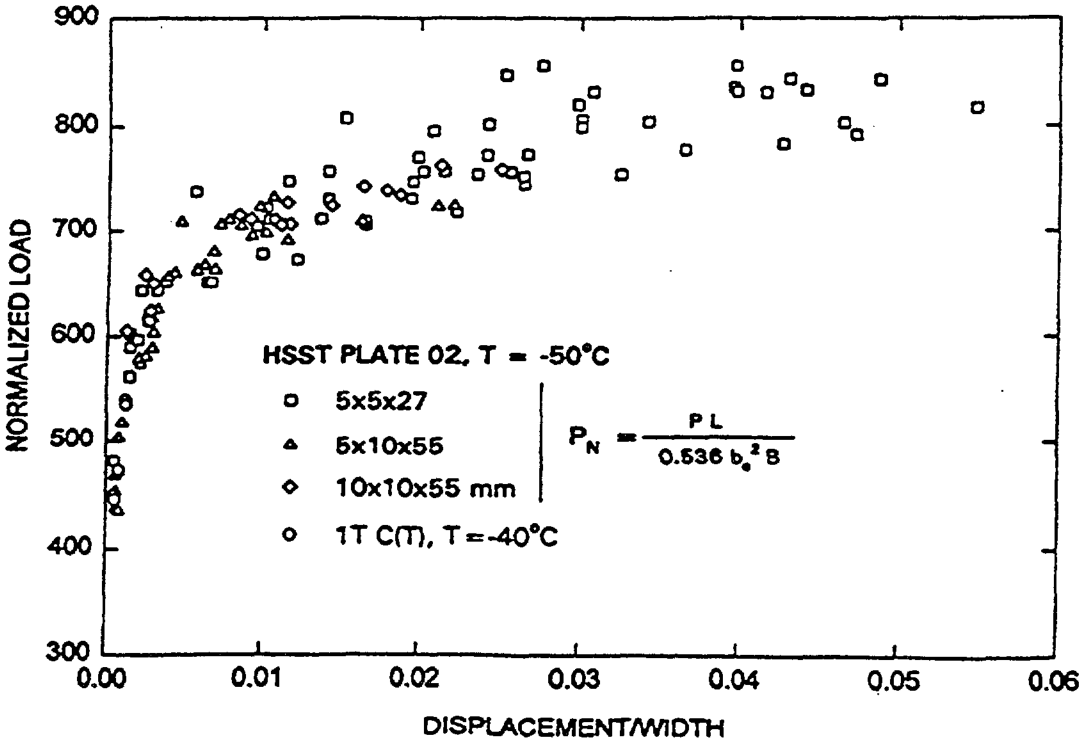
FRACTURE TOUGHNESS TESTS WITH SMALL SPECIMENS OF PLATE 02 AT –50°C EXHIBIT SOME DISPARITIES IN RESULTS RELATIVE TO WEAKEST-LINK SIZE ADJUSTMENT PREDICTIONS



DISPARITY IN RESULTS FOR THREE DIFFERENT SPECIMEN SIZES IS NOT EVIDENT FROM WEIBULL PROBABILITY PLOTS



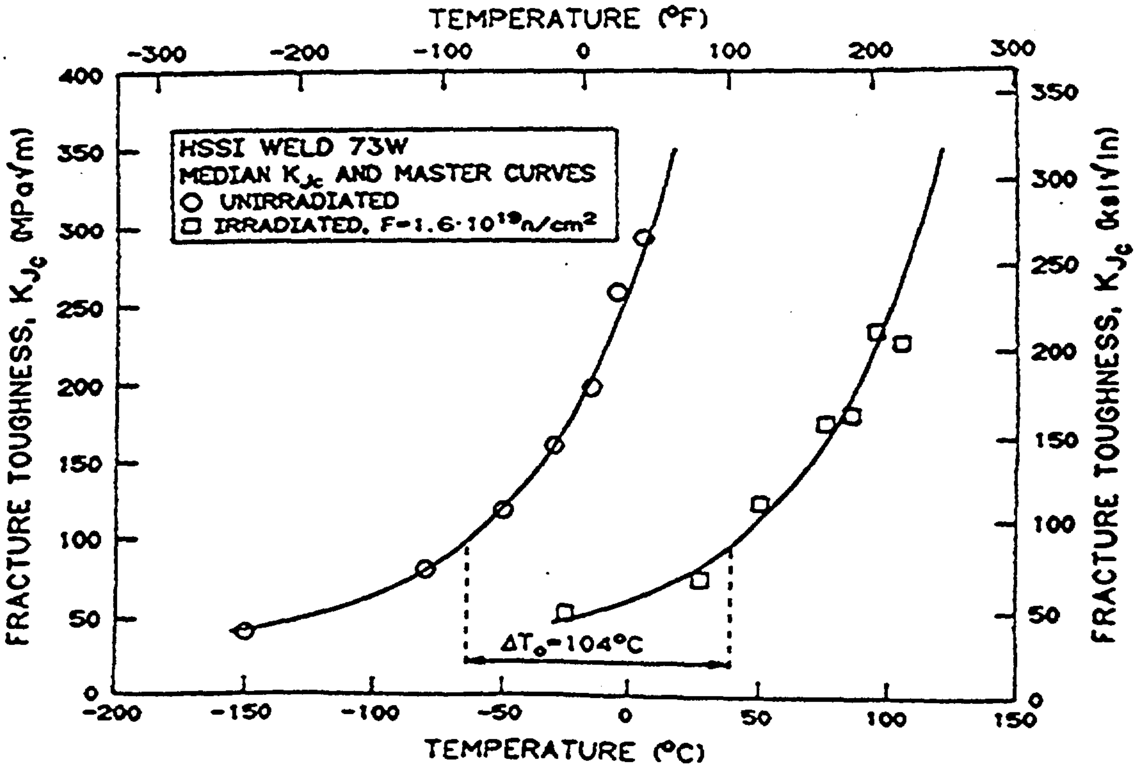
SMALL THREE-POINT BEND AND 1T COMPACT SPECIMENS FOLLOW SAME NORMALIZED LOAD VS PLASTIC DISPLACEMENT KEY CURVE



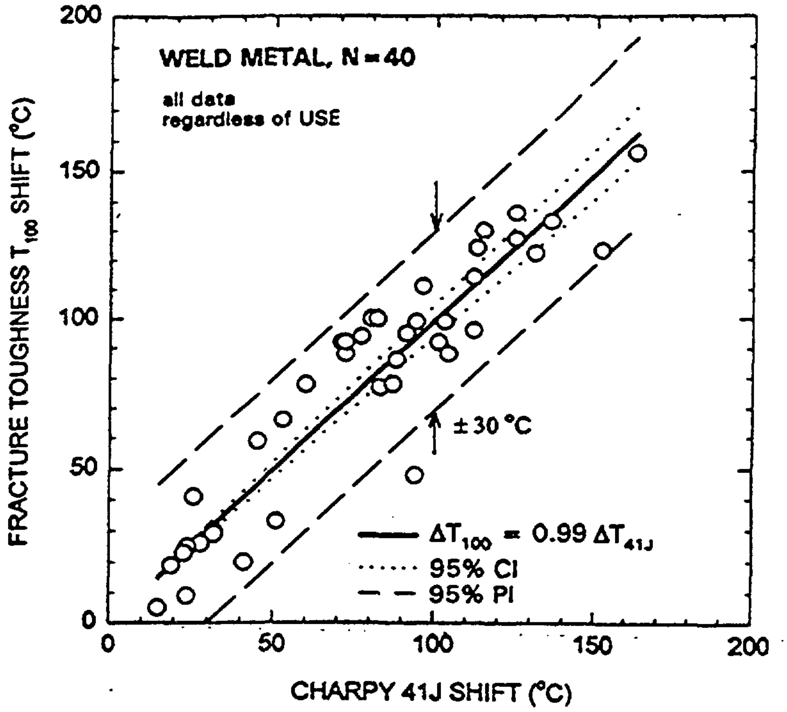
SIZE ADJUSTMENT PROCEDURE ALLOWS THE USE OF PRECRACKED CHARPY SPECIMENS FOR FRACTURE TOUGHNESS CHARACTERIZATION

- PRECRACKED CHARPY SPECIMENS CAN BE USED TO ESTABLISH T_{100} TEMPERATURES (THE MASTER CURVE); HOWEVER, THE TEST TEMPERATURE FOR OPTIMUM RESULTS MUST BE CAREFULLY SELECTED
- THE DATABASE OF LARGE SPECIMENS CAN BE COVERED BY DEVELOPING A 1T MASTER CURVE AND TOLERANCE BOUNDS FOR THE ONE SPECIMEN SIZE
- LOWER BOUND OF FRACTURE TOUGHNESS IS MORE ACCURATELY REPRESENTED BY MASTER CURVE TOLERANCE BOUND THAN BY MASSIVE DATA SETS AND VISUALLY DRAWING IN A LOWER-BOUND CURVE
- 5-mm-THICK SPECIMENS EXHIBIT SAME DISPARITIES IN RESULTS RELATIVE TO WEAKEST-LINK SIZE ADJUSTMENT PREDICTIONS

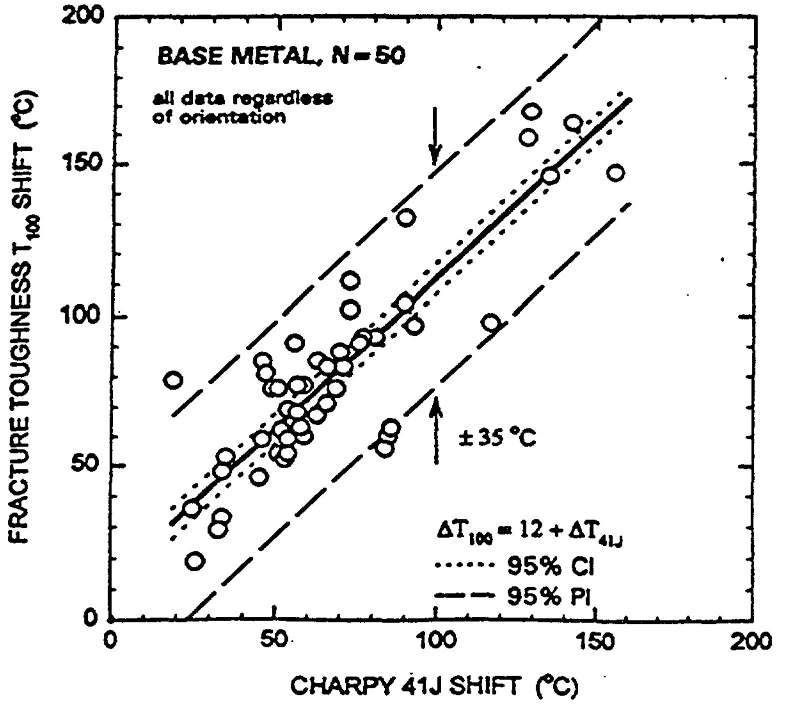
MEDIAN K_{Jc} VALUES AND MASTER CURVE PROCEDURE USED TO DETERMINE ΔT_{100} (ΔK_{Jc100})



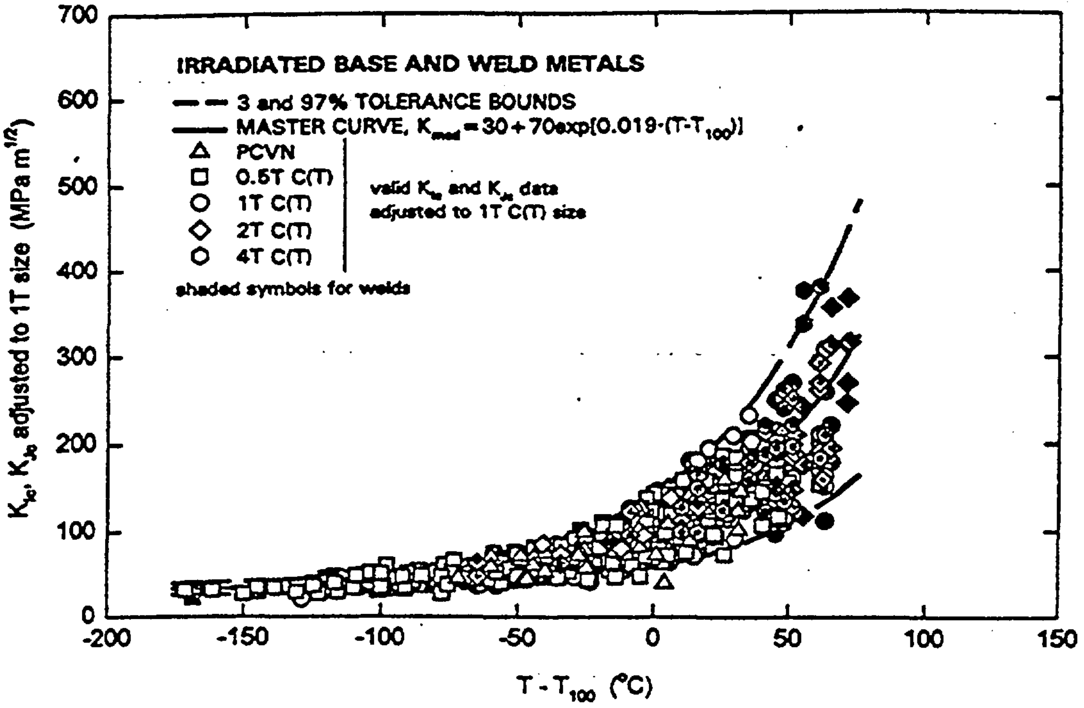
ON AVERAGE, K_{Jc} SHIFT AT 100 MPa√m IS THE SAME AS CVN SHIFT AT 41 J FOR WELD METALS



ON AVERAGE, FRACTURE TOUGHNESS SHIFT IS GREATER THAN CVN 41-J SHIFT BY 12°C FOR BASE METALS



AVAILABLE FRACTURE TOUGHNESS DATA NORMALIZED BY T_{100} DO NOT SUGGEST CHANGE IN SHAPE OF THE MASTER CURVE DUE TO IRRADIATION



ANALYSIS OF RPV STEELS DATABASE REVEALS CORRELATION BETWEEN ΔK_{Jc100} AND ΔT_{41J} FOR BASE AND WELD METALS

- DATABASE INCLUDES K_{Jc} AND CVN DATA FOR 40 WELDS AND 50 BASE METALS
- DATA WERE CONSISTENTLY ANALYZED USING MASTER CURVE APPROACH FOR K_{Jc} AND tanh FOR CVN
- FOR CHARPY 41-J SHIFTS UP TO ABOUT 150°C:
  - FRACTURE TOUGHNESS 100-MPa√m SHIFT IS, ON AVERAGE, THE SAME AS CHARPY 41-J SHIFT FOR WELDS
  - FRACTURE TOUGHNESS 100-MPa√m SHIFT IS, ON AVERAGE, GREATER THAN CHARPY 41-J SHIFT by 12°C FOR BASE METAL
  - CORRELATIONS BETWEEN FRACTURE TOUGHNESS SHIFT AND RADIATION HARDENING IS THE SAME FOR WELD AND BASE METALS

CURRENT INVESTIGATIONS OF CURVE SHIFT METHODOLOGY CONCENTRATE ON DETERMINATION OF UNCERTAINTIES

- FRACTURE TOUGHNESS CURVE SHAPE AND SHIFT FOR HIGHLY EMBRITTLED MATERIALS ($\Delta TT \approx 200°C$, $\Delta\sigma_y \approx 300$ MPa)
  - DESIGN EXPERIMENTAL PROGRAM
  - PERFORM ANALYTICAL INVESTIGATION
  - TEST MATERIAL FROM DECOMMISSIONED RPV
  - EFFECTS OF INTERGRANULAR FRACTURE
- APPLICABILITY OF DATA SETS WITH K_{Jc} DATA <<100 MPa√m FOR MASTER CURVE ANALYSIS
- EVALUATION OF UNCERTAINTIES ASSOCIATED WITH SURVEILLANCE SPECIMENS
  - USE OF PRECRACKED CHARPY SPECIMENS TO DETERMINE T_{100}
  - TYPICAL CHARPY IMPACT SURVEILLANCE DATA

CURRENT INVESTIGATION OF SMALL SPECIMEN TECHNOLOGY CONCENTRATES ON SPECIMEN MEASURING CAPACITY AND SIZE ADJUSTMENT PROCEDURES

- FURTHER TESTING OF PRECRACKED CHARPY SPECIMENS OF DIFFERENT MATERIALS
- FURTHER TESTING OF SMALL SPECIMENS OF DIFFERENT GEOMETRIES FOR COMPARISON WITH LARGER SPECIMENS TO VALIDATE SIZE ADJUSTMENT PROCEDURE
- ANALYTICAL EVALUATION OF SMALL SPECIMENS WITH DIFFERENT GEOMETRIES IS NEEDED
- INVESTIGATION OF MASTER CURVE METHODOLOGY TO LOW-STRENGTH MATERIALS (e.g., A 36 STEEL FOR SUPPORTS) IS NEEDED