# Recent Advances in the Fracture Toughness Reference Curves of ASME Code – Work Progress in Code Case N-830 Revision

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## 1. Introduction

Fracture toughness reference curves should be available to evaluate the structural integrity by fracture mechanics analysis of pressurized components, such that are described in the ASME Code Section XI, Appendix A, Appendix G, Appendix K, etc. In the early 1970's, ASME Code provided the reference fracture toughness curves of ferritic RPV steels, which were based on the available fracture toughness database at that time.

After the Master Curve (MC) method of cleavage fracture toughness of ferritic steels was standardized in 1997 [1], the MC concept has been implemented into the ASME Code in several ways. Code Case (CC) N-629 and N-631 in Section XI and Section III use the fracture toughness reference temperature ($T_o$) to establish an index temperature ($RT_{To}$) for the $K_{IC}$ and $K_{IR}$ curves as an alternative of $RT_{NDT}$. Note that CC N-629 was replaced by CC N-851 to include the proper relationship for $K_{Ia}$ curve index temperature ($T_{KIa}$).

CC N-830 was approved by ASME in 2014 and was the first direct implementation of the $K_{JC}$ MC into the ASME Code. The CC permits use of the 5th percentile lower bound of MC as an alternative to the $K_{IC}$ curve to characterize materials resistance to fracture flaw evaluation. Since that time, work has progressed within the ASME Section XI Working Group on Flaw Evaluation (WGFE) to expand and improve the CC methods [2].

The draft revision of CC N-830 has been modified to include a suite of self-consistent fracture toughness models describing material fracture toughness behavior from lower shelf, through transition, to upper shelf behavior, such as $K_{JC}$, $K_{Ia}$, $J_{IC}$, and J-R. The proposed models were all empirically derived from large database of fracture toughness values, but the model forms were informed from a mechanistic understanding of fracture process that provides a theoretical underpinning to identify empirical trends. As an ultimate goal, the CC N-830-1 (Revision 1) would be a complete suite of models to predict the fracture toughness of ferritic steels ($K_{JC}$, $K_{Ia}$, $J_{IC}$, J-R) from a single MC parameter, $T_o$ value.

The purpose of this paper is to review the technical contents of CC N-830-1 draft [3] which provides fracture toughness models and their interrelationship in the range of fracture mode transitions from cleavage to ductile behavior. Technical background of each model and its limitations are also discussed by comparison of the domestic database and knowledge.

## 2. Fracture Toughness Models

### *2.1. Cleavage Crack Initiation Toughness, $K_{JC}$*

The so-called Master Curve equations can give a specimen size-dependency of measured fracture toughness and a single master curve of temperature dependency in the reference-sized fracture toughness values. The median values of the fracture toughness in the transition temperature range and their distributions are described by a single parameter $T_o$ as below.

$$K_{JC(median)} = 30 + 70 \cdot \exp[0.019(T - T_o)]$$

$$K_O = 31 + 77 \cdot \exp[0.019(T - T_o)]$$

$$K_{JC}^{p} = 20 + (K_O - 20)\{-\ln(1-p)\}^{1/4}$$

p is a percentile value of the distribution and $K_o$ is a temperature-dependent scale parameter as the 63.2% probability of fracture toughness. $T_o$ represents the temperature at which the measured $K_{JC}$ value is 100MPa√m. $K_{JC}$ represents the values after size-correction to 1-inch.

### *2.2. Cleavage Crack Arrest Toughness, $K_{Ia}$*

It is observed that the mean temperature dependence of $K_{Ia}$ follows the form of MC.

$$K_{Ia}^{mean} = 30 + 70 \cdot \exp[0.019(T - T_{KIa})]$$

$$T_{KIa} = T_O + 44.97 \times \exp[-0.00613 \cdot T_O]$$

$T_{KIa}$ is defined as the temperature at which the mean measured $K_{Ia}$ value is 100MPa√m. Since crack arrest is not a weakest-link mechanism, there should not be a size effect like crack initiation. The scatter in $K_{Ia}$ is less than that observed for $K_{JC}$ and there is no effect of the specimen size. A log normal distribution is found to match the data well.

For lower and upper bound curves of percentile p,

$$K_{Ia}^{p} = K_{Ia}^{mean}\,(1 \pm 0.18\,M_p)$$

where $0 < p \leq 0.5$ and $M_p$ is a standardized normal variate in the standard normal distribution.

### *2.3. Ductile Crack Initiation Toughness, $J_{IC}$*

A model describing the temperature dependence of upper shelf fracture toughness ($J_{IC}$) was developed by EricksonKirk et al. It was based on the Zerilli-Armstrong (Z-A) constitutive equation describing the temperature dependence of the flow stress that is common to ferritic steels like in the master curve. They normalized the $J_{IC}$ data sets by the mean $J_{IC}$ at a single temperature 288°C ($J_{IC288}$) and individual data sets of $J_{IC}$ data versus test temperature were fit. The fitted models are as follows.

$$J_{IC}^{mean} = 1.75\{1033 \bullet \exp[-0.01023(T + 273.15)] - 3.325\} + J_{C(US)} - \Delta J_{IC(US)}$$

$$J_{c(US)} = \frac{1-\nu^2}{E_{US}}\{30 + 70 \times \exp[0.019(b_{PF} - 0.16T_O)]\}^2$$

$$\Delta J_{IC(US)} = 1.75\{1033 \cdot \exp[-0.01023(T_{US} + 273.15)] - 3.325\}$$

$$E_{US} = \frac{\{208455 - 71.4T_{US}\}}{1000}$$

$$T_{US} = b_{PF} + 0.84\, T_O$$

Where $b_{PF}$ is the product form dependent bias as 54.5 °C for base metal (plate/forging), 49.5 °C for non-Linde 80 welds, and 38.0 °C for Linde 80 welds.

The distribution on $J_{IC}$ is a function of both temperature and prior hardening, as defined by the mean value of $J_{IC}$ at 288 °C ($J_{IC288}$). The standard deviation for $J_{IC}$ is defined as:

$$\sigma_{\Delta JIC} = A \cdot \exp[B(T - 288)]$$

$$A = 9.03 \cdot \exp(1.12 \cdot \mathrm{P})$$

$$B = \mathrm{MIN}\{0, (0.0009 \cdot \mathrm{P} - 0.0045)\}$$

$$\mathrm{P} = \mathrm{MIN}\{1, \mathrm{MAX}[0, \mathrm{MIN}(P_1, P_2)]\}$$

$$P_1 = \frac{J_{IC(288)}}{120} - 0.46$$

$$P_2 = \frac{J_{IC(288)}}{800} + 0.51$$

For lower and upper bound curves of percentile p,

$$J_{IC}^{p} = J_{IC}^{mean} \pm \sigma_{\Delta JIC} \cdot M_p$$

*2.4. Upper Shelf Crack Growth, J-R*

J-R curve models have mostly been formulated as a function of Charpy upper shelf energy (USE). However, in the current approach, J-R curves are predicted from information on $J_{IC}$ and the product form of the material. $J_{IC}$ and its temperature dependence are predicted from $T_o$ as shown in the previous section.

J-R curves are represented by the following two-parameter power-law curve:

$$J_x^{mean} = \mathrm{C} \times (\Delta a)^n$$

$$\mathrm{C} = 1.6 \times J_{IC}^{mean}$$

$$\mathrm{n} = 0.059 \times C^{0.36}$$

$$\mathrm{x} = \Delta \mathrm{a}$$

For lower and upper bound curves of percentile p,

$$J_X^p = \exp\{\ln[J_X^{mean} \pm M_p \times RMSD\}$$

Values of root mean square deviation (EMSD) depend on the product form: 0.112 for forging(A508), 0.138 for plate(A533B), 0.131 for RPV welds, and 0.206 for Linde 80 RPV welds.

*2.5. Relationship between $K_{JC}$ and $J_{IC}$, $T_{US}$*

$T_{US}$ is defined as the temperature at which the $K_{JC}$ curve and $J_{IC}$ curve intersect each other. $T_{US}$ may represent the onset of the upper shelf temperature.

$$T_{US} = b_{PF} + 0.84\, T_O$$

The bias factor $b_{PF}$ depends on the product form:
54.5 °C for base metal, 49.5 °C for non-Linde 80 welds, 38.0 °C for Linde 80 welds.

*2.6. Relationship between $K_{JC}$ and $K_{Ia}$, $T_{KIa}$*

It is generally recognized that steels with higher amount of hardening (or embrittlement) tend to have less separation between the cleavage crack initiation ($K_{JC}$) and cleavage crack arrest ($K_{Ia}$) curves. From a large amount of data, the relationship was fitted by the following equation.

$$T_{KIa} = T_O + 44.97 \cdot \exp[-0.00613\, T_O]$$

## 3. Comparison with fracture toughness database

The Master Curve of cleavage crack initiation toughness, $K_{JC}$, has already been verified by a tremendous number of database sets. Therefore, verification of the CC N-830-1 procedure is mainly focused on the linkage model between $K_{JC}$ and $J_{IC}$, which had been considered as independent of each other.

In this paper, $J_{IC}$ values and J-R curves, which are predicted through the CC N-830-1 procedure by using a single measured value of $T_o$, are compared with those properties measured for two extremely different domestic RPV materials.

Fig. 1 shows the plots from a low-toughness Linde 80 weld after neutron irradiation. Prediction by MC $T_o$ value seems very accurate for this material. Compared to other materials, Linde 80 weld has much larger database to develop the prediction models. Note that data points in Fig. 1(a) have different neutron fluences but the effects on the plot are not significant for the current discussion.

Fig. 2 shows the plots from a high-toughness modern forging steel, SA508-Gr.3. For this material, the prediction by CC N-830-1 is not very accurate while conservative. Similar findings were also reported by several research groups. The $J_{IC}$ prediction capability for this material may be limited by the fact that a relatively small number of database sets were used for modeling of this material.

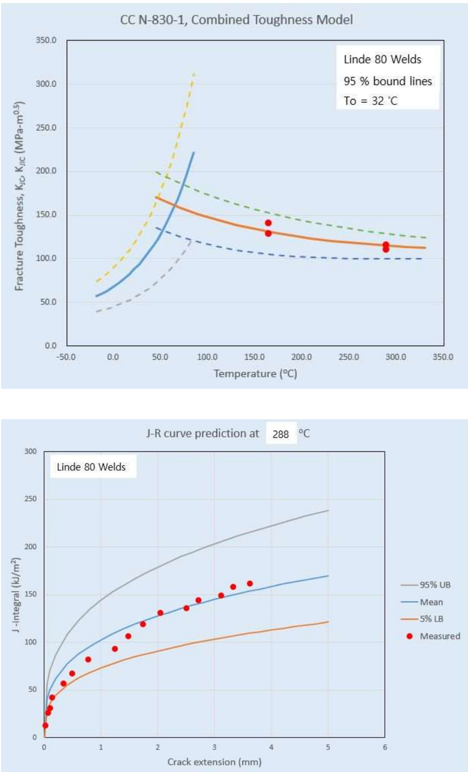


Fig. 1. Measured values and the prediction of ductile fracture toughness by using $T_o$ value of a low-toughness Linde 80 weld material: (a) $J_{IC}$ converted to $K_{JC}$ (b) J-R curve

## 4. Conclusion

WGFE (Working Group on Flaw Evaluation) of ASME Code Section XI is developing a revised Code Case N-830-1, which provides a complete suite of self-consistent fracture toughness models for ferritic steels in the range from the lower shelf to upper shelf. Only the reference temperature, $T_o$, measured by the Master Curve testing is the necessary parameter for the prediction models. The models have been developed mainly by fitting the available database sets which are practically very large but different in the amount of data for each material. Therefore, the accuracy of the prediction may depend on the category of the materials. Nevertheless, the procedure should be very useful to engineers and the models can be improved further.

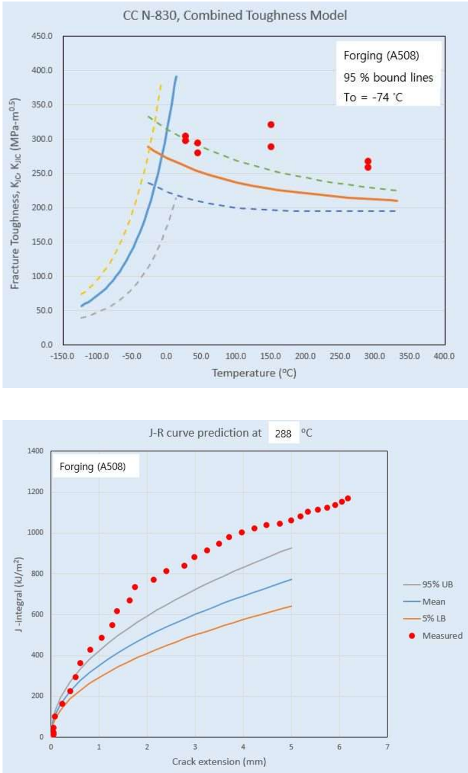


Fig. 2. Measured values and the prediction of ductile fracture toughness by using $T_o$ value of a high-toughness SA508-Gr.3 base material: (a) $J_{IC}$ converted to $K_{JC}$ (b) J-R curve

## REFERENCES

[1] ASTM Standard E 1921-97, "Standard Test Method for Determination of Reference Temperature, $T_o$, for Ferritic Steels in the Transition Range", ASTM, 1997

[2] Communications within the ASME Code Section XI, WGFE Committee, ASME Code Week Meetings, 2020

[3] MRP-418 Revision 1, "Technical Basis for ASME Code Case N-830-1, Revision 1 – Direct Use of Master Curve Fracture Toughness for Pressure-Retaining Materials of Class 1 Vessels, Section XI", EPRI, 2019