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# **STRUCTURAL INTEGRITY ASSESSMENT PROCEDURES FOR EUROPEAN INDUSTRY**

**SINTAP**

## **SUB-TASK 3.3 REPORT: FINAL ISSUE DETERMINATION OF FRACTURE TOUGHNESS FROM CHARPY IMPACT ENERGY: PROCEDURE AND VALIDATION**

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## SUMMARY

### DETERMINATION OF FRACTURE TOUGHNESS FROM CHARPY IMPACT ENERGY: PROCEDURE AND VALIDATION

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One of the key inputs for any structural integrity assessment is the fracture toughness, usually determined by an appropriate fracture mechanics-based test. However, in many situations data are not available and cannot be generated. In these cases it is necessary to use a correlation between Charpy impact energy and fracture toughness.

In this report, a procedure is described for determining best-estimates of fracture toughness data from Charpy impact energy. Since no single correlation can be applied to all parts of the toughness transition curve, it is necessary to apply various correlation approaches; the three described here are:

- A lower bound correlation for the brittle (lower shelf) regime
- A statistical method for the transition regime (the 'Master Curve')
- A lower bound correlation for the ductile (upper shelf) regime

Guidance is also provided for

- Determination of Charpy 27 J transition temperature from other Charpy data
- Converting J and CTOD fracture toughness values into  $K_{mat}$  fracture toughness
- Accounting for the influence of strain rate
- Treatment of sub-size Charpy data

For each section, validation details are given in a corresponding appendix, providing details of aspects such as accuracy of the predictions and circumstances where the guidance may not be applicable.

The report brings together a number of published and well validated methods into a single reference source and is applicable to a wide range of steels operating in all areas of the toughness transition regime.

|                  |    |
|------------------|----|
| Cover Pages      | 2  |
| Text/Table Pages | 13 |
| Figure Pages:    | 6  |
| Appendix Pages:  | 46 |

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| CONTENTS   |                                                                               | Page |
|------------|-------------------------------------------------------------------------------|------|
| 1.         | INTRODUCTION                                                                  | 3    |
| 2.         | TYPES OF CHARPY DATA                                                          | 3    |
| 3.         | SELECTION OF CORRELATION                                                      | 3    |
| 4.         | LOWER BOUND CORRELATION FOR LOWER SHELF/TRANSITION BEHAVIOUR                  | 4    |
| 5.         | MASTER CURVE CORRELATION                                                      | 4    |
| 5.1        | General Description                                                           | 4    |
| 5.2        | Derivation of Approach and Recommended Expression                             | 5    |
| 6.         | DETERMINATION OF $T_{27J}$ FROM CHARPY VALUES AT OTHER TEMPERATURES           | 6    |
| 7.         | RELATIONSHIP BETWEEN K, J AND CTOD FRACTURE TOUGHNESS                         | 7    |
| 8.         | INFLUENCE OF STRAIN RATE                                                      | 7    |
| 9.         | UPPER SHELF CHARPY BEHAVIOUR                                                  | 9    |
| 10.        | TREATMENT OF SUB-SIZE CHARPY DATA                                             | 10   |
| 11.        | OTHER GUIDANCE/LIMITATIONS                                                    | 10   |
| 12.        | SUMMARY                                                                       | 10   |
|            | ACKNOWLEDGEMENTS                                                              | 11   |
|            | REFERENCES                                                                    | 11   |
|            | TABLE                                                                         | 13   |
|            | FIGURES                                                                       | F1   |
| APPENDIX 1 | VALIDATION OF LOWER BOUND, LOWER SHELF CORRELATION                            | A1/1 |
| APPENDIX 2 | MASTER CURVE APPROACH                                                         | A2/1 |
| APPENDIX 3 | PREDICTION OF CHARPY IMPACT ENERGIES FROM EXTRAPOLATION AT OTHER TEMPERATURES | A3/1 |
| APPENDIX 4 | CONVERSION OF FRACTURE TOUGHNESS PARAMETERS                                   | A4/1 |
| APPENDIX 5 | INFLUENCE OF STRAIN RATE                                                      | A5/1 |
| APPENDIX 6 | UPPER SHELF CORRELATION                                                       | A6/1 |
| APPENDIX 7 | TREATMENT OF SUB-SIZE CHARPY DATA                                             | A7/1 |

## **DETERMINATION OF FRACTURE TOUGHNESS FROM CHARPY IMPACT ENERGY: PROCEDURE AND VALIDATION**

British Steel plc

### **1. INTRODUCTION**

In an ideal situation, fracture toughness data for use in structural integrity assessments are generated through the use of appropriate fracture mechanics-based toughness tests. In reality, such data are often not available and cannot be easily obtained due to lack of material or the impracticability of removing material from the actual structure. In such circumstances, and in the absence of appropriate historical data, the use of correlations between Charpy impact energy and fracture toughness can provide the fracture toughness value to be used in the assessment.

A single correlation applicable to all parts of the transition curve and all materials does not exist. In the following sections a number of different correlations are described which can be selected as appropriate to the particular case being assessed. These were selected following the review of existing correlations carried out under Sub-Task 3.1. Guidance on related aspects such as conversion between fracture toughness parameters, treatment of sub-size Charpy data and the considerations necessary for impact loading is also given.

### **2. TYPES OF CHARPY DATA**

Charpy impact energy data for a material will usually comprise one of four forms, Fig. 1:

- (i) Knowledge of the fact that the material has met the Charpy requirements of a particular grade (a given value of J at T°C).
- (ii) A test certificate showing a Charpy energy and test temperature (usually three repeats).
- (iii) A full Charpy transition curve.
- (iv) A full Charpy transition curve together with percentage crystalline fracture appearance.

Item (i) represents the minimum (lowest quality) data for using a correlation, while item (iv) is the maximum of useful Charpy data for use in correlations. Very few correlations have been published where Charpy properties are expressed in terms of lateral expansion and this quantity is not considered further in this report.

On account of these potential differences a number of correlations are offered within the present document which enable full benefit to be made of the quality of the data.

### **3. SELECTION OF CORRELATION**

Due to the shape of the Charpy transition curve, there is no single correlation which can be used for the lower shelf, transition and upper shelf areas. The decision as to which correlation to be used therefore depends on the type of data available, the likely Charpy behaviour of the material at the design operating temperature and the nature of the estimate required (lower bound or best estimate).

Three basic correlation approaches are described in this document.

- 1. Lower Shelf, Lower Bound
- 2. Master Curve (transition regime)
- 3. Upper Shelf, Lower Bound

For (1), only one expression is given.

For (2), one expression is given which is applicable to lower shelf and transition behaviour but with the potential to account for thickness and strain rate effects and selection of appropriate probability levels.

For (3), two correlations are given which enable the user to select the most appropriate expression. Figure 2 shows a flowchart for the selection of appropriate correlation based on available data, toughness regime and nature of the estimate required.

#### 4. LOWER BOUND CORRELATION FOR LOWER SHELF/TRANSITION BEHAVIOUR

A lower bound correlation based on a wide range of steels is given by<sup>(1)</sup>:

$$K_{mat_{25}} = 12 \sqrt{Cv} \quad \dots (1)$$

where  $K_{mat_{25}}$  is the estimated K-based fracture toughness of the material in  $\text{MPa}\sqrt{\text{m}}$  for a thickness of 25 mm, and Cv the Charpy impact energy (V-notch) in J.

The fracture toughness evaluated in accordance with Equation (1) applies to 25 mm thick specimens. The resultant calculated  $K_{mat}$  must therefore be corrected for the appropriate thickness by

$$K_{mat} = \left[ (K_{mat_{25}} - 20)(25/B)^{\frac{1}{4}} \right] + 20 \quad \dots (2)$$

where  $K_{mat}$  = K-based toughness for a thickness B. For through-thickness cracks, B = section thickness, while for surface and embedded cracks B is approximately equal to the crack length, 2c. Further aspects are given in Appendix 1.

#### 5. MASTER CURVE CORRELATION

##### 5.1 General Description

The so-called Master Curve Approach<sup>(2,3,4)</sup> is based on correlation between a specific Charpy transition temperature ( $T_{28J}$ ) and a specific fracture toughness transition temperature ( $T_{100 \text{ MPa}\sqrt{\text{m}}}$ ). The relationship is then modified to account for:

- Thickness effect
- Scatter
- Shape of fracture toughness transition curve
- Required probability of failure

The method requires the definition of the 28 J Charpy transition temperature. Where this is not known, extrapolation from both lower or higher energies can be made within certain limits of validity; this is described later.

The selection of 28 J as the reference point on the Charpy curve was originally made since it corresponds to the increasing part of the transition curve and is relevant to materials' testing standards which frequently require a minimum Charpy impact energy of 27 J. The slight discrepancy between 27 and 28 J arose due to the conversion in the original correlation of Marandet & Sanz where 20 ft lb was converted to the metric equivalent of 27.16 J, which to be conservative was rounded up to 28 J. However, for the purpose of the current correlation 27 J can also be considered to be appropriate. The fracture toughness at the reference temperature should be low enough to preclude ductile tearing and to eliminate any effects of extensive plasticity. As a fracture toughness value of  $100 \text{ MPa}\sqrt{\text{m}}$  fulfils these criteria, the temperature corresponding to  $K_{mat} = 100 \text{ MPa}\sqrt{\text{m}}$  was therefore selected.

##### 5.2 Derivation of Approach and Recommended Expression

Brittle fracture results can be thickness corrected according to Equation (2), where for any two thicknesses  $B_1$  and  $B_2$  the fracture toughness levels are related through:

$$K_{B2} = (K_{B1} - K_{min})(B_1/B_2)^{1/4} + K_{min} \quad \dots (3)$$

where  $K_{min}$  is the lower bound fracture toughness, which for steels is close to  $20 \text{ MPa}\sqrt{\text{m}}$ . For surface cracks, B is equivalent to the crack length, 2c.

The above equation has been validated for a large number of both low and high strength structural steels and for specimen thicknesses ranging from 10 mm to 200 mm. Even though definitive proof of any statistical model is very difficult, the successful application of the model for more than 100 materials might be considered as a comparatively strong validation.

The scatter of brittle fracture toughness results can be described as:

$$P_f = 1 - \exp\left(-\left(\frac{K_I - K_{min}}{K_0 - K_{min}}\right)^4\right) \quad \dots (4)$$

where  $P_f$  is the cumulative failure probability at a stress intensity factor level  $K_I$  and  $K_0$  is a specimen thickness and temperature dependent normalisation parameter which corresponds to a 63.2% failure probability.

The temperature dependence of  $K_0$  in  $\text{MPa}\sqrt{\text{m}}$  can be described by:

$$K_0 = \alpha + \beta \cdot \exp[\gamma \cdot (T - T_0)] \quad \dots (5)$$

where  $\alpha + \beta = 108 \text{ MPa}\sqrt{\text{m}}$ ,  $T_0$  is the temperature (in °C) at which the mean fracture toughness is  $100 \text{ MPa}\sqrt{\text{m}}$  and is a material constant.

Experimentally it has been found that the shape of the fracture toughness transition curve for ferritic structural steels is only slightly material and yield strength dependent. Therefore, the values of  $\alpha$ ,  $\beta$  and  $\gamma$  are practically material independent. The resulting equation for the temperature dependence of  $K_0$ , corresponding to 25 mm thickness, is:

$$K_0 = 31 + 77 \exp[0.019(T - T_0)] \quad \dots (6)$$

This expression is shown graphically in Fig. 3.

The mean relationship between the 28 J and 100 MPa  $\sqrt{m}$  Charpy and fracture toughness transition temperatures  $TK_{28J}$  and  $TK_{100 MPa \sqrt{m}}$ , respectively, is given by:

$$TK_{100 MPa \sqrt{m}} = T_{28J} - 18^\circ C (\pm 15^\circ C) \quad \dots (7)$$

This is shown graphically in Fig. 4.

A further modification allows for strain rate effects, addressed in Section 8. By combining Equations (3) (= thickness effect), (4) (= scatter), (6) (= shape of transition curve) and (7) (= relationship between Charpy and fracture toughness reference temperatures), the fracture toughness transition curve can be described for brittle fracture in the transition region based on knowledge of the Charpy 28 J transition temperature ( $\approx 27$  J) using the following expression:

$$K_{mat} = 20 + \{ 11 + 77 \cdot \exp(0.019 \cdot [T - T_{28J} + 18^\circ C]) \} \left( \frac{25}{B} \right)^{1/4} \cdot \ln \frac{1}{-P_f} \}^{1/4} \quad \dots (8)$$

|           |                                                             |
|-----------|-------------------------------------------------------------|
| T         | = design temperature ( $^\circ C$ )                         |
| $T_{28J}$ | = 28 (or 27) J Charpy transition temperature ( $^\circ C$ ) |
| B         | = specimen thickness (mm)                                   |
| $P_f$     | = probability of failure                                    |
| Std. dev. | = $13^\circ C$                                              |

A set of transition curves for 25 mm specimen thickness and different failure probabilities is shown in Fig. 5.

Validation: Appendix 2.

## 6. DETERMINATION OF $T_{27J}$ FROM CHARPY VALUES AT OTHER TEMPERATURES

When the temperature corresponding to the 27 J Charpy transition temperature is not known, this can be determined by extrapolation from Charpy impact energy values at other temperatures. However, because of the range of shapes of Charpy transition curves, examples shown in Fig. 6, only extrapolation over a limited Charpy energy range is permitted. The recommended values for extrapolation are given in Table 1<sup>(5,6)</sup>, and are shown in Fig. 7.

The downward limit to extrapolation from  $T_{27J}$  is  $-30^\circ C$ , the upward limit  $40^\circ C$ . These limits should be strictly adhered to. This approach should be used with caution for modern low-C, low-S steels which can have steeper transition curves than that suggested in the above table. In such cases the 27 J temperature estimated from significantly higher temperatures can be predicted unconservatively.

It is, however, important to recognise that the Charpy energy transition behaviour will not represent the transition behaviour in a real structure. The Charpy test is carried out under impact loading on a relatively small scale specimen with a blunt V-notch. Correlations between Charpy test behaviour and fracture mechanics toughness tests are therefore empirical with no real underlying fundamental basis. The plane strain fracture toughness curve against temperature does not show any dramatic drop in toughness on temperatures corresponding to the Charpy test 27 J temperature, but the real plane strain fracture toughness shows a relatively gradual change with temperature with something of an upswing at the higher temperature end.

The transition temperature behaviour shown by the Charpy test, and that on which avoidance of brittle fracture in welded structure depends, is really the deviation from plane strain conditions for finite limited thicknesses, allowing increased toughness approaching that for plane strain conditions.

Validation: Appendix 3.

## 7. RELATIONSHIP BETWEEN K<sub>J</sub> AND CTOD FRACTURE TOUGHNESS

K, J and CTOD values can all be generated in a fracture toughness test. In some instances it may be necessary to correct between these parameters, for example when a CTOD value has been determined in a fracture toughness test and a K approach is needed for the analysis.

An equivalent  $K_{mat}$  can be determined from a CTOD ( $\delta$ ) value in accordance with the following two expressions for ferritic steels.

$$K_{mat}(\delta) = \left[ \frac{1.5 \rho_y CTOD E}{(1-\nu^2)} \right]^{0.5} \quad \dots (9)$$

$$K_{mat}(\delta) = \left[ \frac{1.3 \sigma_y CTOD E}{(1-\nu^2)} \right]^{0.5} \quad \dots (10)$$

where  $\sigma_y$  is the yield strength and  $\sigma_f$  is the flow stress given by

$$\frac{(\sigma_y + UTS)}{2} \quad \dots (11)$$

For duplex and superduplex stainless and weldments the coefficient in Equation (9) can be taken as 2.2, that for Equation (10) 1.8.

The lowest of the two values calculated in accordance with expressions (9) and (10) should be used as the  $K_{mat}$  for subsequent analysis.

Validation: Appendix 4.

## 8. INFLUENCE OF STRAIN RATE

High strain rates tend to shift the fracture toughness transition curve upwards along the temperature axis, shown schematically in Fig. 8. The strain rate sensitivity of fracture toughness is a consequence of the increase in yield strength of steels with increasing loading rate. The strain rate sensitivity is greater for lower strength steels than for high strength steels.

The procedure described below enables the determination of strain rate - corrected fracture toughness from Charpy impact energy. The method entails three principal steps:

- (i) Use correlation to convert Charpy energy to static toughness.
- (ii) Obtain an estimate of the temperature shift as a function of stress rate.

(iii) Shift the static toughness curve by this amount to obtain dynamic toughness.

A simplified expression for derivation of the temperature shift of the fracture toughness transition curve<sup>(7)</sup> is given by

$$\Delta T_{\varepsilon} = \frac{1440 - \rho_y}{550} \left( \ln \left( \frac{\varepsilon}{\varepsilon_0} \right) \right)^{1.5} \quad \dots (12)$$

where  $\Delta T_{\varepsilon}$  is the temperature shift arising from a strain rate  $\varepsilon$  and  $\varepsilon_0 = 0.0001 \text{ s}^{-1}$

The application of a strain rate correction to the Master Curve Approach (Section 5) has been derived in terms of a stress intensity factor rate ( $\dot{K}$ ), since the application of an effective strain rate  $\varepsilon$  to a crack tip situation necessitates crude approximation.

The shape of the Master curve is unaffected by the loading rate. Any correction must therefore be applied to the transition temperature for  $K_{mat} = 100 \text{ MPa}\sqrt{\text{m}}$ , where  $B = 25 \text{ mm}$ . This reference temperature is termed  $T_0$ .

The Zener-Holloman strain rate dependence of  $\sigma_y$  is given by<sup>(8,9)</sup>:

$$\sigma_y = f(T \cdot \log \left[ \frac{A}{\dot{\varepsilon}} \right]) \quad \dots (13)$$

where  $T$  is temperature in Kelvin and  $A$  is the strain rate parameter. Re-writing (13) in terms of  $\dot{K}$  gives

$$T_0 \cdot \ln \left( \frac{A}{K_0} \right) = \text{constant} \quad \dots (14)$$

where the 'constant' can be expressed in terms of a reference loading rate transition temperature. For quasi-static loading ( $\dot{K}_1 = 1 \text{ MPa}\sqrt{\text{m}} \text{ s}^{-1}$ ) the reference temperature  $T_0$  can be termed  $T_{01}$ . Renaming  $(\ln A)$  in Equation (14) as  $\Gamma$  leads to the following expression for the loading rate induced temperature shift<sup>(10)</sup>.

$$\Delta T_0 = \frac{T_{01} \cdot \ln(\dot{K}_1)}{\Gamma - \ln(\dot{K}_1)} \quad \dots (15)$$

Empirical fits to these data show that the parameter  $\Gamma$  can be described in terms of yield strength and  $T_{01}$ .

$$\Gamma = 9.9 \exp \left\{ \left[ \frac{T_{01}}{190} \right]^{1.66} + \left[ \frac{\rho_y}{722} \right]^{1.09} \right\} \quad \dots (16)$$

Figure 9<sup>(10)</sup> shows examples of calculated values of  $\Delta T_0$  for a range of  $T_0$  temperatures and yield strengths at one stress intensity rate.

This loading rate dependence has been validated for  $\dot{K}$  between  $1 \times 10^{-1}$  and  $1 \times 10^6 \text{ MPa}\sqrt{\text{m}} \text{ s}^{-1}$ .

A combination of expressions (15) and (16) enables the loading rate shift for  $T_{K100}$  ( $T_o$ ) to be evaluated based on knowledge of the loading rate, yield strength and  $T_{K100}$  at quasi-static loading rate.

$$\Delta T_o = \frac{T_{01} \ln(\dot{K})}{\left[ 9.9 \exp \left[ \left( \frac{T_o}{190} \right)^{1.66} + \left[ \frac{\rho \gamma}{722} \right]^{1.09} \right] \right] - \ln(\dot{K})} \quad \dots (17)$$

The relationship between  $\dot{\epsilon}$  and  $\dot{K}$  can be crudely approximated by:

$$\dot{K} = E \dot{\epsilon} \sqrt{\pi a} \quad \dots (18)$$

Validation: Appendix 5.

## 9. UPPER SHELF CHARPY BEHAVIOUR

When Charpy behaviour is on the upper shelf (defined for the present project as follows: Charpy tests are considered to exhibit upper shelf behaviour when the fracture appearance is 100% shear) the correlations described in Sections 4 and 5 are not appropriate. A lower bound estimation of upper shelf fracture toughness is given by<sup>(11,12)</sup>:

$$K_{mat} = 0.54 C_v + 55 \quad \dots (19)$$

This expression is only recommended when  $C_v > 60$  J. The resultant correlation is shown in Fig. 10.

Fracture toughness values calculated in accordance with the above correlation can be compared with values derived according to the following expression which is not necessarily a lower bound<sup>(12)</sup>:

$$\left( \frac{K_{mat}}{\sigma_y} \right)^2 = 0.52 \left( \frac{C_v}{\sigma_y} - 0.02 \right) \quad \dots (20)$$

Figure 11 shows the resultant predicted fracture toughness values for various strength levels using Equation (20). For fracture toughness values at temperatures above ambient, the following values are provided for guidance only from BS PD 6539<sup>(13)</sup>.

| Material                                     | Temperature Range (°C) | Fracture Toughness (K <sub>I</sub> at 0.2 mm Crack Extension) (MPa√m) |             |
|----------------------------------------------|------------------------|-----------------------------------------------------------------------|-------------|
|                                              |                        | Mean                                                                  | Lower Bound |
| Si-killed C-Mn Steel                         | 300-380                | 164                                                                   | 99          |
| Al-killed C-Mn Steel                         | 300-380                | 196                                                                   | 146         |
| Wrought AISI 316                             | 300-600                | 140                                                                   | 105         |
| 2½Cr1Mo Steel                                | 100-500                | 150                                                                   | 100         |
| Austenitic Steels and Welds                  | All                    | 220                                                                   | 132         |
| Austenitic Steels and Welds (thermally aged) | All                    | 150                                                                   | 80          |

Validation; Appendix 6.

## 10. TREATMENT OF SUB-SIZE CHARPY DATA

When the plate thickness is less than 10 mm, testing with standard sized Charpy V-notch specimens is impossible. In such cases the testing must be based on sub-sized specimens. The difficulty lies in extrapolating the result from the sub-sized specimen to correspond to the result from a standard sized specimen. The extrapolation can be based either directly upon the measured parameter e.g. impact energy, or on some transition temperature criterion<sup>(14,15)</sup>.

Due to the fact that the effect of thickness on Charpy behaviour varies according to the region of the transition curve a criterion based on transition temperature is more appropriate than one based on impact energy. For a standard Charpy specimen of 10 mm square cross section 28 J corresponds to 35 J/cm<sup>2</sup>. The shift in this transition temperature associated with sub-sized Charpy specimens,  $\Delta T_{SS}$ , can be described as<sup>(15)</sup>:

$$\Delta T_{SS} = 51.4 \cdot \ln \left[ 2 \left( \frac{B}{10} \right)^{0.25} - 1 \right] \quad \dots (21)$$

This expression is shown graphically in Fig. 12.

For upper shelf behaviour the effect is reversed but there is no single expression to predict the influence of thickness in the ductile regime.

Validation: Appendix 7.

## 11. OTHER GUIDANCE LIMITATIONS

Constraint effects associated with weld strength mismatch are not incorporated in this procedure.

Where correlations between Charpy energy and fracture toughness are made for weld metal and HAZ microstructures, the Charpy specimen should sample the most brittle microstructure.

The thickness effect represented by expression (3) is only valid for brittle fracture since for ductile fracture the toughness actually increases with thickness. This is because upper shelf behaviour is propagation controlled for which there is no statistical size effect. Conversely, for the lower shelf fracture toughness ( $K_{mat}$  typically less than 50 MPa $\sqrt{m}$ ) there is no statistical size effect since the initiation criterion is no longer dominant and the fracture becomes propagation controlled.

## 12. SUMMARY

A method is proposed for determining fracture toughness values from knowledge of the Charpy impact behaviour of steels. The principal features of this method are:

- A lower bound correlation for lower shelf behaviour (Equation (1))
- Thickness correction for brittle fracture (Equation (2))
- The Master Curve correlation for brittle fracture (Equation (8)) incorporating size and scatter effects
- Guidance for determining  $T_{27J}$  from Charpy energies at other temperatures
- Relationships describing  $K_{max}$ -CTOD-J conversions (Equations (9) and (10))
- Influence of loading rate on fracture toughness transition temperature (Equation (17))
- Correlations for upper shelf behaviour (Equations (18) and 19)
- Treatment of sub-size Charpy data (Equation (20))

Selection of correlation is made based on the type of Charpy data available, the region of the transition curve and the type of result required (lower bound or best estimate).

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EJF

**TABLE 1**  
**INFERRED CHARPY VALUES FROM**  
**TEMPERATURES ABOVE AND BELOW  $T_{27J}$**

| Difference Between Operating Temperature and 27 J Charpy Transition Temperature | Assumed Charpy Impact Energy (J) |
|---------------------------------------------------------------------------------|----------------------------------|
| -30                                                                             | 5                                |
| -20                                                                             | 10                               |
| -10                                                                             | 18                               |
| 0                                                                               | 27                               |
| +10                                                                             | 41                               |
| +20                                                                             | 61                               |
| +30                                                                             | 81                               |
| +40                                                                             | 101                              |

Note:

1. Interpolation between temperatures is permissible.
2. Extrapolations from higher temperatures than shown above should be used with great caution.

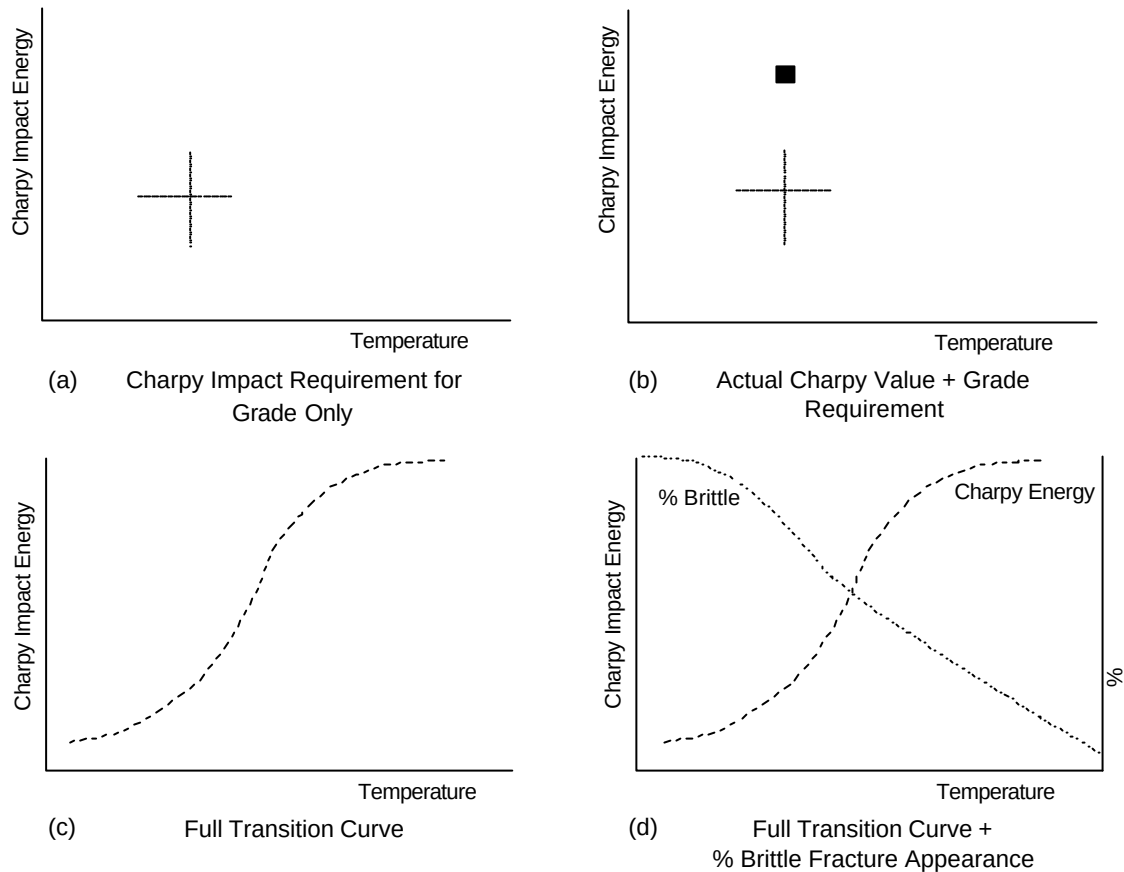


FIG. 1(a-d)

TYPICAL TYPES OF CHARPY IMPACT ENERGY DATA

(D0643D06)

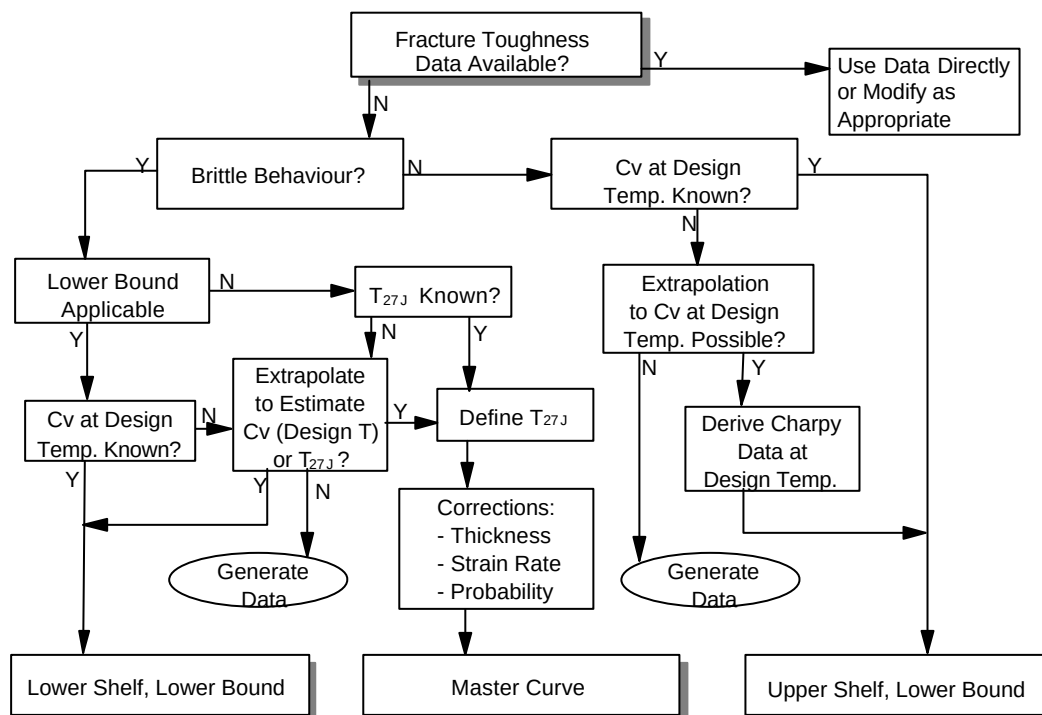


FIG. 2

FLOWCHART FOR SELECTION OF APPROPRIATE CORRELATION

(D0643D06)

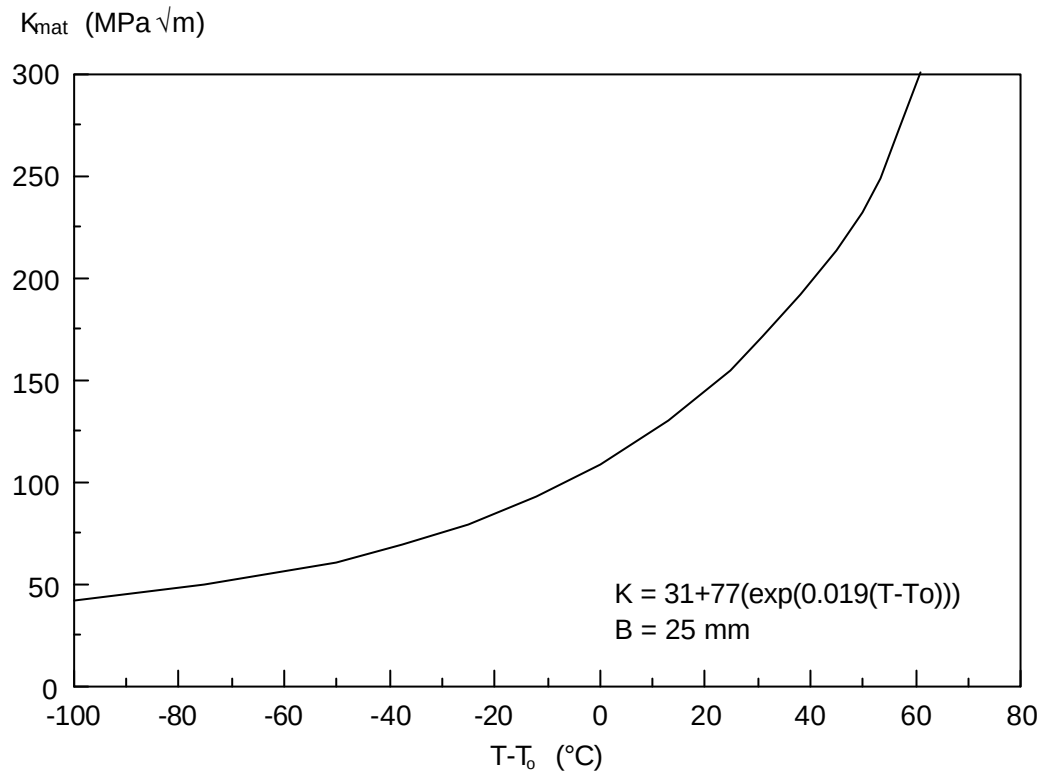


FIG.3

TEMPERATURE DEPENDENCE OF  $K_I$

(D0643D06)

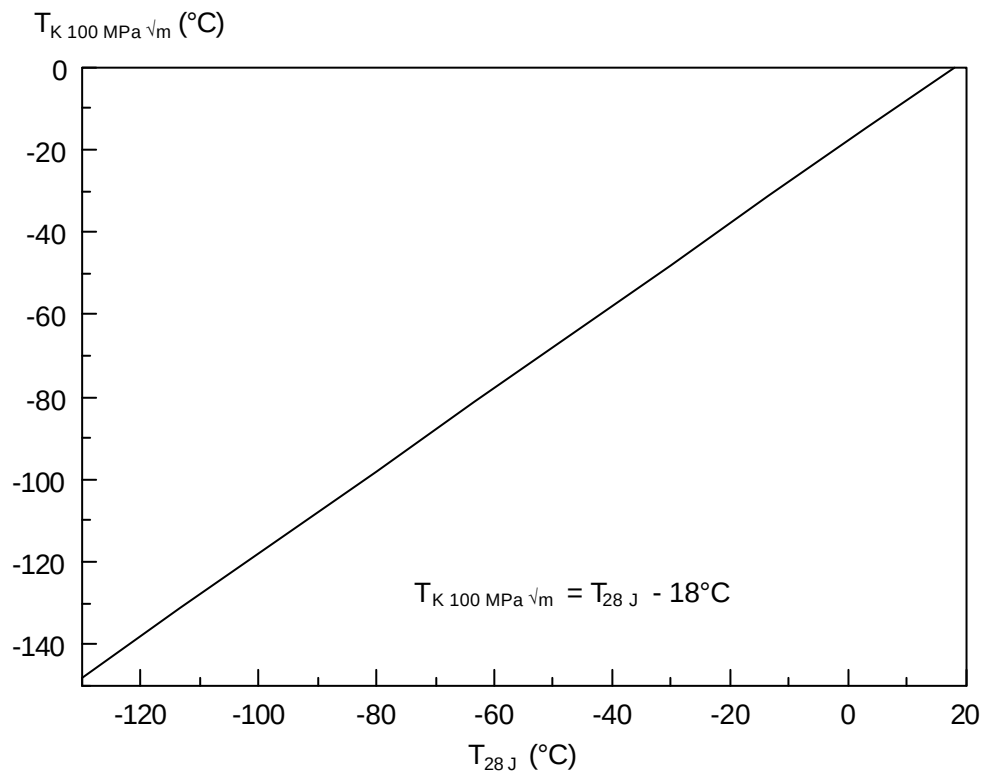


FIG.4

MEAN RELATIONSHIP BETWEEN CHARPY 28 J TEMPERATURE  
AND  $K_{mat}$  (100 MPa  $\sqrt{m}$ ) TEMPERATURE  
(STANDARD DEVIATION = 15°C)

(D0643D06)

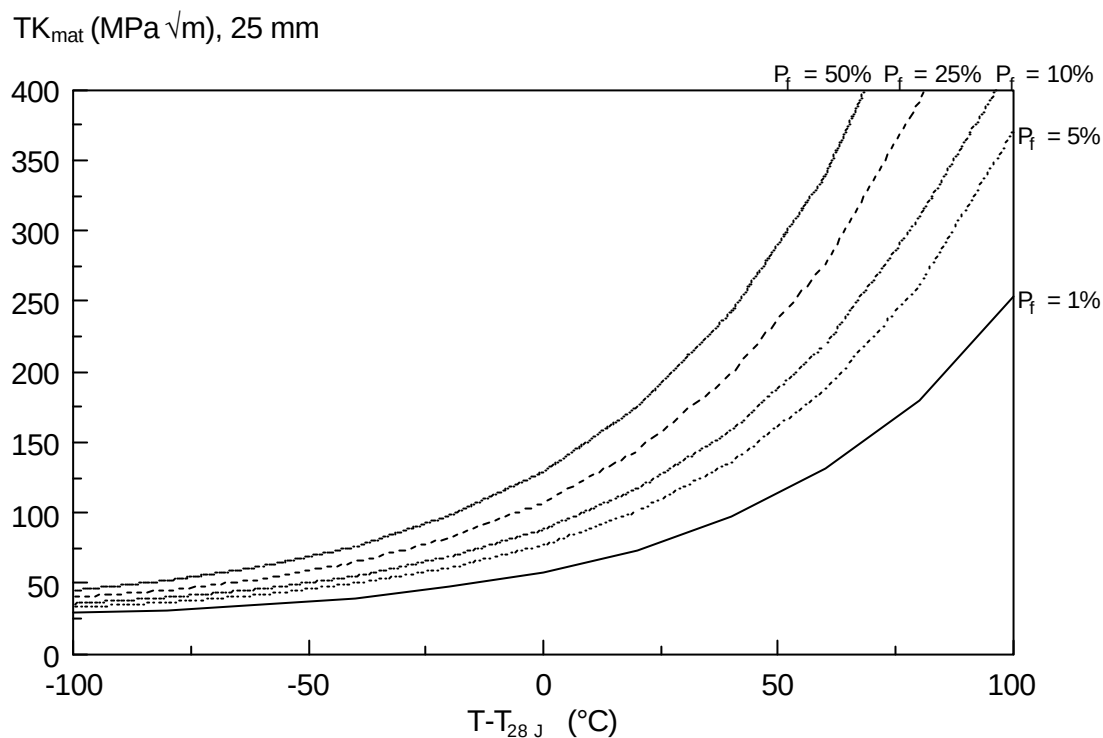


FIG.5

**FRACTURE TOUGHNESS TRANSITION CURVES FOR  
25 mm THICKNESS AND VARYING FAILURE PROBABILITIES**

(D0643D06)

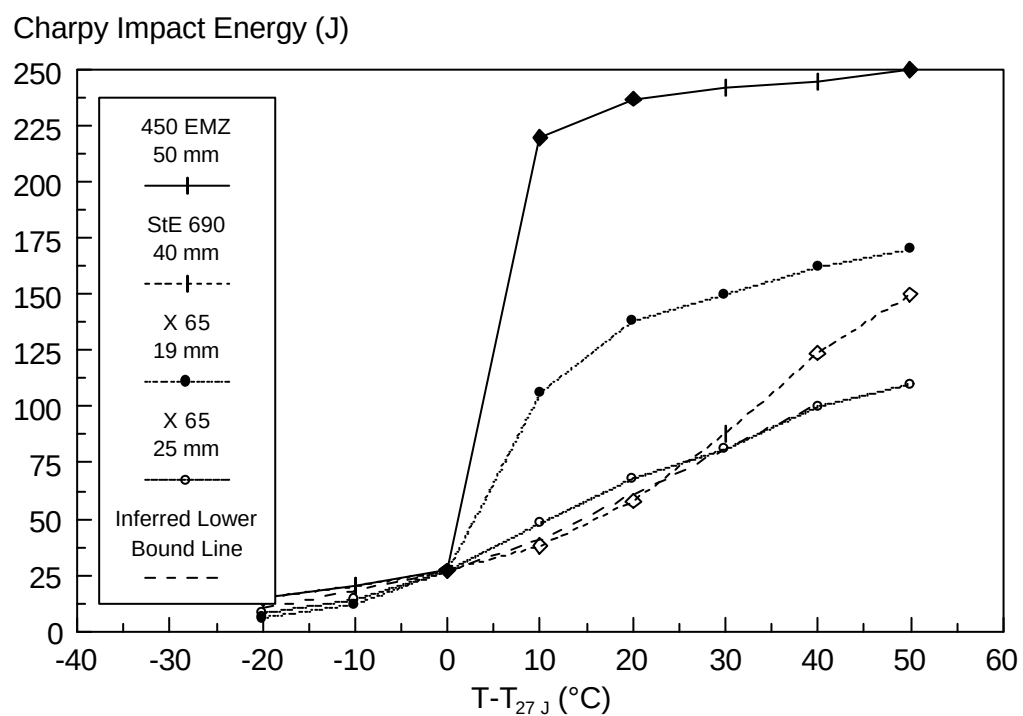


FIG.6

**EXAMPLES OF CHARPY IMPACT TRANSITION CURVES  
REFERRED TO 27 J TEMPERATURE**

(D0643D06)

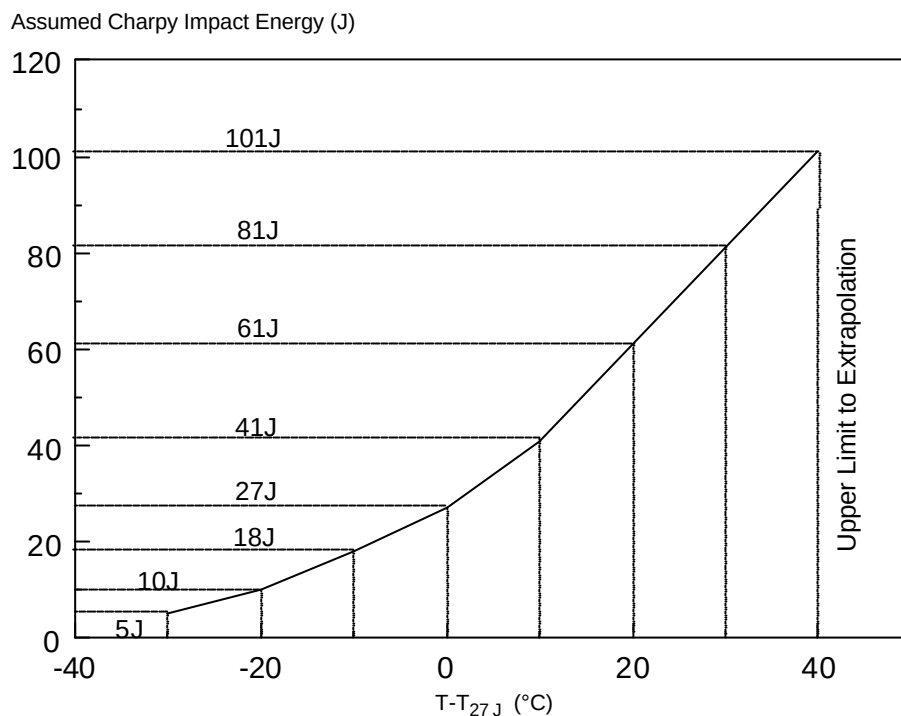


FIG. 7

RECOMMENDED METHOD FOR EXTRAPOLATION OF CHARPY  
VALUES ABOVE AND BELOW THE 27 J TEMPERATURE

(D0643D06)

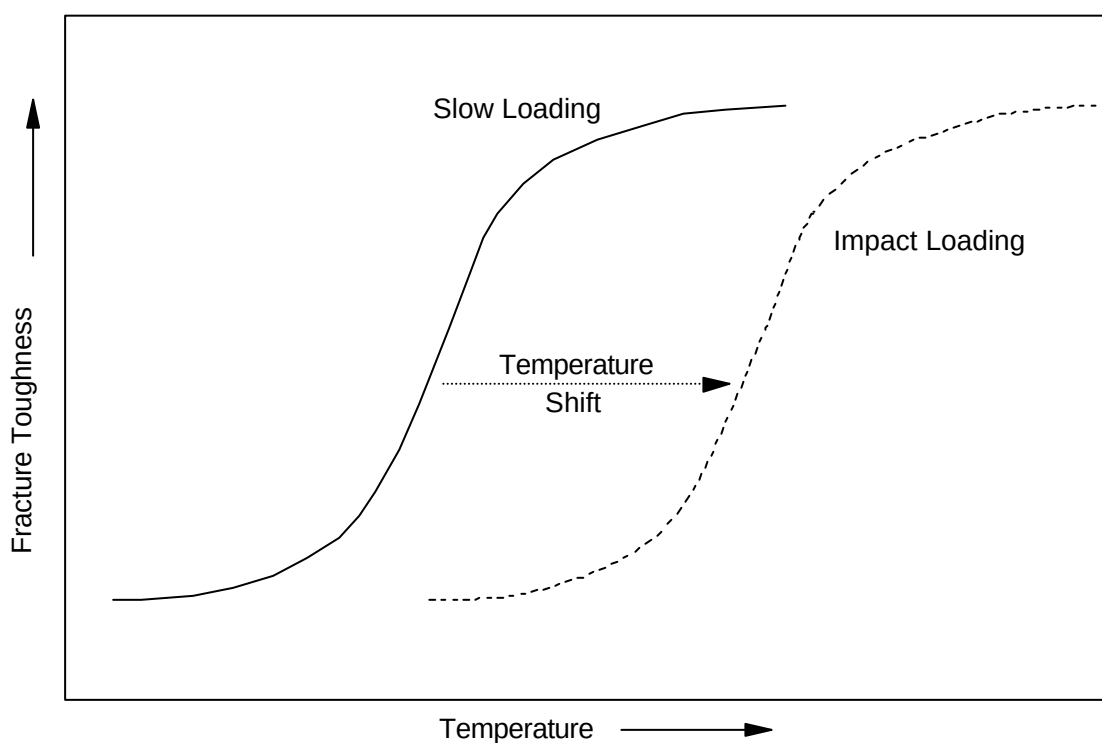


FIG. 8

SCHEMATIC REPRESENTATION OF THE EFFECT OF LOADING  
RATE ON THE FRACTURE TOUGHNESS TRANSITION CURVE

(D0643D06)

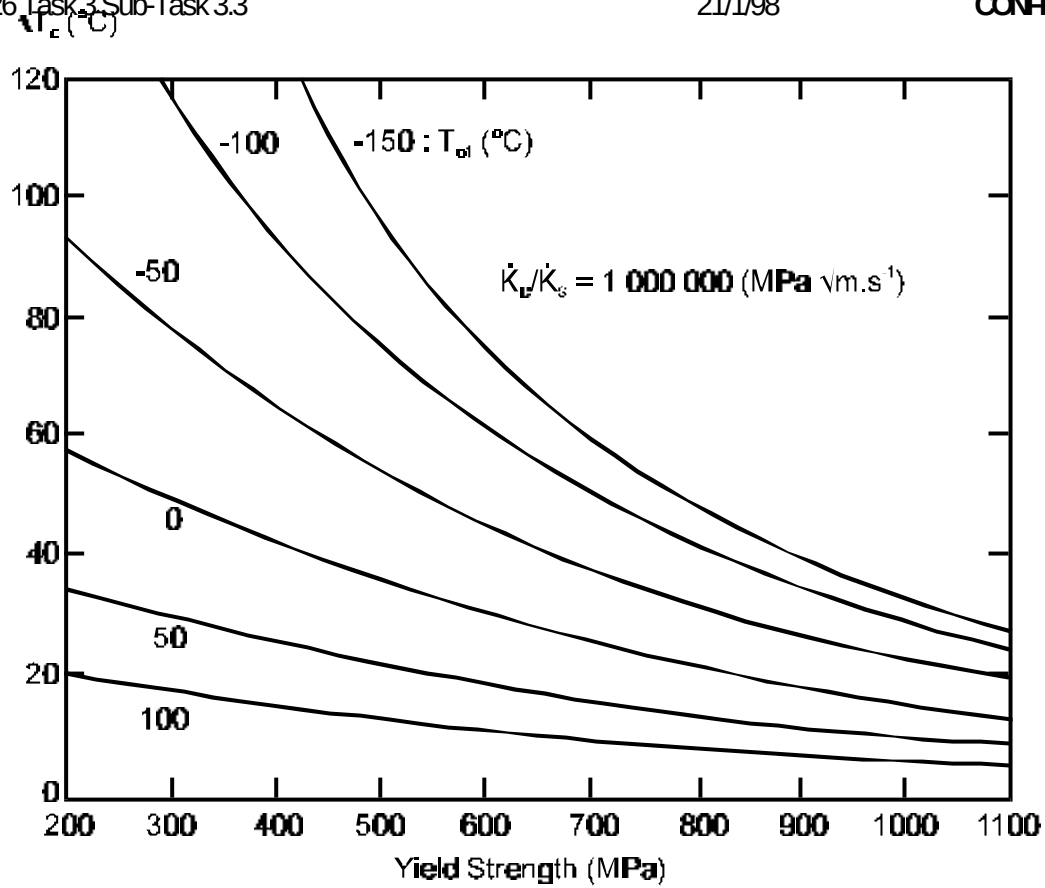


FIG. 9

EXAMPLE OF TRANSITION TEMPERATURE SHIFT ( $\Delta T_0$ )  
DUE TO DYNAMIC LOADING

(D0643D06)

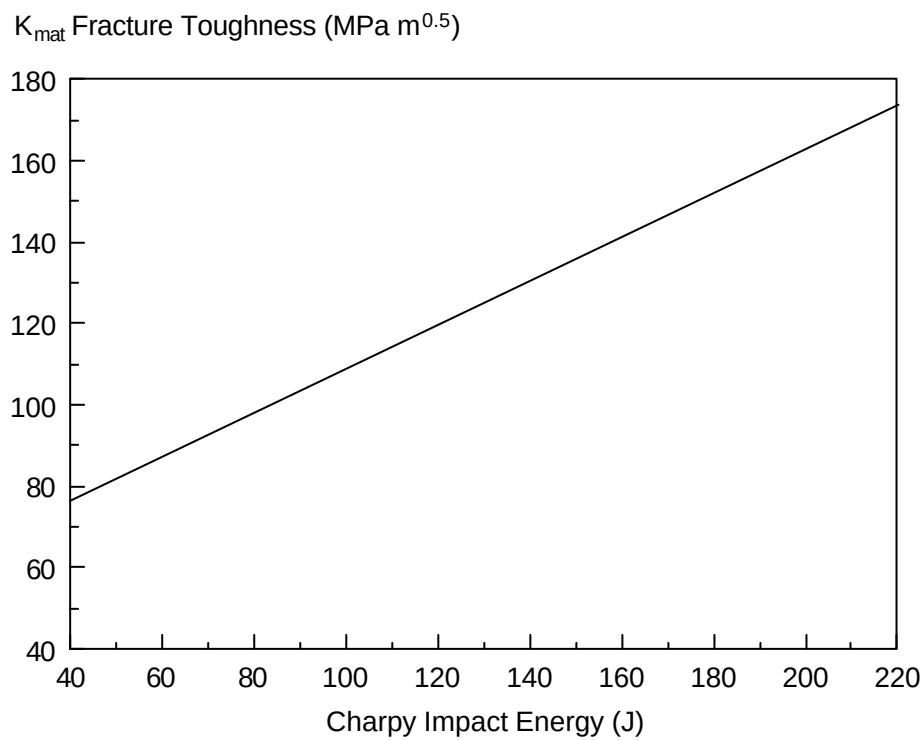


FIG. 10

UPPER SHELF CORRELATION OF EQUATION (19)

(D0643D06)

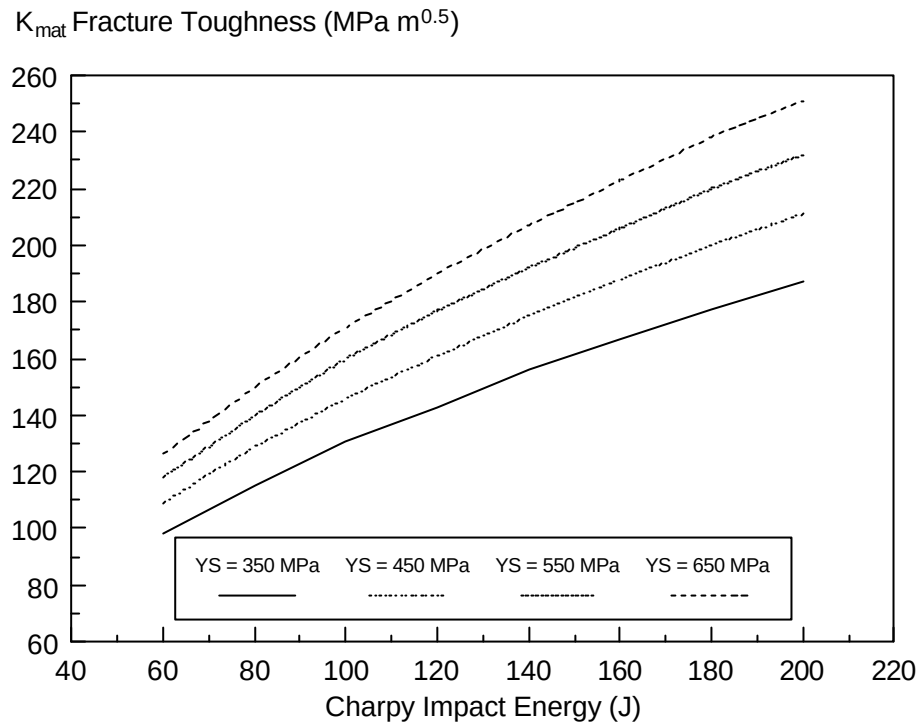


FIG.11

UPPER SHELF CORRELATION (EQUATION (20))  
FOR VARIOUS YIELD STRENGTHS

(D0643D06)

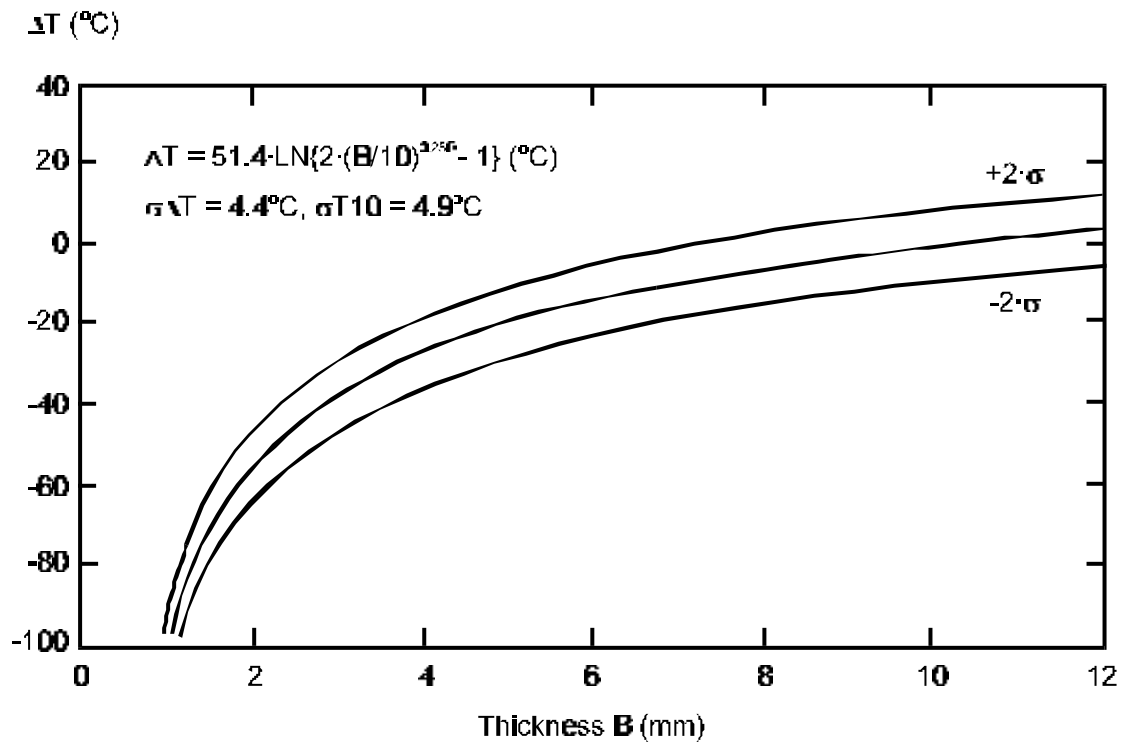


FIG.12

EFFECT OF SPECIMEN THICKNESS ON SHIFT OF  
CHARPY 35 J/cm<sup>2</sup> TRANSITION TEMPERATURE  
(= 28 J FOR 10 mm SQUARE SPECIMEN)

(D0643D06)

## APPENDIX 1

### VALIDATION OF LOWER BOUND, LOWER SHELF CORRELATION

The Master Curve Approach<sup>(A1.1)</sup> can be used to determine a lower bound correlation: At a Charpy energy level of 28 J, the use of the Master Curve Approach with the lower 5<sup>th</sup> percentile of fracture toughness and a 90% confidence level leads to Equation (1) in the main text. This formula is shown in comparison with other correlations<sup>(A1.1)</sup>, in Fig. A1.1. The formula for thickness correction (Equation (2)) is derived from weakest link theory whereby the probability of fracture increases in proportion to the length of crack front in accordance with various derivations<sup>(A1.2, A1.3, A1.4)</sup>. The full derivation can be found in the listed references.

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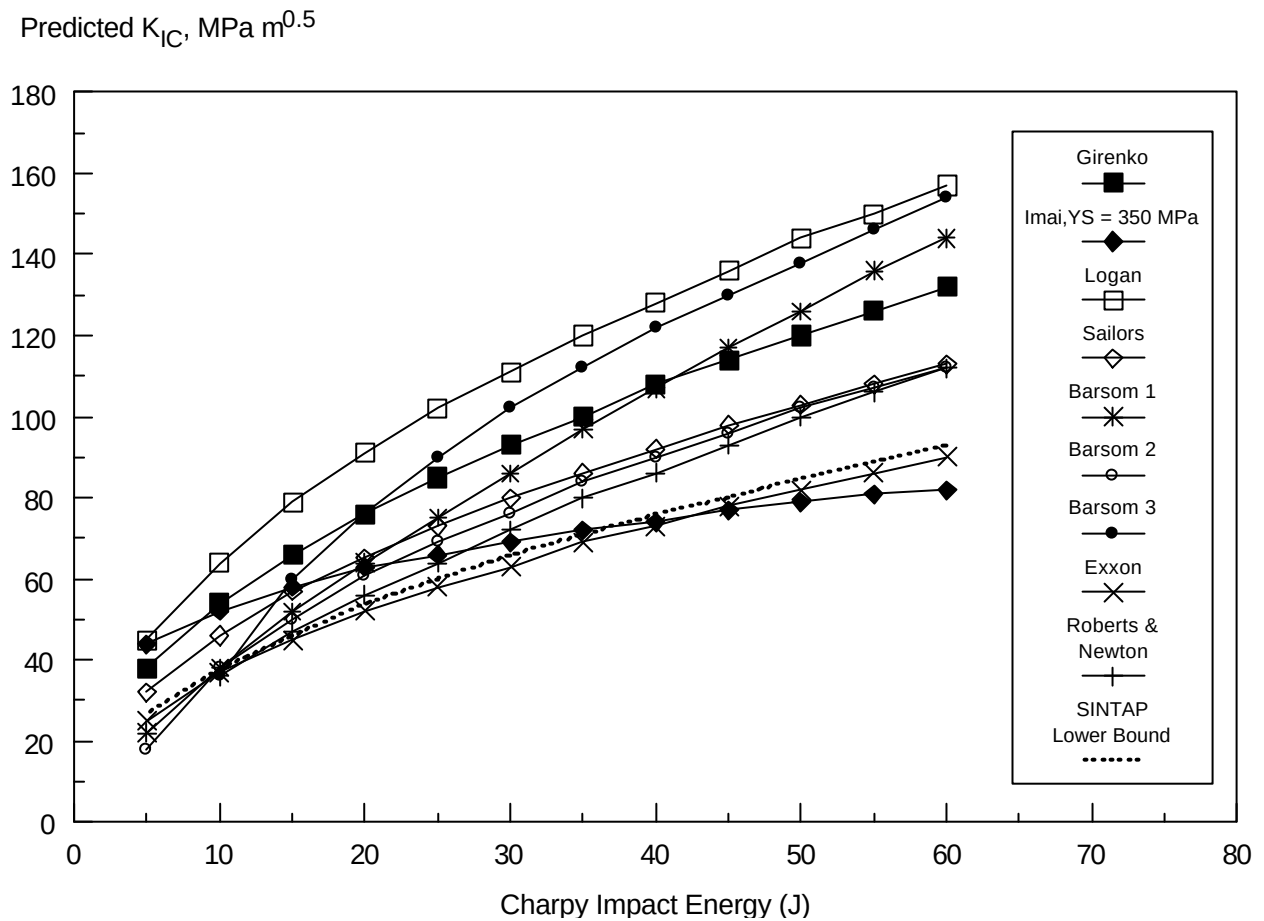


FIG. A11

SINTAP LOWER BOUND CORRELATION IN  
COMPARISON WITH OTHER PUBLISHED CORRELATIONS

(D0643D08)

## APPENDIX 2

### MASTER CURVE APPROACH

#### A2.1 RELATIONSHIP BETWEEN TRANSITION TEMPERATURES

##### A2.1.1 General Description

The fundamental step in establishing a correlation between Charpy and fracture toughness properties is the establishment of a relationship between impact energy and fracture toughness or between specific Charpy energy and fracture toughness reference transition temperatures. In the case of the Master Curve, this relationship has been established for a Charpy impact energy level of 28(or 27)J and a fracture toughness value of  $100 \text{ MPa} \sqrt{\text{m}}$ , corrected for a specimen thickness of 25 mm. The selection of  $100 \text{ MPa} \sqrt{\text{m}}$  as the reference fracture toughness was made to ensure that no significant loss of constraint and/or ductile tearing occur and that a statistical size effect is present. The derived relationship is given as:

$$TK_{100 \text{ MPa} \sqrt{\text{m}}} = T_{28 \text{ J}} - 18^\circ\text{C} (\pm 15^\circ\text{C}) \quad \dots (\text{A2.1})$$

##### A2.1.2 Validation by VTT

This expression was derived initially for pressure vessel steels<sup>(A2.1)</sup> but has since been validated on a wide range of steels.

Wallin et al<sup>(A2.2, A2.3)</sup> and Di Fant et al<sup>(A2.4)</sup> have demonstrated a good fit for data on 25 mm specimens and data corrected for 25 mm specimen thickness, Fig. A2.1. Similar data for steels in the yield strength range 400-1500 MPa under LEFM behaviour, and for high strength steels with yield strength greater than 600 MPa are shown in Fig. A2.2. Extension of this validation to thin, high strength steels in U and square section beam configurations<sup>(A2.5)</sup> has also demonstrated that the majority of data lie within the 95% confidence limits of the correlation, Fig. A2.3.

##### A2.1.3 Validation by IEHK and IRSID

Work by Liessem<sup>(A2.6)</sup> on 29 steels up to a strength level of 890 MPa has shown good agreement with Equation (A2.1), while work on parent plate and welds<sup>(A2.3)</sup> showed a slightly different correlation where the factor  $-18^\circ\text{C}$  in Equation (A2.1) being replaced by  $-8^\circ\text{C}$ . These relations are shown in comparison with the original Sanz<sup>(A2.7)</sup> proposal in Fig. A2.4, demonstrating the generally close agreement between the expressions derived on different steels and by different workers.

##### A2.1.4 Validation by British Steel

CTOD data for 50 steels comprising linepipe, sections, jumbo columns and high strength steels have been analysed. The CTOD data were converted to  $K_{\text{mat}}$  data with  $m = 1.5$  (see Appendix 4), thickness corrected and the  $TK_{100 \text{ MPa} \sqrt{\text{m}}}$  determined. The resulting plot of  $T_{27 \text{ J}}$  v  $TK_{100 \text{ MPa} \sqrt{\text{m}}}$  is shown in Fig. A2.5, together with the mean and 95% confidence limits of the Master Curve fit. A number of data points lie outside the confidence limits. Those lying above the +2.0 Sd line are mainly from steels which exhibit severe directionality of properties due to heavily deformed grain structure, such as in linepipe and the flange-web junction area of sections. In these cases, the fracture toughness specimens showed severe splitting on the fracture surfaces together with 'woody' type fracture in the case of sections. The predictions of Equation (A2.1) are not accurate for these instances. Other work suggests that such splitting occurs when a heavy crystallographic texture is present in the steel. Those points lying below the -2.0 Sd line were generally associated with low upper shelf fracture toughness values.

Further analysis of pipe data shows that those data fitting the predictions well did not show splits on the fracture surface of the fracture toughness specimen and were from results on pipe plate (which had not been formed into pipe). Subsequent forming into pipe generally resulted in an upward shift in  $T_{27 \text{ J}}$  which was greater than the upward shift in  $TK_{100 \text{ MPa} \sqrt{\text{m}}}$ . The net effect is that data for pipe do not fit the correlation as well as plate results. Logically, data on formed pipe showing splits on the fracture surface showed the greatest deviation from the predicted line.

However, the range of steels assessed in this part covered  $T_{27J}$  temperatures ranging from approximately -100 to +100°C, thicknesses from 10 mm to 120 mm and yield strengths from 235 to 850 MPa. The degree of fit can be considered to be satisfactory on account of this variety of materials.

## **A2.2 SHAPE OF FRACTURE TOUGHNESS TRANSITION CURVE**

Experimentally it has been found that the shape of the fracture toughness transition curve for steel is only slightly material and yield strength dependent. The expression considered most appropriate is given by:

$$K_0 = 31 + 77 (\exp[0.019(T-T_0)]) \quad \dots (A2.2)$$

This has been verified for a large number of pressure vessel steels and welds by Wallin<sup>(A2.1, A2.2, A2.3)</sup>, Fig. A2.6(a), and for a range of structural steel plates by Liessem et al<sup>(A2.6, A2.8)</sup>, Fig. A2.6(b). Other analysis has confirmed the suitability of the expression and where differences occur, these are minor.

## **A2.3 COMPARISON OF MEASURED AND PREDICTED FRACTURE TOUGHNESS**

### **A2.3.1 Parent Plate Data from ECSC Sponsored Projects**

Two recent ECSC projects<sup>(A2.9, A2.10)</sup> have included Charpy impact energy and fracture toughness transition curves in a format suitable for comparison of predicted and measured toughness. This comparison is reported in Ref. A2.11. Figure A2.7(a) shows data from Ref. A2.11 which was derived in the course of a Round-Robin exercise on fracture toughness testing. The original study showed that some areas of this material showed anomalously high fracture toughness due to the fact that they were taken from the plate edge. The subsequently censored data for temperatures of -65°C and -120°C are shown in comparison with the 5, 50 and 95% failure probability lines derived in accordance with the Master Curve. A good fit to the data is clearly evident. Examples of data determined on a range of steel plates as part of a project on the Eurocode 3 toughness requirements<sup>(A2.10)</sup> are shown in Figs. A2.7(b-d). The data shown were originally CTOD values and were corrected to  $K_{mat}$  (see Appendix 4) using  $m = 1$  and 2, as demonstrated by the error bars for each data point. These data include plates up to 75 mm thick and, while the majority of previous validations have been for thin material, demonstrate that the method still holds for thicker material.

There are only a limited number of data points for the measured fracture toughness values from Ref. A2.10 and these data were therefore pooled with data on Q&T and as-rolled A533B steel in thicknesses of 50 mm and 80 mm respectively<sup>(A2.12, A2.13)</sup>. The comparison of predicted and measured fracture toughness data for this pooled data set is shown in Fig. A2.8. 63% of the points lie above the line showing that the method tends to underestimate the fracture toughness from the  $T_{27J}$  transition temperature.

### **A2.3.2 Weld Metal Data from ECSC Sponsored Projects**

The inclusion of a weld metal data set in this validation is highly relevant since added confidence can be placed in the method if the approach also holds for weld metal. A multipass SAW weld on 50 mm thick S355J2 plate was the subject of an extensive round-robin exercise on weld metal fracture toughness testing<sup>(A2.14)</sup>. A comparison of data at -20°C and -60°C against the predicted relationship is shown in Fig. A2.9. The mean measured value of fracture toughness at -60°C lies exactly on the predicted mean line, while values at -20°C tend to lie above the mean line, again indicating conservative predictions.

### **A2.3.3 Data for Pressure Vessel and Thin High Strength Steels**

Extensive validation for these materials has been published previously<sup>(A2.1-A2.5)</sup> and the application of the method to these steels is well proven. A recent example for an ultrahigh strength steel is given in Fig. A2.10, while data for weld metal in a thin (5 mm) configuration are compared with the predictions in Fig. A2.11.

### **A2.3.4 Data for Parent Plate**

The accuracy of the predictions for parent plate in the yield strength range 235 to 690 MPa has been assessed by British Steel. The data points shown in Fig. A2.12 were determined from CTOD results on SENB specimens and were corrected to  $K_{mat}$  values using  $m = 1, 1.5$  and 2 (Appendix 4). The resultant values are represented by points connected by a vertical line. The predicted lines were determined using the mean relationship between  $TK_{100 MPa} \sqrt{m}$  and  $T_{27J}$ , as were all the predictions discussed in Sections A2.3.5 to A2.3.8.

### A2.3.5 Data for Linepipe

The accuracy of the Master Curve predictions for linepipe has been assessed for X65 linepipe in a range of thicknesses both before and after forming into pipe (termed plate and pipe respectively), Figure A2.13. Figure A2.13(a) shows reasonable agreement between actual and predicted toughness while Figs. A2.13(c) and (d) show generally unconservative predictions. An analysis of the data shown in Fig. A2.5 shows that the actual  $K_{mat} = 100 \text{ MPa} \sqrt{\text{m}}$  temperature for many of the pipe steels is greater than that predicted by the equation relating  $TK_{100 \text{ MPa} \sqrt{\text{m}}}$  to  $T_{27 \text{ J}}$ . This is discussed in Section A2.1.4.

### A2.3.6 Data for Weld Metals and HAZs

Data for two weld metals and their HAZs in weldments made on StE690 grade plate are shown in Fig. A2.14. Only one datapoint was available for each weld metal and it is therefore only possible to make general comment on these. The actual data for the undermatched weld metal was in the region of the 5% line but the data for the overmatched weld metal fell far outside the 5% line indicating potentially unconservative predictions. However, the microstructures sampled by the Charpy specimen and that present at the initiation site of the SENB specimen were not compared; differences between measured and predicted toughness could therefore be due to microstructural variation.

The data for the fusion line positions were determined on through-thickness notched SENB specimens and Charpy specimens extracted from areas of GHAZ. There was some scatter in the HAZ toughness of the undermatched weld but very little in the case of the overmatched weld HAZ. For the undermatched case, the mean of the three datapoints lies just below the 5% line. However, the mean fracture toughness for the overmatched case lies significantly below the 5% line and may be attributable to the mis-match induced constraint associated with an overmatched weldment. The Master Curve, nor any other correlation method, does not account for this effect.

### A2.3.7 Data for Sections

A range of sections (beams, columns and joists) in the as-rolled condition<sup>(A2.10)</sup> has also been assessed. Emphasis was placed on the influence of test position within each section and both Charpy impact energy and fracture toughness were determined at each position. The positions assessed were:

- $\frac{1}{6}$  flange width (standard test position, longitudinal orientation)
- Flange-web junction
- Web root

These positions are shown in Fig. A2.15 and the resulting comparisons in Fig. A2.16. The agreement between predicted and measured fracture toughness is generally good and conservative in most cases, except for the case of a Grade S275 joist in the web root position which showed lower shelf behaviour for the test temperatures assessed. In this case, Fig. A2.16(e), the increase in fracture toughness with temperature is overestimated by the Master Curve.

A similar analysis for jumbo sections with flange thicknesses up to 120 mm shows generally good agreement between actual and predicted toughness, demonstrating that the method is capable of handling thick as well as thin steel plates and sections. For thick specimens however, the relative position of the Charpy impact specimen becomes more important and must reflect the initiating microstructure found in the fracture toughness specimen.

### A2.3.8 Comparison of Actual and predicted $K_{mat}$ Values

A comparison of the measured and predicted fracture toughness values for the British Steel plates, sections, linepipe, HAZs and weld metals is shown in Fig. A2.17. The mean relationship between  $T_{27 \text{ J}}$  and  $T_{100 \text{ MPa} \sqrt{\text{m}}}$  was used for this comparison. The failure probability in this analysis was 50% and the assumed  $m$  value, used in the conversion between CTOD and  $K_{mat}$ , was 1.5. Theoretically, the points should be scattered with 50% above the 1:1 line and 50% below. The fact that the proportions lying above and below the line are 51% and 49% demonstrates good agreement between theory and practice.

## A2.4 OVERVIEW

The validity of the Master Curve Approach for pressure vessel-type steels and thin high strength steels is already well established. Further examples of its application have been demonstrated here with data sets from parent plates,

sections, linepipe, weld metals and HAZs. While some variation in the accuracy of the predictions is inevitably present, the generally satisfactory nature of the predictions for what can be considered as a wide range of materials is further evidence supporting the approach.

A number of situations have been identified which could potentially result in unconservative predictions; these include:

- Presence of splits on fracture surface of fracture toughness specimens due to crystallographic texture; this gives a lower fracture toughness than would be predicted from knowledge of T27J alone.
- Through-thickness variation of microstructure and properties and the subsequent difficulty in ensuring that the Charpy specimen samples the same microstructure as initiates the fracture in fracture toughness specimens.
- Mis-match induced constraint.
- Cold worked material (e.g. some pipe applications)

However, the instances where the predictions are unconservative appear to be few and the Master Curve method tends to give generally safe predictions of fracture toughness.

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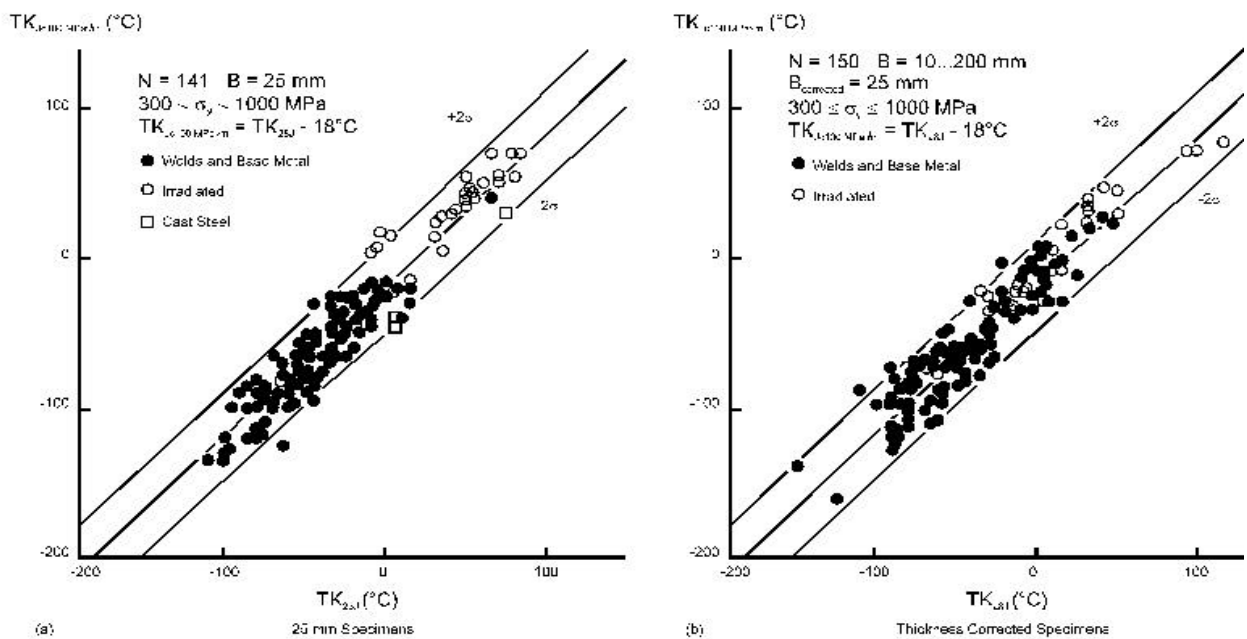


FIG. A21(a and b)

VALIDATION OF CORRELATION BETWEEN  
 $T_{28 J}$  AND  $TK_{100 MPa} \bar{\sigma}_m$  ACCORDING TO WALLIN

(D0643D10)

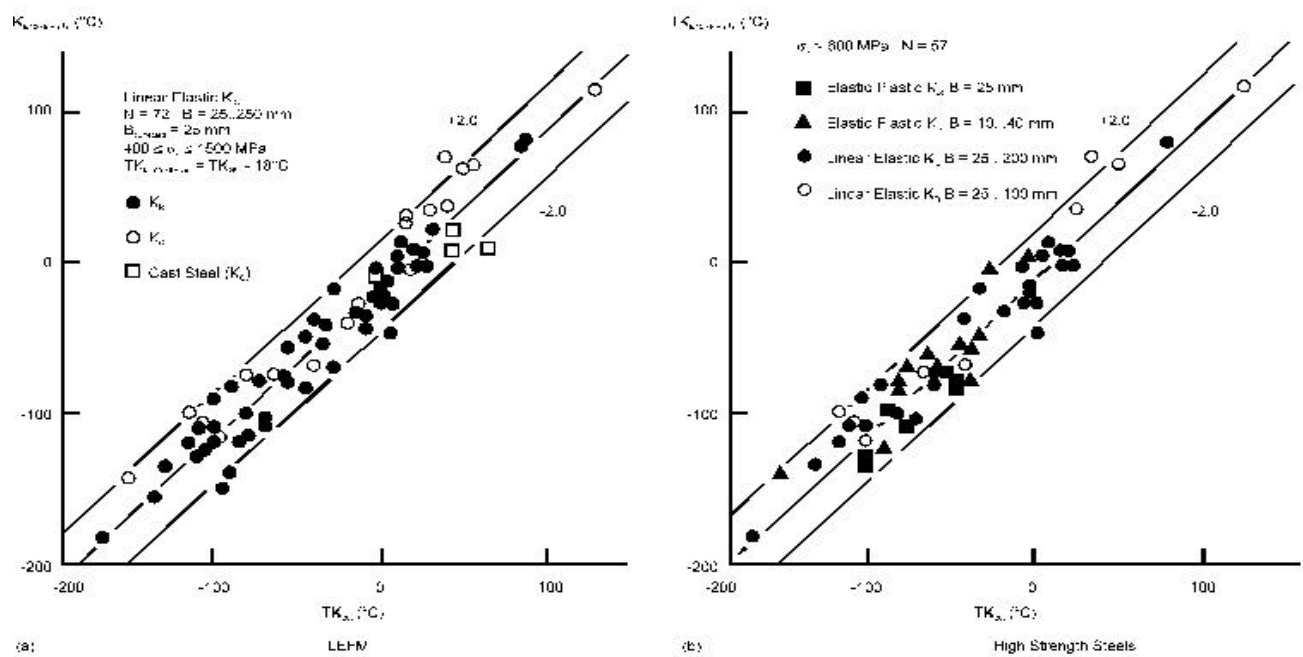


FIG. A22(a and b)

VALIDATION OF CORRELATION BETWEEN  
 $T_{28 J}$  AND  $TK_{100 MPa} \bar{\sigma}_m$  FOR LFRM AND HIGH  
STRENGTH STEELS ACCORDING TO WALLIN

(D0643D10)

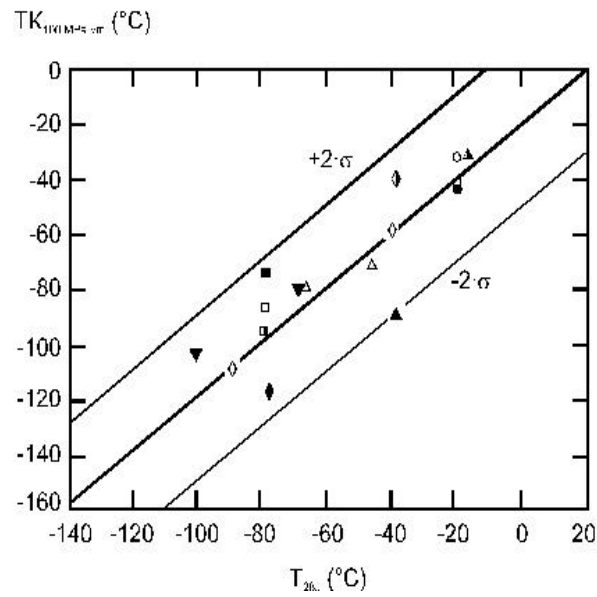


FIG. A23

COMPARISON OF  $TK_{100\text{ MPa } 0\text{ m}}$  WITH  $T_{28\text{ J}}$  FOR  
THIN HIGH STRENGTH STEELS (A25)

(D0643D10)

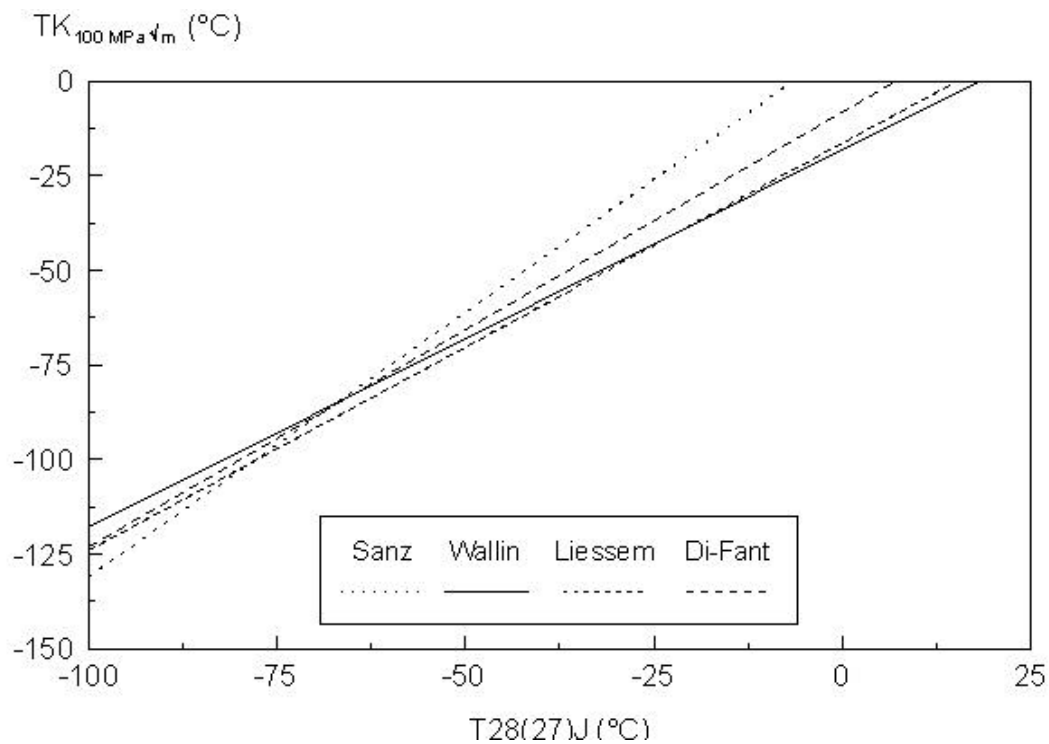


FIG. A24

COMPARISON OF CORRELATIONS  
ACCORDING TO DIFFERENT WORKERS

(D0643D10)

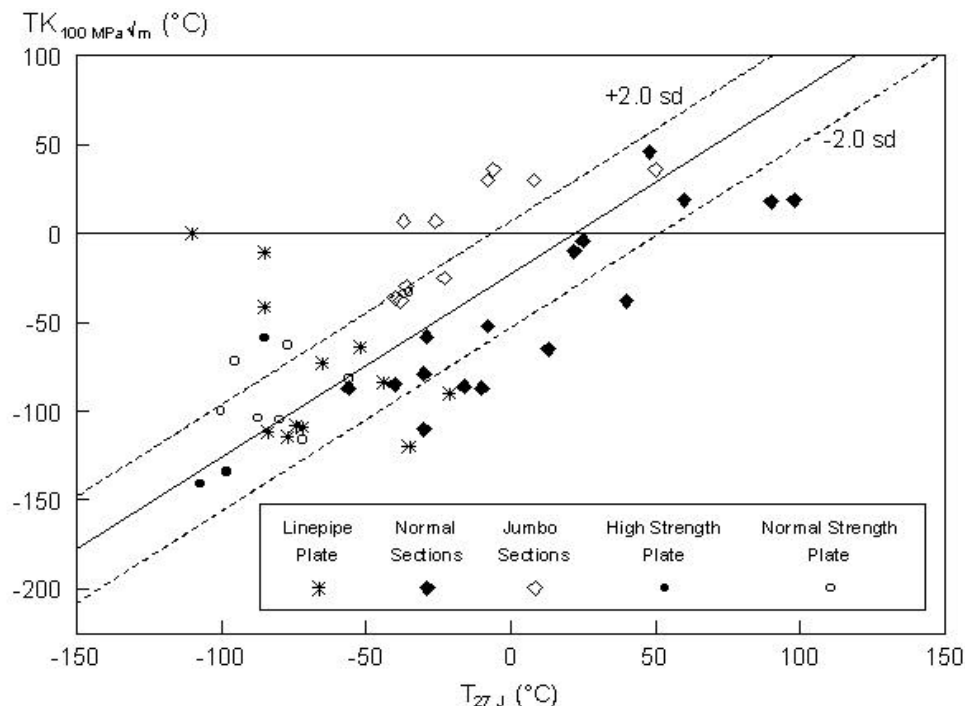
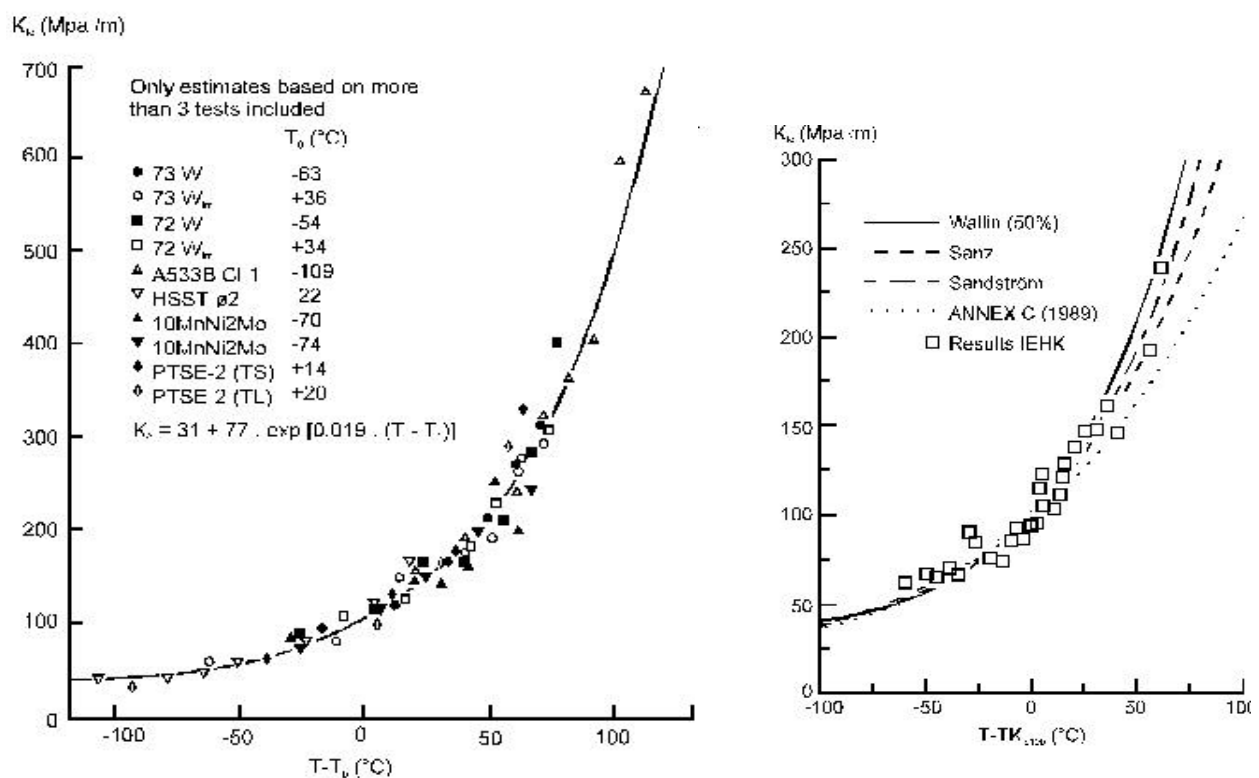


FIG. A25

COMPARISON OF CORRELATION WITH BRITISH STEEL  
DATA FOR PLATES AND SECTIONS

(D0643D10)



(a)

Wallin(A2.1)

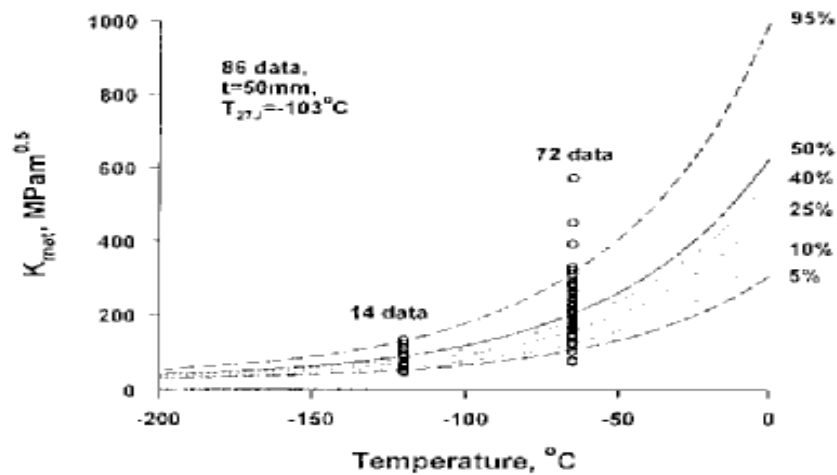
(b)

Comparison by Liessem(A2.8)

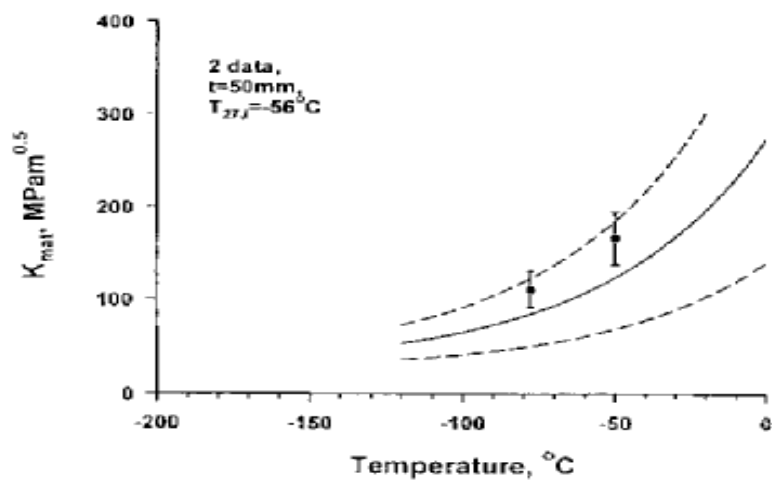
FIG. A26(a and b)

TEMPERATURE DEPENDENCE OF  $K_0$

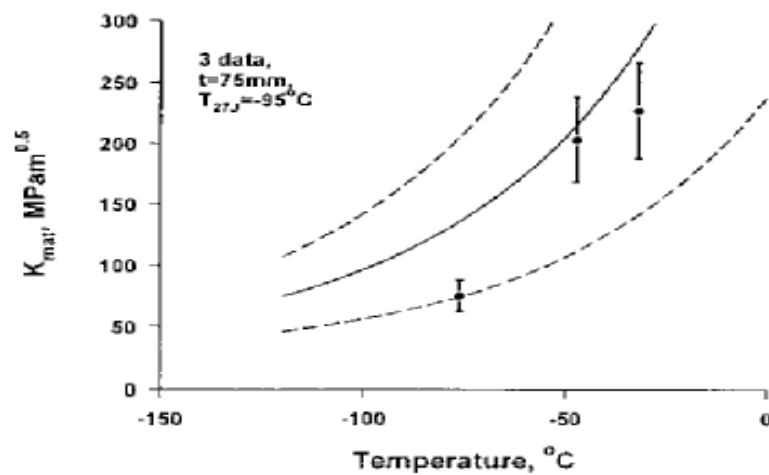
(D0643D10)



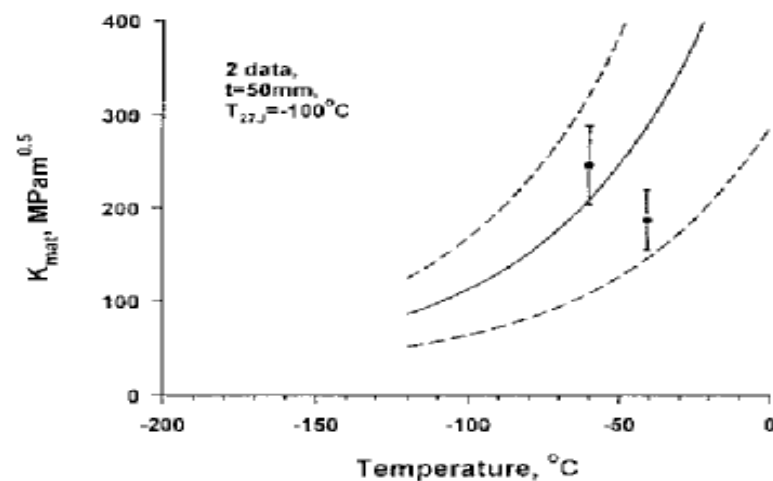
(a) ECSC Round Robin Data on S355J2



(b) 50 mm Thick S275JR



(c) 75 mm Thick S355J2



(d) 50 mm Thick 450EMZ

FIG. A27(a-d) VALIDATION FOR PARENT PLATES FROM ECSC (A2.9, A2.10) DATA SETS

(D0643D11)

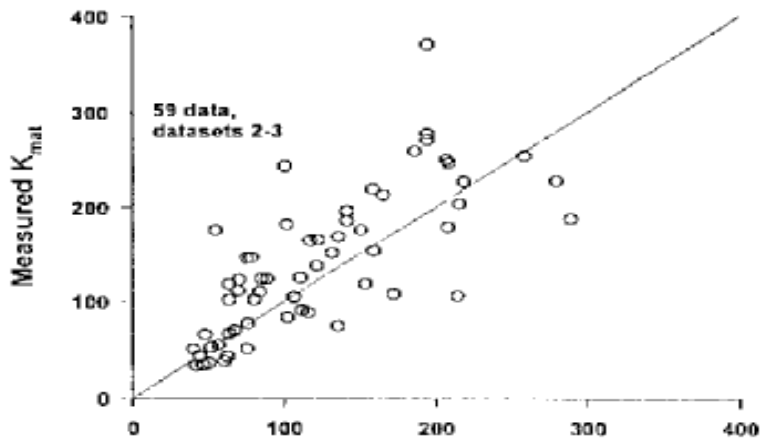


FIG. A2.8 COMPARISON OF MEASURED AND PREDICTED  $K_{mat}$  VALUES FOR POOLED DATASET OF EN10025 TYPE STEELS AND A533B STEEL (A2.11)

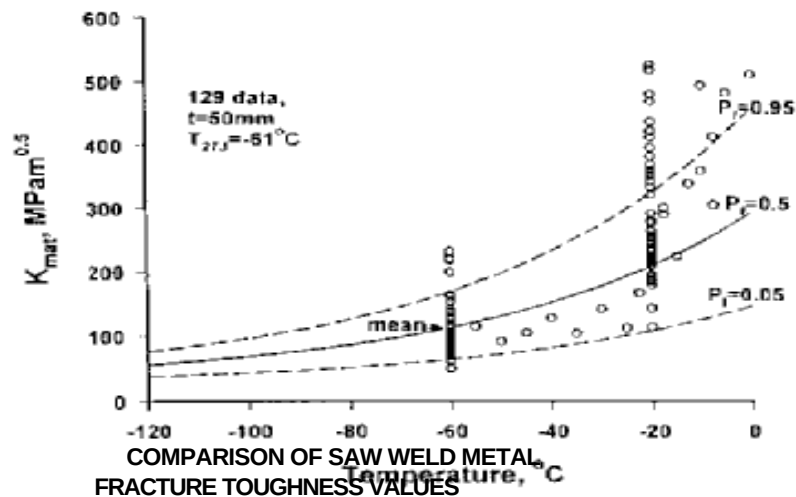


FIG. A2.9 COMPARISON OF SAW WELD METAL FRACTURE TOUGHNESS VALUES WITH PREDICTIONS (A2.14)

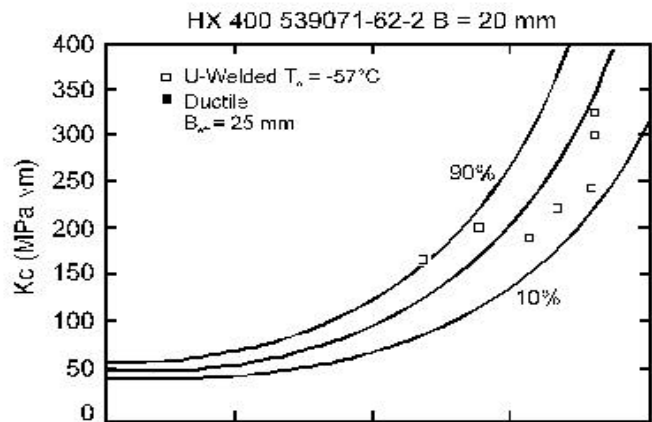


FIG. A2.10 COMPARISON OF MEASURED AND PREDICTED FRACTURE TOUGHNESS FOR 20 mm THICK 1200 MPa YIELD STRENGTH PROFILES (D0643D11)

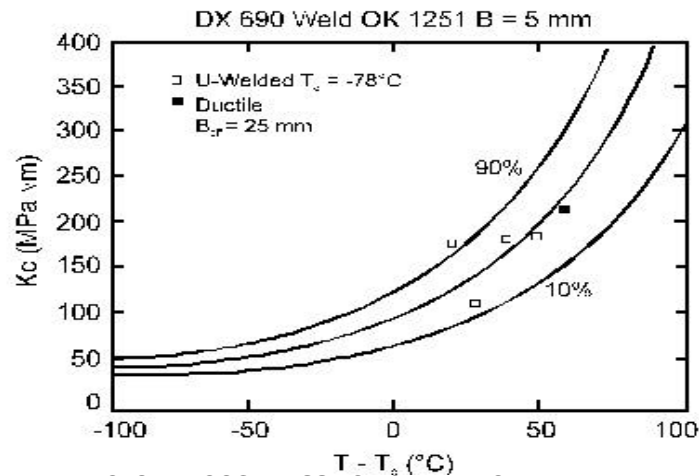
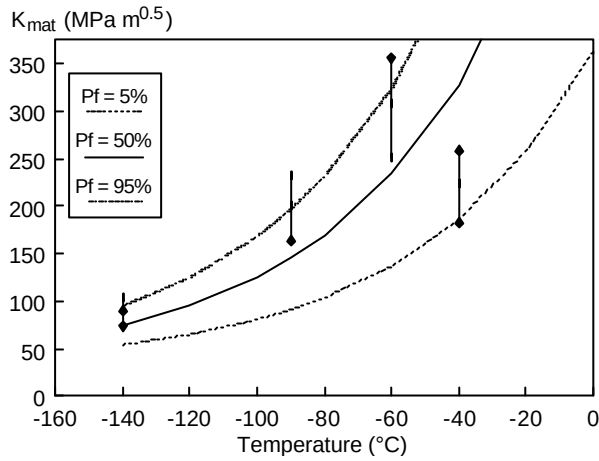
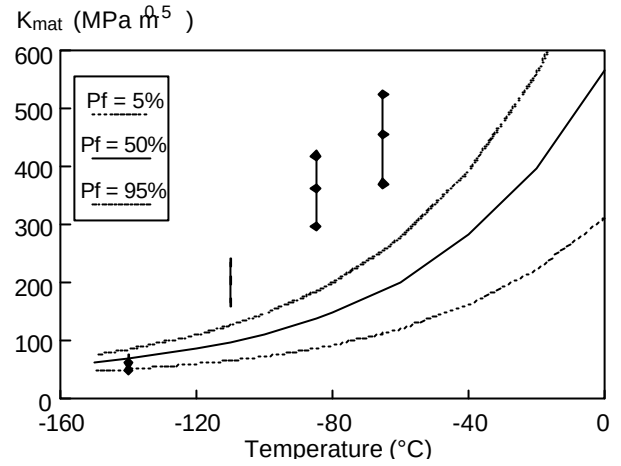


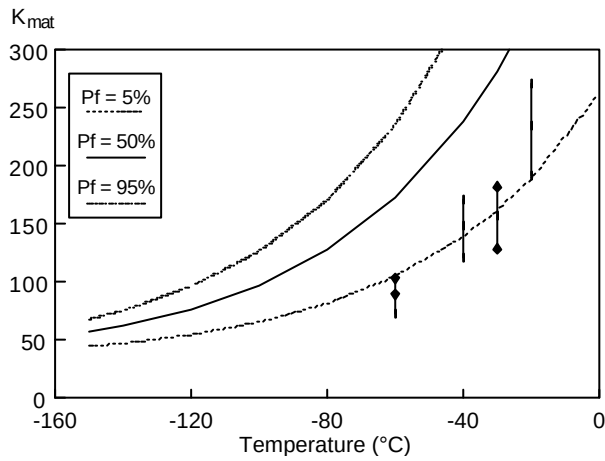
FIG. A2.11 600 MPa YIELD STRENGTH WELD METAL



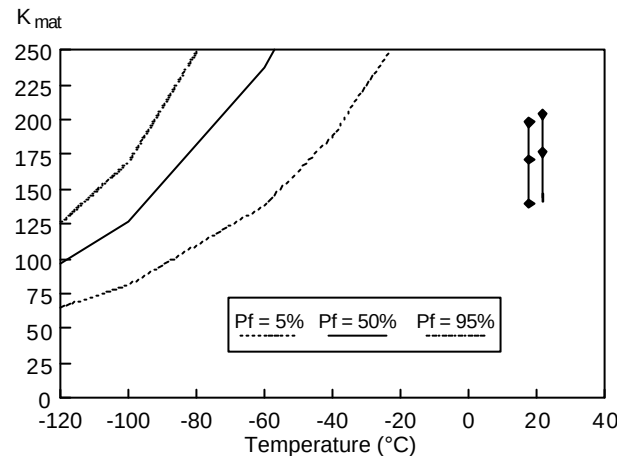
(a) 355EMZ Offshore Steel (TMCR)



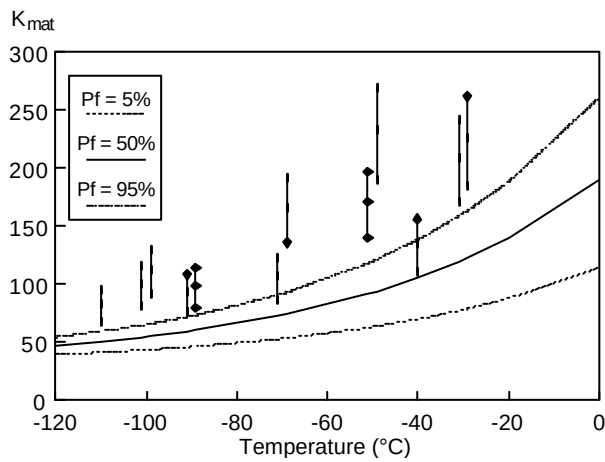
(b) 450EMZ Offshore Steel (Q&T)



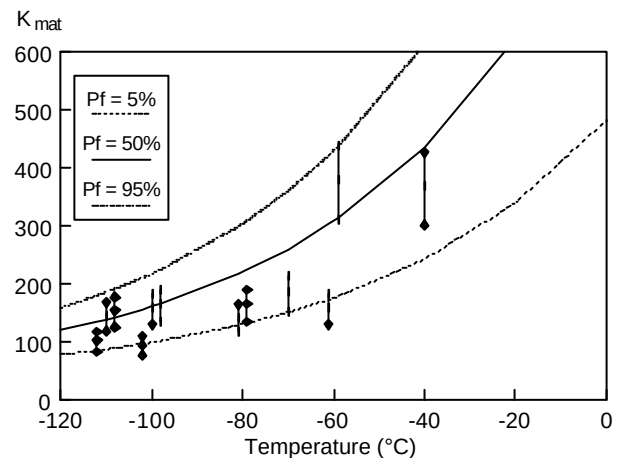
(c) StE690 High Strength Steel - 40 mm (Q&T)



(d) StE690 High Strength Steel - 55 mm (Q&T)



(e) Grade B Ship Plate (As-rolled)

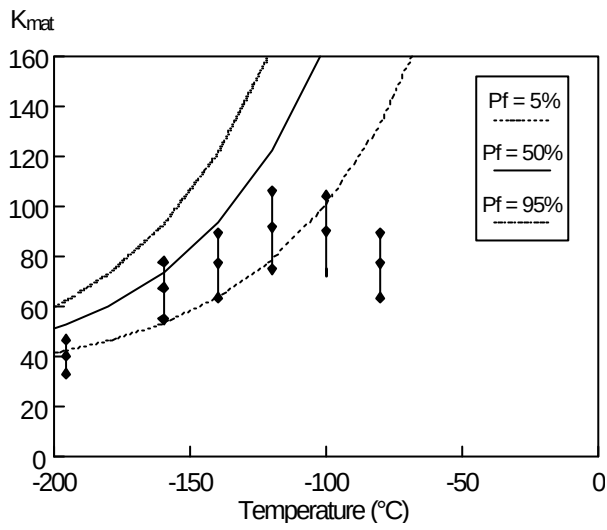


(f) Grade 440F Ship Plate (AC)

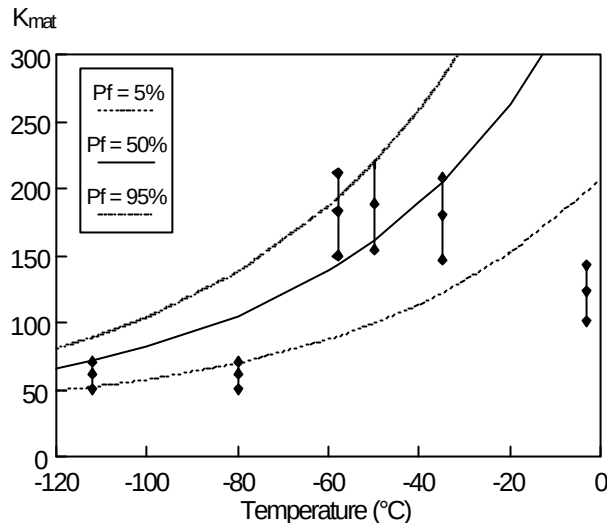
FIG. A2.12(a-f)

COMPARISON OF PREDICTIONS WITH  
TEST DATA FOR PLATE STEELS

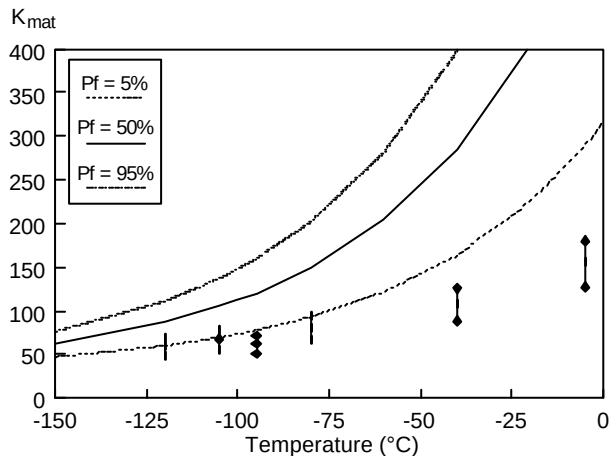
(D0643D10)



(a) X65 Linepipe (Pipe),

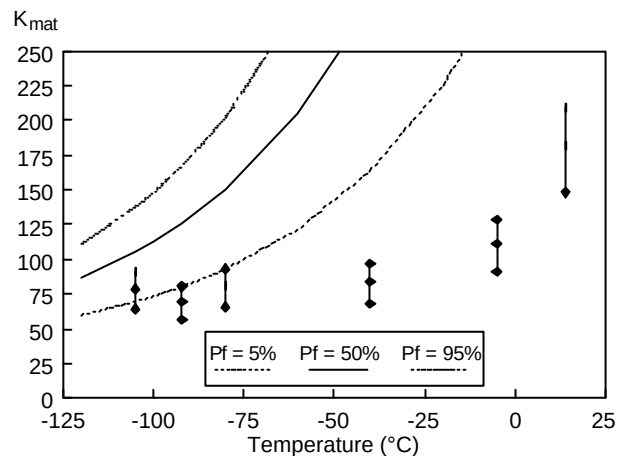


(b) X65 Linepipe (Pipe),



36 inch dia. x 15.9 mm

(c) X65 Linepipe (Pipe),  
42 inch dia. x 17.5 mm



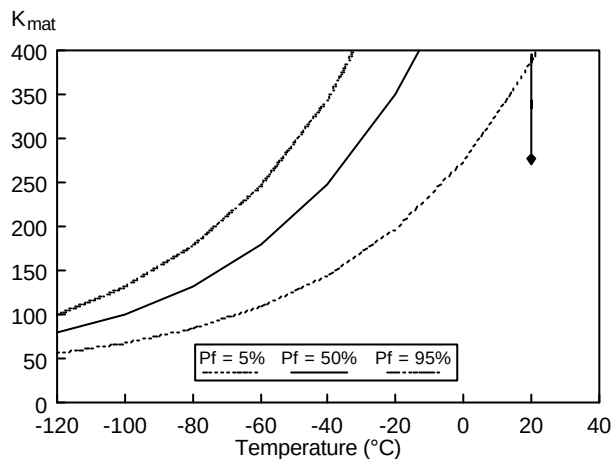
36 inch dia. x 25.4 mm

(d) X65 Linepipe (Plate),  
42 inch dia. x 17.5 mm

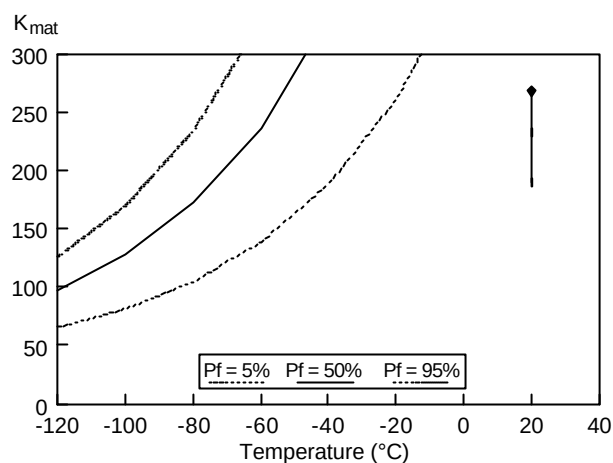
FIG. A2.13(a-d)

COMPARISON OF PREDICTIONS  
WITH DATA FOR LINEPIPE

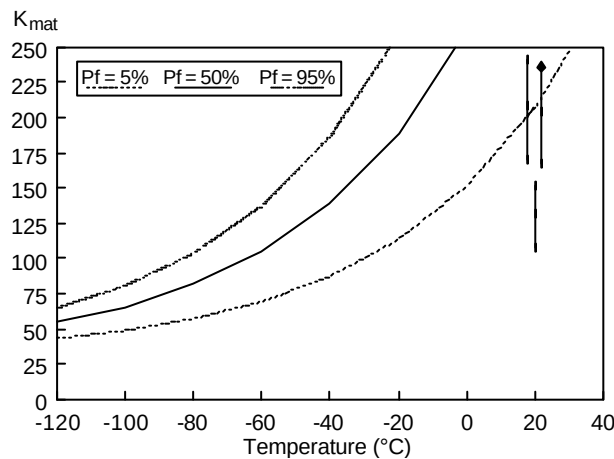
(D0643D10)



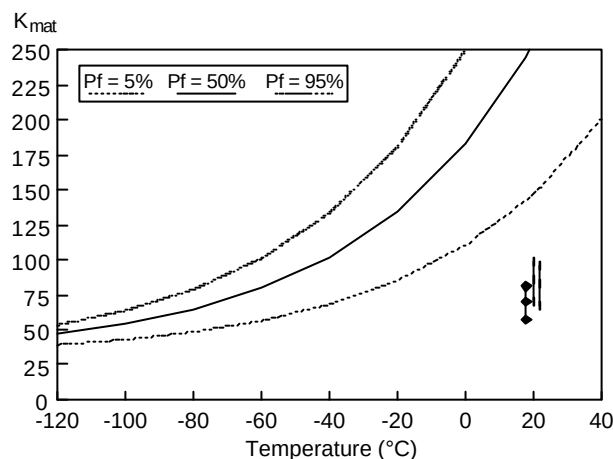
(a) Undermatched Weld metal in StE690 Plate  
(SD3-1Ni-1/4Mo)



(b) Overmatched Weld Metal in StE690 Plate  
(Fluxocord 42)



(c) Fusion Line in Undermatched Weld in StE690 Plate



(d) Fusion Line in Overmatched Weld in StE690 Plate

FIG. A2.14(a-d)

**COMPARISON OF PREDICTIONS WITH  
DATA FOR WELD METAL AND HAZ**

(D0643D10)

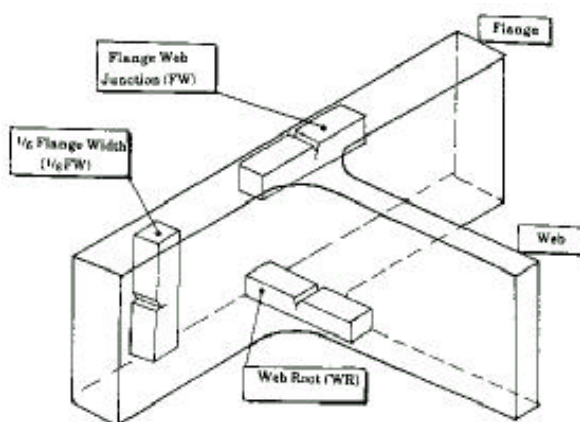


FIG. A2.15

**TEST POSITION NOMENCLATURE FOR SECTIONS**

(D0643D10)

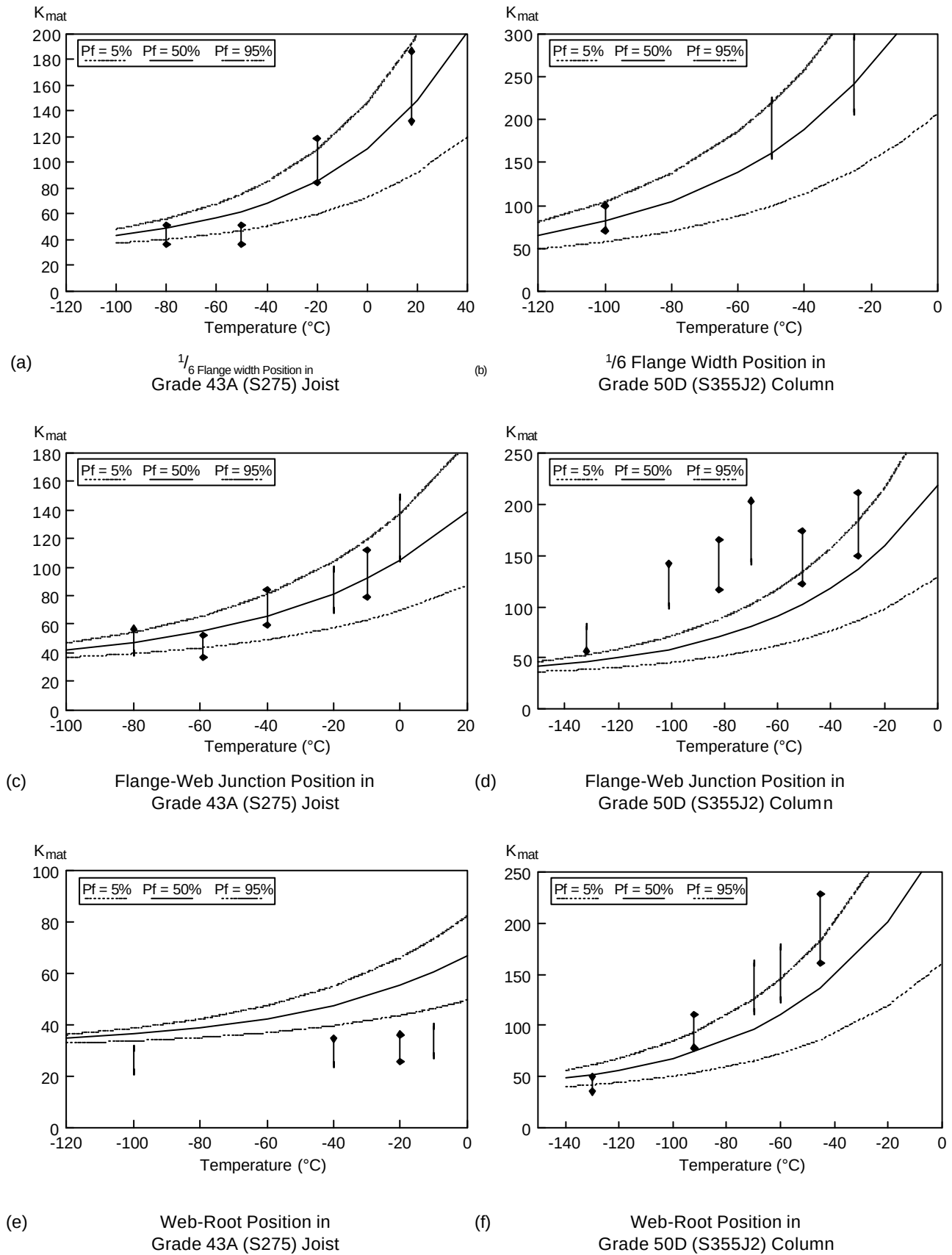


FIG. A2.16(a-f)

COMPARISON OF PREDICTIONS WITH  
DATA FOR SECTIONS

(D0643D10)

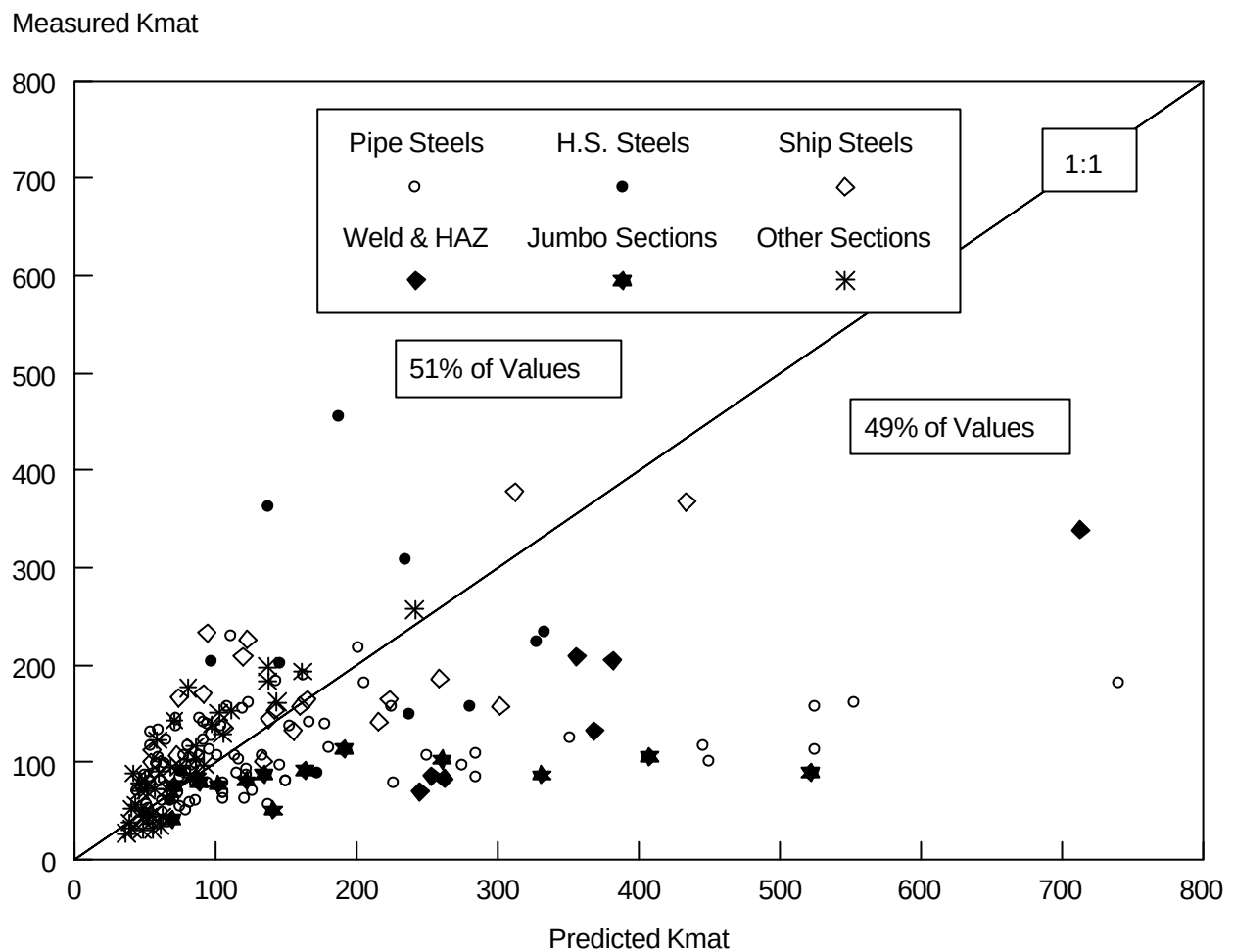


FIG. A2.17

COMPARISON OF MEASURED AND PREDICTED  $K_{mat}$  VALUES  
FOR BRITISH STEEL DATA USING MEAN RELATIONSHIP BETWEEN  
 $TK_{100 MPa} \bar{\sigma}_m$  AND  $T_{273}$ , AND WITH 50% FAILURE PROBABILITY

(D0643D10)

### APPENDIX 3

#### PREDICTION OF CHARPY IMPACT ENERGIES FROM EXTRAPOLATION AT OTHER TEMPERATURES

##### A3.1 GENERAL PROBLEM

The Master Curve Approach requires knowledge of the 28(27)J transition temperature. Where a steel has only been tested at one temperature, this will often not equate to  $T_{27J}$ . In such cases a method of extrapolation is necessary to determine  $T_{27J}$  for subsequent analysis. Problems with such extrapolation include:

- (i) Allowance for the vast number of shapes of Charpy transition curves.
- (ii) The gradual change in recent years in the relationship between absorbed energy and % ductile fracture, where for some modern steels relatively high energies can be associated with low % ductile fracture in both parent plate<sup>(A3.1)</sup> and HAZ<sup>(A3.2)</sup>.

##### A3.2 AVAILABLE APPROACHES

There are two generally recognised methods for extrapolation of Charpy impact energy:

- (i) Approach described in British Standards<sup>(A3.3, A3.4)</sup>
- (ii) Approach derived by VTT<sup>(A3.5)</sup>

The approach used in BS 5950 and BS 5400 uses a tabular format which describes assumed Charpy impact energies at temperatures above and below  $T_{27J}$ . A similar approach is used in the British Standard for pressure vessels (BS 5500). The extrapolation is allowed for downward temperature shifts of 30°C (5 J) and upward shifts of 40°C. The approach is referred to in subsequent analysis as the BSI Approach.

The second approach<sup>(A3.5)</sup> relates the assumed Charpy energy at temperatures referred to  $T_{35} \text{ J/cm}^2$  ( $= T_{27J}$  for a 10 mm square Charpy specimen) to the yield strength and upper shelf energy in accordance with

$$T - T_{35 \text{ J/cm}^2} = 21.6 \left[ \frac{\sigma_y}{467} \right]^{0.56} \ln \left[ \frac{CV(CV_{us} - 35)}{35(CV_{us} - CV)} \right] \quad \dots (A3.1)$$

where  $\sigma_y$  is the yield strength and  $CV_{us}$  the upper shelf Charpy impact energy in  $\text{J/cm}^2$ . Curves generated<sup>(A3.5)</sup> for various yield strengths and upper shelf energies are shown in Fig. A3.1. This approach is referred to subsequently as the VTT Approach.

##### A3.3 COMPARISON OF METHODS

The ability of the two methods to predict the 27 J temperature from temperatures above and below was assessed using eight Charpy transition curves with different characteristics. The steels assessed are summarised in Table A3.1. The Charpy transition curves are shown in Figs. A3.2 and A3.3 for the structural and linepipe steels, respectively.

For each steel the  $T_{27J}$  temperature was predicted from the temperatures corresponding to Charpy impact energy levels of between 20 and 100 J, at 20 J intervals. The resultant predicted 27 J temperatures are shown in comparison with the actual  $T_{27J}$  value for the eight steels in Fig. A3.4 (structural steels) and Fig. A3.5 (linepipe steels).

For steels with relatively steep transition curves (355EMZ, 450EMZ, X65 (19.1 mm)) the resultant  $T_{27J}$  calculated from energies greater than 27 J leads to non-conservative estimates of  $T_{27J}$  when using both methods of prediction. There is little difference between the estimated values based on the two methods. The error in  $T_{27J}$  when extrapolated from the 60 J temperature is ~10-20°C, that associated with extrapolation from the 100 J temperature is ~20-35°C. The error in both cases is on the non-conservative side, i.e. the predicted  $T_{27J}$  is too low.

For the other steels, the BSI approach generally gives better estimates of  $T_{27J}$ ; errors in general are on the conservative side. The accuracy of the predictions obviously depends on how closely the BSI assumed Charpy transition curve reflects the actual Charpy behaviour; for the X60 (17.5 mm) plate the predictions are particularly good.

The VTT method, which requires knowledge of the upper shelf energy, tends to give predicted transition curves which are not steep enough. Consequently the 27 J temperature predicted from higher energies is often too low and therefore non-conservative. There are some cases where the VTT approach gives better predictions but in these instances the BSI approach is still conservative. In addition, the VTT approach requires a definition of the upper shelf energy, a value that is unlikely to be known in many instances. It is suggested therefore that the BSI approach is more suitable, provided that extrapolation range is limited (30°C below  $T_{27J}$  to 40°C above) and that the transition between lower and upper shelf is not overly steep, a phenomenon promoted by low carbon and sulphur levels.

#### A3.4 PREDICTION FROM COMPOSITION

Prediction from composition on a simplistic basis based on carbon and sulphur levels represented by the parameter used by Graville<sup>(A3.6)</sup> ( $\%C + 10(\%S)$ ) was found to give too large a scatterband due to the influence of other factors not taken into account (orientation, grain structure, other alloying elements etc.) as shown in Fig. A3.6.

#### REFERENCES

- A3.1 J.P. Laures et al: 'Changes in Charpy Impact Properties of Pressure Vessel Steels Over the Past 25 Years', The Welding Institute, Report No. 5583/3/1989.
- A3.2 P. Nevasmaa, O. Kortelainen and K. Wallin: 'The Role of LBZ in Evaluating HAZ Toughness Test Data in Low-Impurity TMCP Steels', Second European Conference on Joining Technology, Eurojoin 2, Florence, 16-18 May 1994, Institute Italiano della Saldatura.
- A3.3 British Standard BS 5950:Part 1:1990, 'Structural Use of Steelwork in Buildings; Code of Practice for Design in Simple and Continuous Construction', British Standards Institution, 1990.
- A3.4 F.M. Burdekin: 'Material Aspects of BS 5400:Part 6', Paper 4, 'The Design of Steel Bridges', Granada Publications, Ed. Rockey & Evans (1981).
- A3.5 K. Wallin: 'Methodology for Selecting Charpy Toughness Criteria for Thin High Strength Steels: Part 1: Determining the Fracture Toughness', Jernkontorets Forskning, Report No. 4013/89, 28th December 1994.
- A3.6 B.A. Graville: 'Correlations Between Charpy Properties and the Nil Ductility Transition Temperature', Project 1-1, CSA Verification Program for the Offshore Structures Code, Graville Associates Inc., 1988.

**TABLE A31  
STEELS ASSESSED**

| Grade  | Thickness<br>(mm) | Condition | YS<br>(MPa) | T27J<br>(°C) |
|--------|-------------------|-----------|-------------|--------------|
| 355EMZ | 50                | TMCR      | 366         | -106         |
| 450EMZ | 50                | Q&T       | 490         | -98          |
| StE690 | 40                | Q&T       | 735         | -83          |
| StE690 | 55                | Q&T       | 803         | -104         |
| X60    | 17.5              | TMCR      | 452         | -74          |
| X65    | 17.5              | TMCR      | 489         | -85          |
| X65    | 19.1              | TMCR      | 483         | -84          |
| X65    | 25.4              | TMCR      | 505         | -65          |

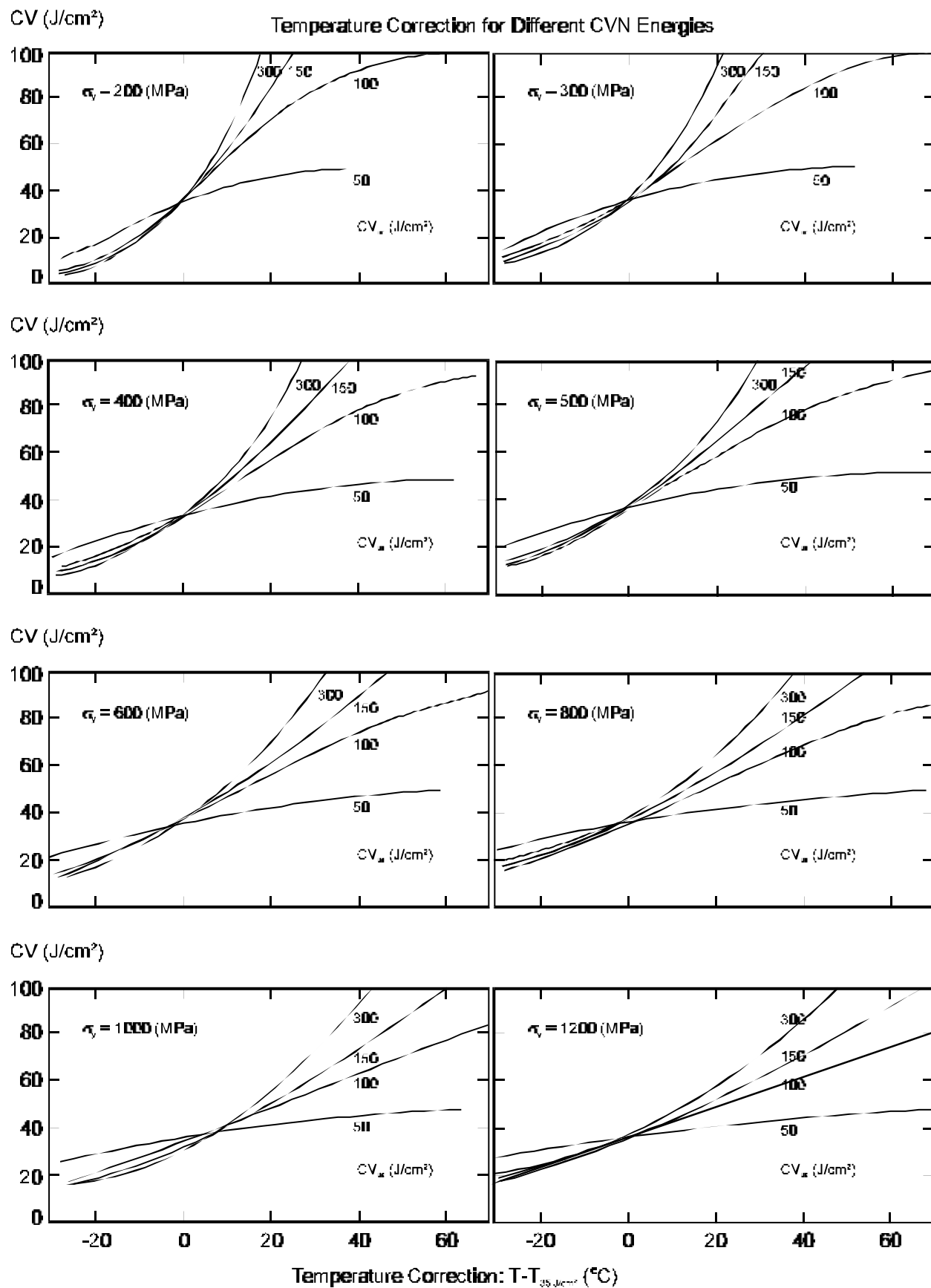


FIG. A31

CHARPY TRANSITION CURVES AS A FUNCTION OF

(D0643D14)

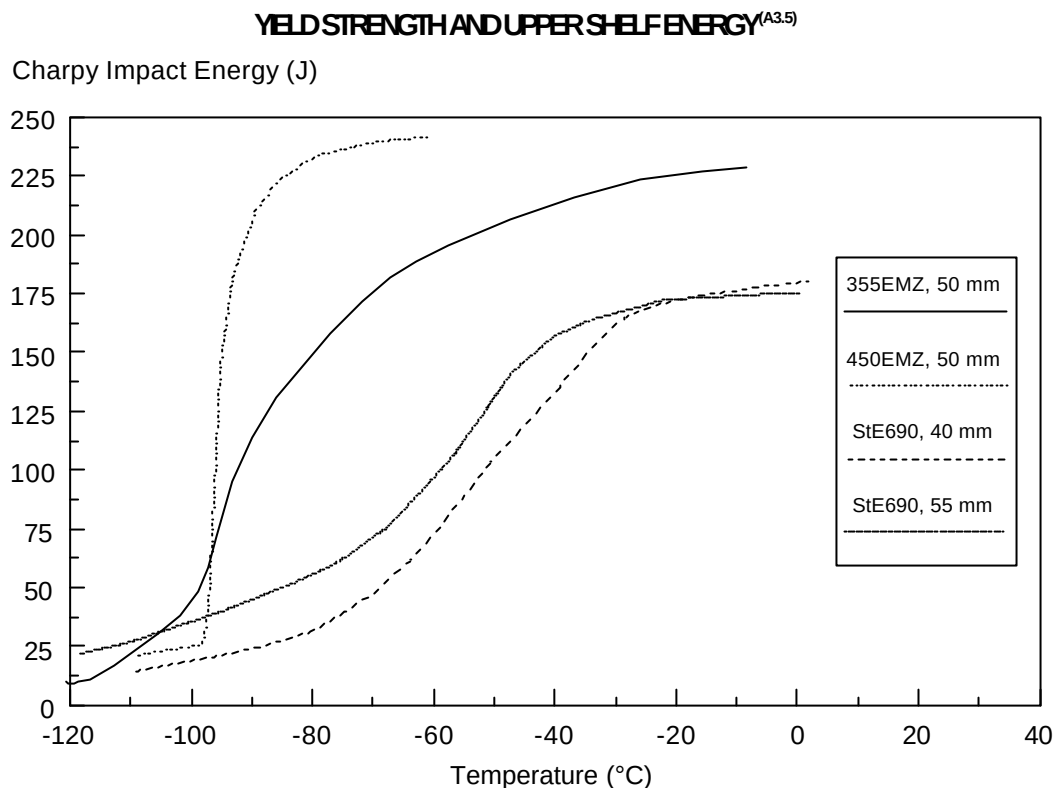


FIG. A32

**CHARPY TRANSITION CURVES FOR  
STRUCTURAL STEELS ASSESSED**

(D0643D14)

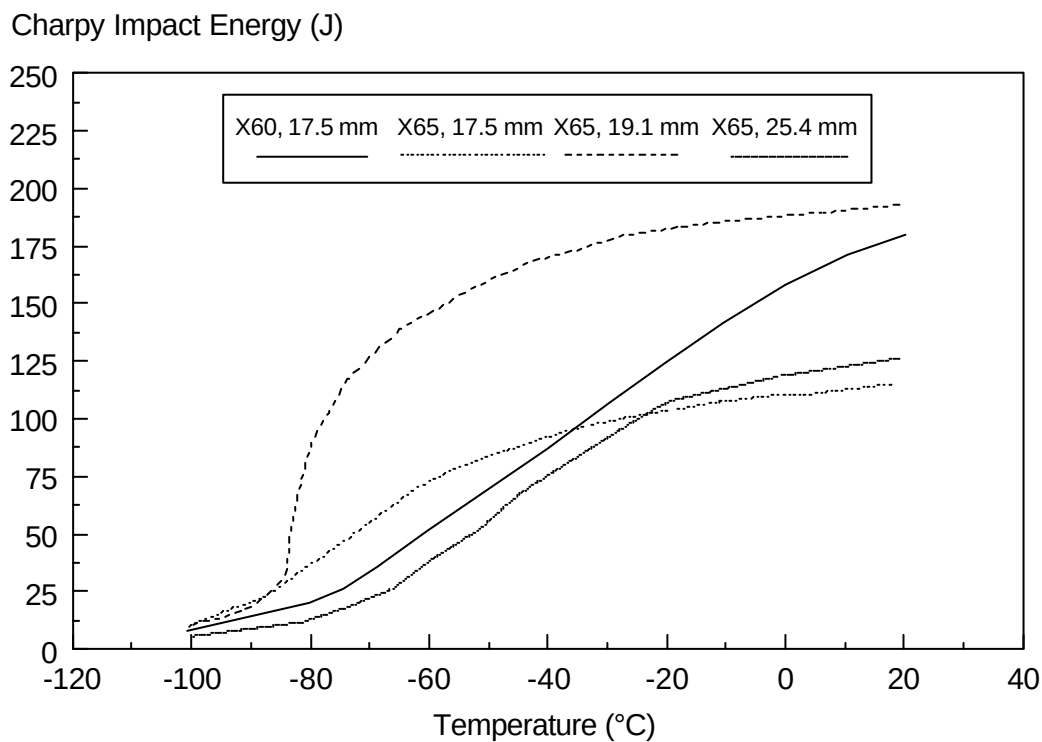
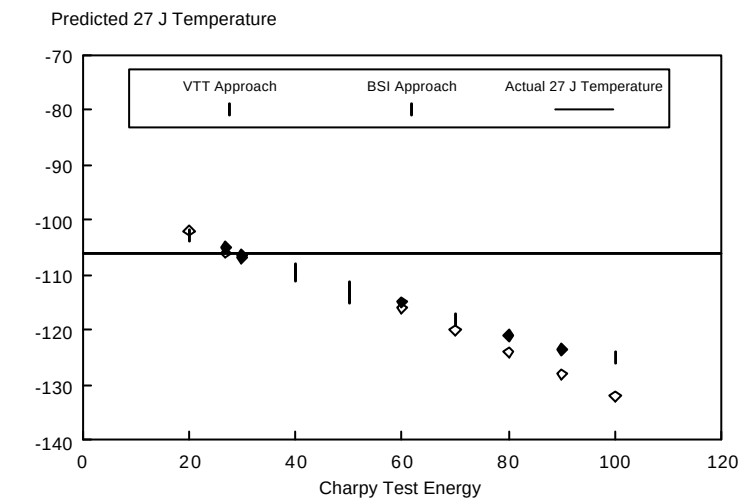


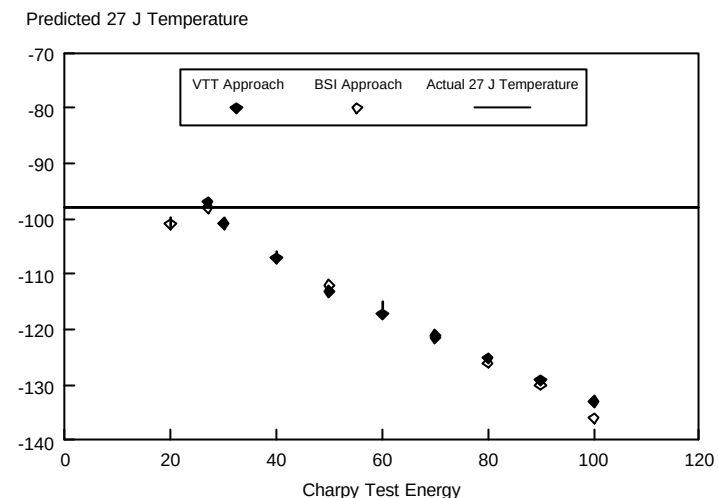
FIG. A33

**CHARPY TRANSITION CURVES FOR  
LINEPIPE STEELS ASSESSED**

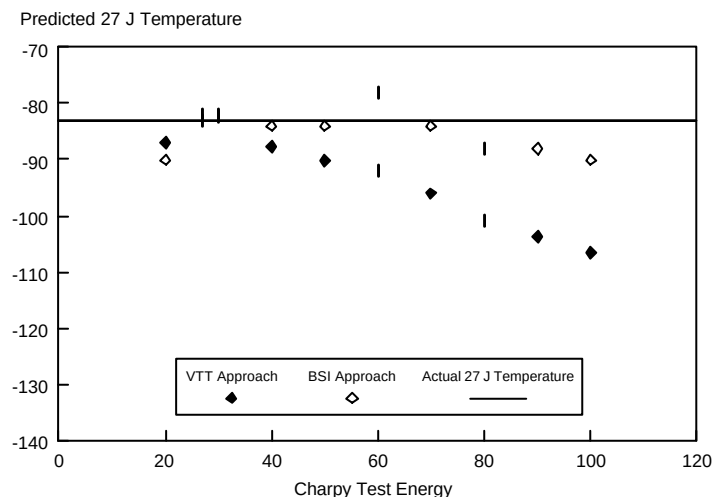
(D0643D14)



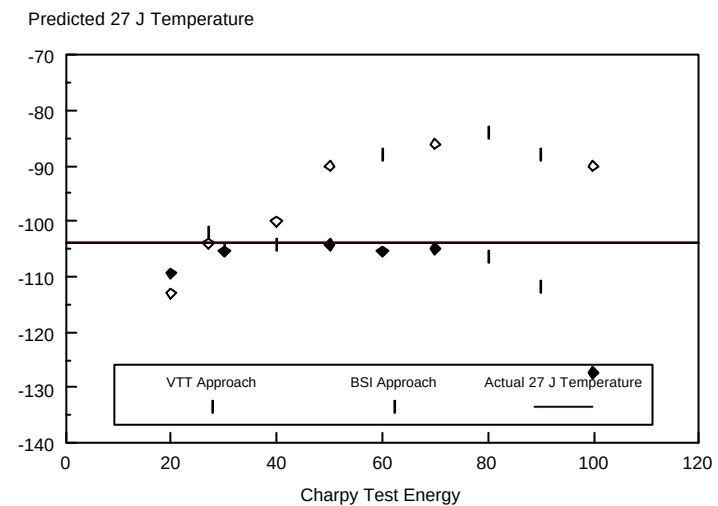
(a) 355EMZ, 50 mm



(b) 450EMZ, 50 mm



(c) StE690, 40 mm



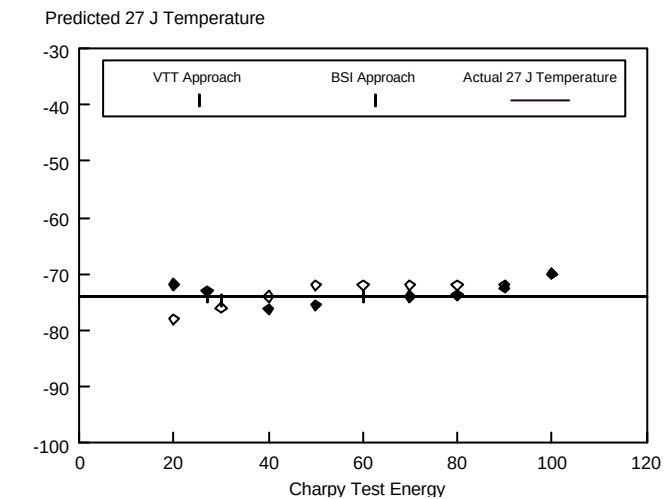
(d) StE690, 55 mm

FIG. A34(a-d)

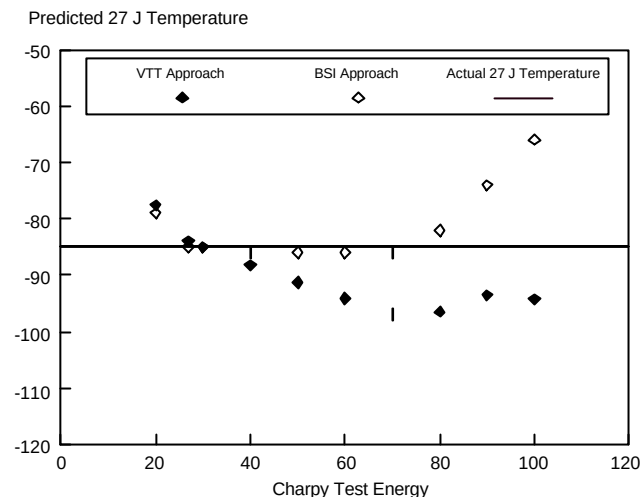
COMPARISON OF ACTUAL AND PREDICTED 27 J TEMPERATURES FOR  
FOUR STRUCTURAL STEELS

(D0643D15)

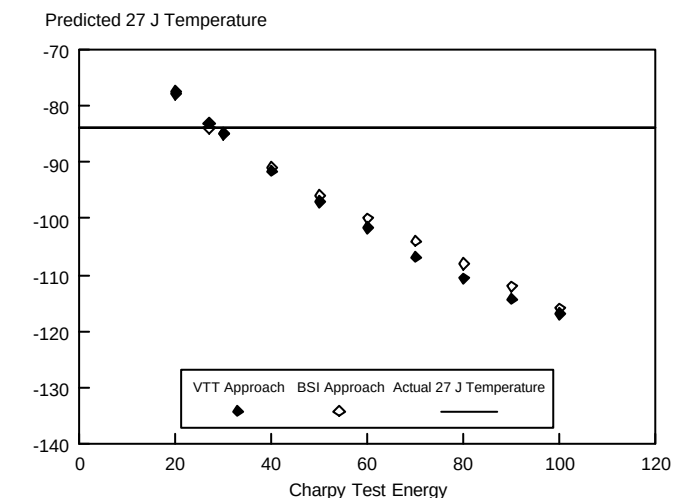
A3/F3



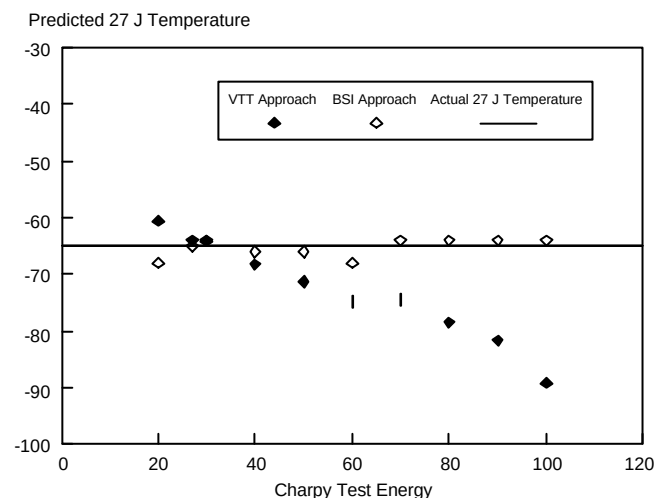
(a) X60, 17.5 mm



(b) X65, 17.5 mm



(c) X65, 19.1 mm



(d) X65, 25.4 mm

FIG. A3.5(a-d)

COMPARISON OF ACTUAL AND PREDICTED 27 J TEMPERATURES FOR  
FOUR LINEPIPE STEELS

(D0643D15)

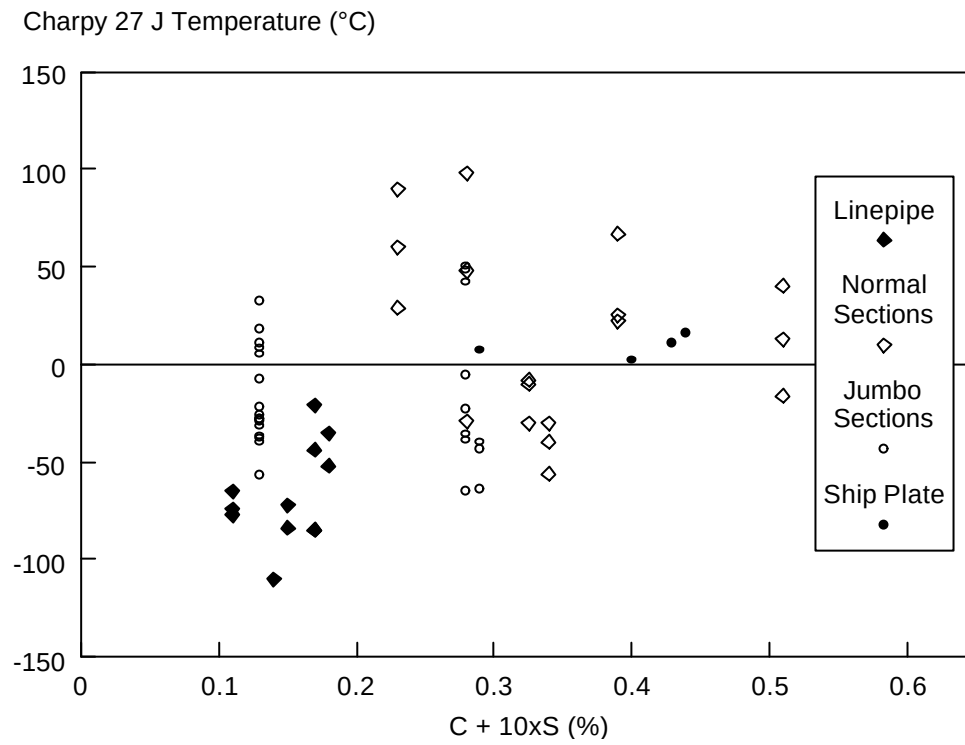


FIG. A3.6

CHARPY 27 J TEMPERATURE AS A FUNCTION OF (C+10 S)%

(D0643D14)

## APPENDIX 4

### CONVERSION OF FRACTURE TOUGHNESS PARAMETERS

The relationship between  $K_{mat}$  and CTOD can be expressed as a simple expression:-

$$K_{mat} = \left| \frac{\sigma \cdot m \cdot CTOD}{1 - \nu^2} \right|^{0.5}$$

where  $\sigma$  is the yield or flow stress and  $m$  a coefficient depending on whether yield or UTS is used. Various studies have been carried out to determine the value of  $m$  which depends generally on the work hardening of the material and the region of the fracture toughness transition curve in which the test is being carried out.

Figure A4.1 shows typical data for parent material<sup>(A4.1, A4.3)</sup>, Fig. A4.2 for welds, Fig. A4.3 for HAZs and Fig. A4.4 for duplex and super-duplex stainless steel plate and weldments.

The resultant derived  $m$  values for a range of steels are as follows.

| Ref. | Steel Types           | Weld or Parent   | Yield Strengths (MPa) | $m_y$     | $m_t$          |
|------|-----------------------|------------------|-----------------------|-----------|----------------|
| A4.1 | S355J2                | Parent           | 350                   | 1.77      | 1.39           |
| A4.2 | S355J2                | Weld             | 350                   | 1.50-1.58 | Not determined |
| A4.3 | TMCR, Q&T Structural  | Parent           | 350-800               | 1.59      | 1.34           |
| A4.4 | Duplex & Super-duplex | Parent & Weld    | 490-780               | 2.26      | 1.84           |
| A4.5 | StE36                 | Weld Metal & HAZ | 370                   | 1.46-1.74 | Not determined |

For a perfectly plastic material, the value of  $m$  for using in conjunction with the yield stress has been calculated as 1.48<sup>(A4.6)</sup>, while others<sup>(A4.7, A4.8)</sup> have suggested that the value of  $m$  depends on the strain hardening coefficient (yield/tensile ratio) and the  $a/W$  ratio<sup>(A4.8)</sup>, although this latter fact is disputed by others<sup>(A4.5)</sup>.

The expression suggested in Ref. A4.8 is given by:-

$$m_{ys} = 0.8016 (a/W) + 1.3165 \left( \frac{UTS}{\sigma_s} \right) - 0.07573$$

However, the application of this formula to a wide range of fracture toughness data was found to generally overestimate the value of  $m$ <sup>(A4.3)</sup>.

CTOD values can also be determined using the so-called  $\delta_5$  approach. CTOD values measured using this approach and the conventional approach can be considered to be approximately equal, Fig. A4.5, providing that the rotation factor is adjusted to approximately 0.25-0.40, for  $a/W$  values between 0.16 and 0.5<sup>(A4.9)</sup>.

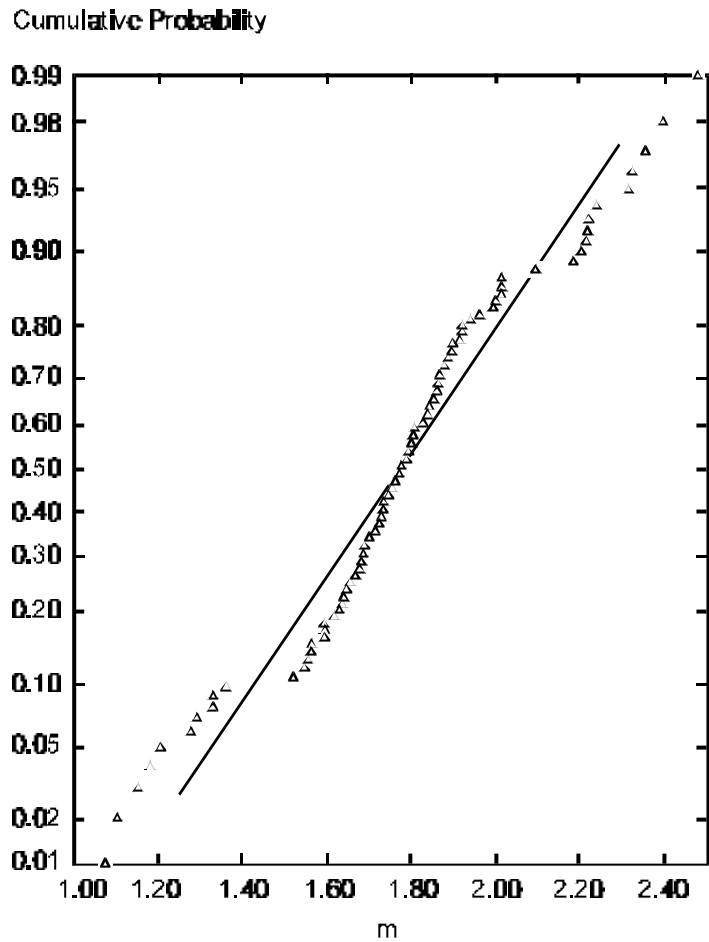
Based on this analysis the recommended values of  $m$  based on yield strength and UTS, respectively, are

$$\left. \begin{array}{l} m_y = 1.5 \\ m_y = 1.3 \end{array} \right\} \text{For structural steels, weld metals and HAZs}$$

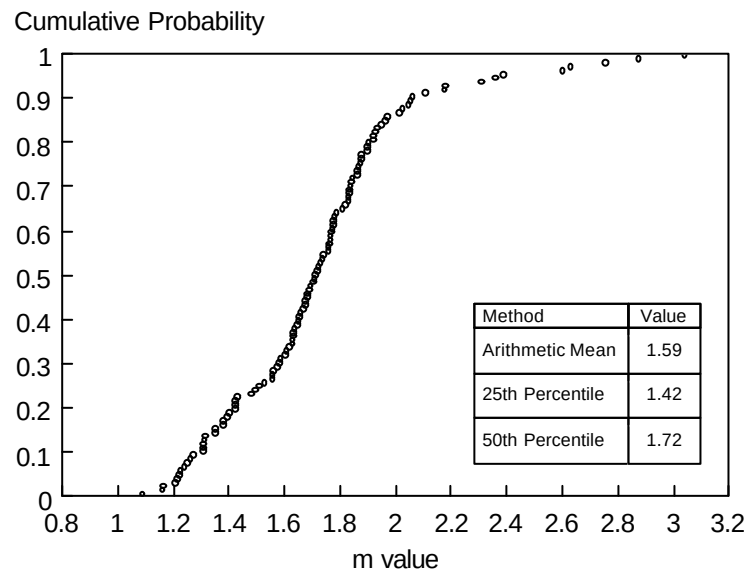
These values will be generally conservative when used to estimate  $K_{mat}$  from  $CTOD_{mat}$  data.

## REFERENCES

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- A4.4 C.S. Wiesner, Private Communication, June 1997.
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(a) Cumulative Normal Plot for m Values of S355JR Plate<sup>(A4.1)</sup>



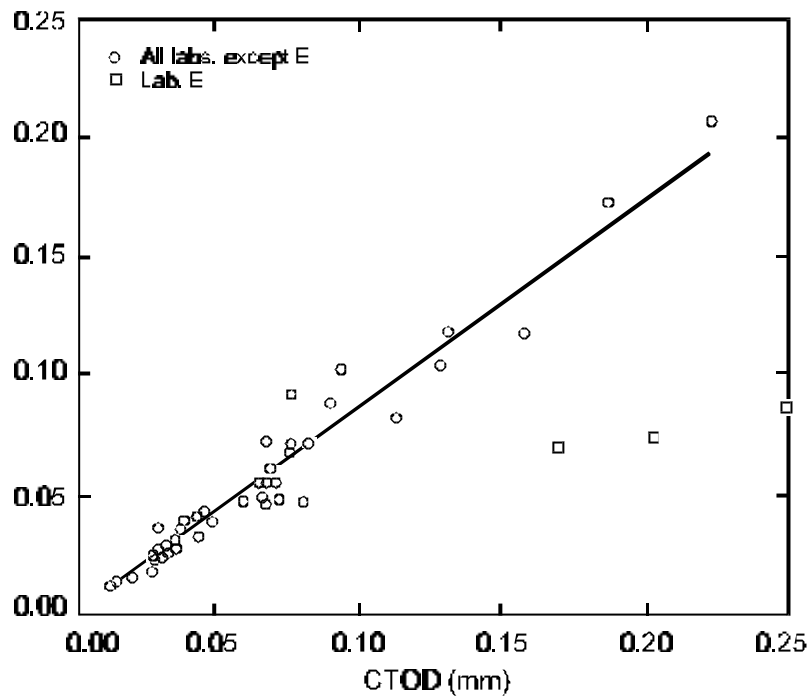
(b) Cumulative Normal Plot for m Values of Various Structural Steels<sup>(A4.3)</sup>

A4.1(a and b)

CUMULATIVE DISTRIBUTIONS OF M VALUES  
FOR PARENT PLATE

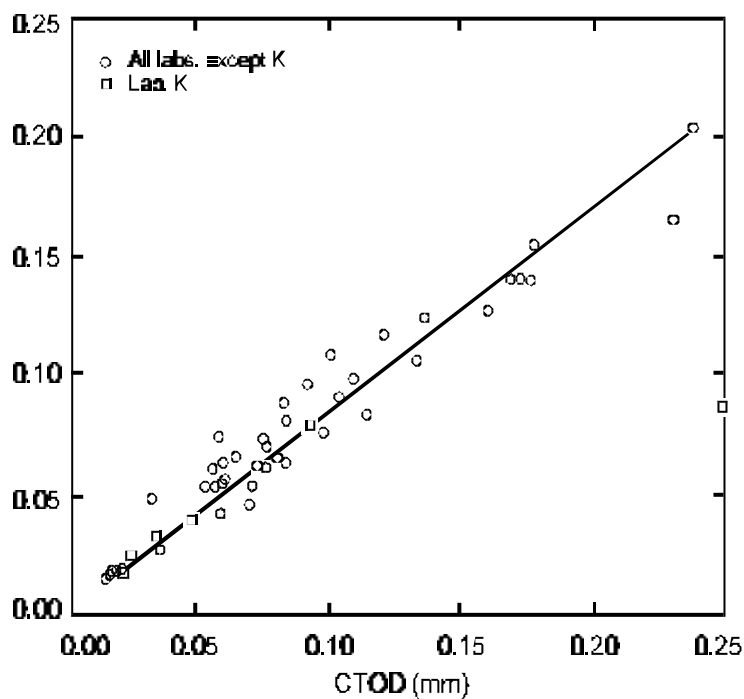
(D0643D17)

$J$  (MJ/m<sup>2</sup>)



(a) Bx2B SENB Specimen;  $m = 1.50$

$J$  (MJ/m<sup>2</sup>)

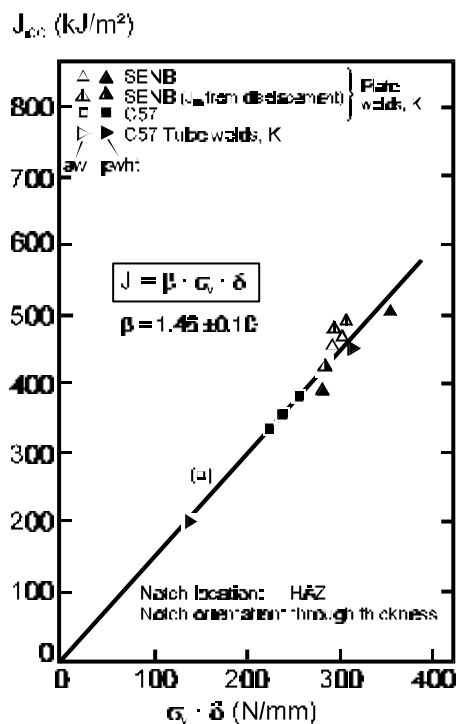


(b) BxB Specimen;  $m = 1.58$

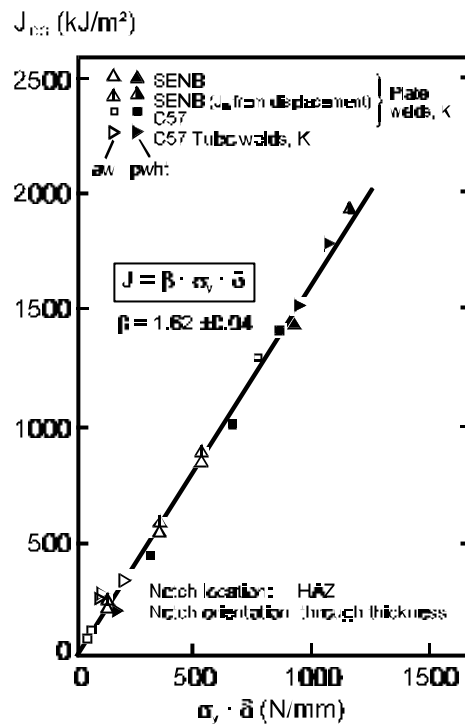
FIG. A42(a and b)

RELATIONSHIP BETWEEN  $J$  AND CTOD  
FOR WELD METAL IN S355J2 STEEL<sup>(A4.2)</sup>

(D0643D17)



(a) Initiation Toughness

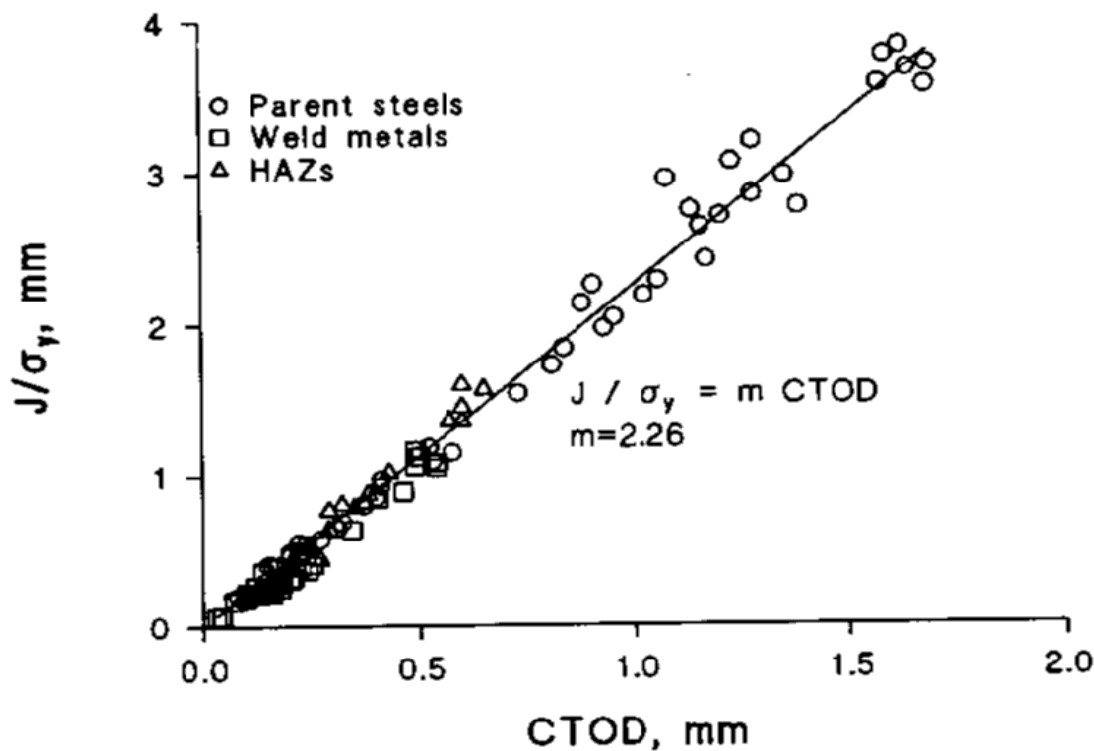


(b) All Data

FIG. A4.3(a and b)

RELATIONSHIP BETWEEN  $J$  AND  $\sigma_y$  CTOD  
FOR SIE36 HAZ<sup>(A4.5)</sup>

(D0643D17)



A4.4

DATA FOR DUPLEX AND SUPER-DUPLEX  
STAINLESS STEELS AND WELDMENTS<sup>(A4.4)</sup>

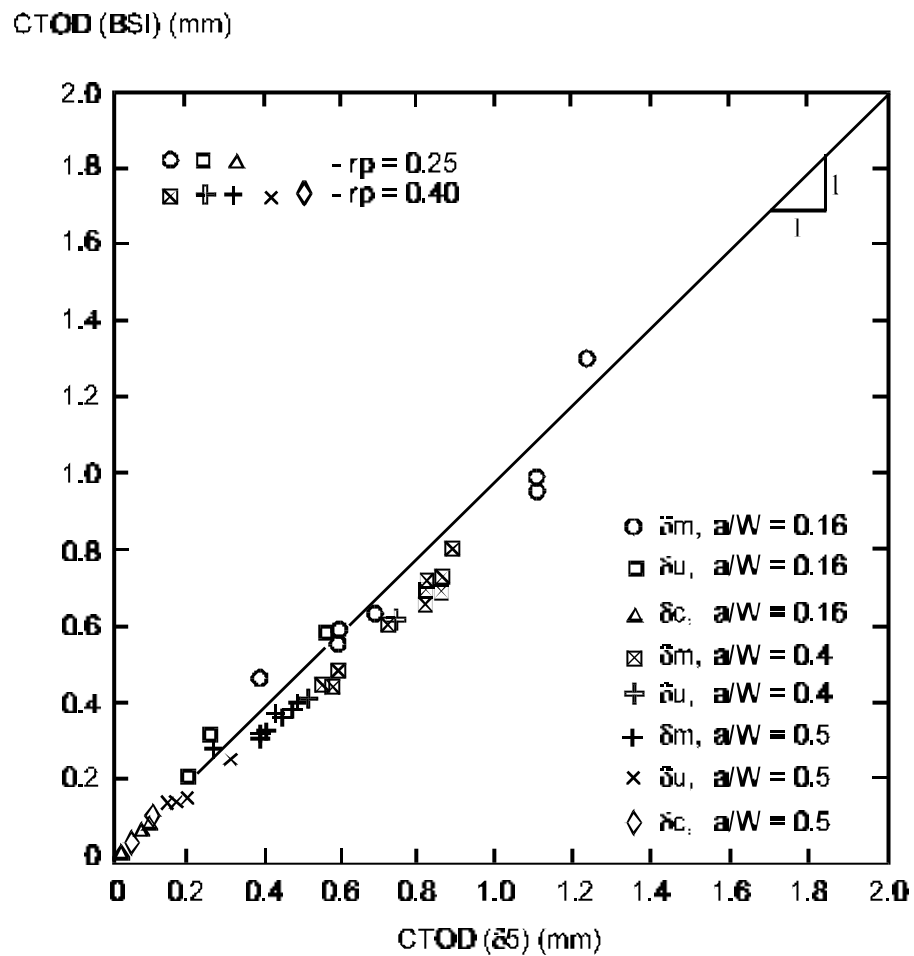


FIG. A45

COMPARISON OF CONVENTIONAL (BSI) DEFINED  
CTOD AND EQUIVALENT  $d_5$  MEASUREMENT<sup>(A4.9)</sup>

(D0643D17)

## APPENDIX 5

### INFLUENCE OF STRAIN RATE

#### A5.1 GENERAL CONCEPTS

The upwards shift in temperature of a fracture toughness transition curve with increasing strain rate can be attributed to the increase in yield strength associated with the increased strain rate. The strain rate effect on the yield strength has traditionally been described by a model of thermally activated yielding with the Zener-Hollomon strain rate parameter<sup>(A5.1)</sup>, usually expressed in the form<sup>(A5.2)</sup>:

$$\sigma_y = f \left[ T \cdot \log \left( \frac{A}{\dot{\epsilon}} \right) \right] \quad \dots (A5.1)$$

where T is in K and A is the strain rate parameter, being a function of the activation energy of the yield process.

Extension of this concept enables the temperature shift due to strain rate influence,  $\Delta T_\epsilon$ , to be described. A number of expressions are available for this, the most widely documented being those described in References (A5.3) and (A5.4), viz:

$$\Delta T_\epsilon = \frac{1440 - \sigma_y}{550} \cdot \left[ \ln \left( \frac{\dot{\epsilon}}{\dot{\epsilon}_0} \right) \right]^{1.5} \quad \dots (A5.2)$$

where  $\dot{\epsilon}_0 = 0.0001 \text{ s}^{-1}$ .

$$\Delta T_\epsilon = (83 - 0.08 \sigma_y) \dot{\epsilon}^{0.17} \quad \dots (A5.3)$$

for  $10^{-3} \text{ s}^{-1} \leq \dot{\epsilon} \leq 10 \text{ s}^{-1}$  and  $\sigma_y \leq 965 \text{ MPa}$ .

A comparison of these two expressions is given for four strain rates in Fig. A5.1. Equation (A5.3) gives a greater predicted influence of strain rate at higher yield strengths. However, the maximum difference in predicted toughness transition temperature shift is only 14°C.

In addition, where it is necessary to correct between stress intensity rates ( $\dot{K}$ ) and strain rates ( $\dot{\epsilon}$ ) various complications arise since the strain rate value varies depending on where it is defined (e.g. in the plastic zone, at the plastic-elastic interface or at the crack tip). However, generally in a structure the following approximations can be applied<sup>(A5.5)</sup>.

$$\dot{K} \approx E \dot{\epsilon} \sqrt{\pi a} \quad (A5.4)$$

However, the relationship between  $\dot{K}$  and  $\dot{\epsilon}$  can also be expressed in terms of  $K_{IC}$  and  $\sigma_y$  such that:

$$\frac{\dot{K}}{K_{IC}} = \frac{\sigma}{\sigma_y} \quad \dots (A5.5)$$

which in terms of  $\dot{\epsilon}$  gives:

$$\dot{\epsilon} = \frac{F \epsilon K_c}{\sigma_y} \quad \dots (A5.6)$$

## A5.2 TREATMENT OF STRAIN RATE EFFECTS IN THE MASTER CURVE APPROACH

The extension of the Master Curve Approach for the treatment of strain rate effects is detailed in Ref. A5.6. The shape of the Master Curve is essentially unaffected by loading rate, the Zener-Hollomon parameter is therefore applied to the reference temperature  $T_0$ . The loading rate-induced temperature shift depends on the log of the strain rate parameter ( $A$ ), which in turn is defined as  $\Gamma$  where

$$\Gamma = (\ln A)$$

$\Gamma$  values for a range of materials have been derived<sup>(A5.3, A5.7-A5.11)</sup> but recognition procedures used in Ref. A5.6 enables  $\Gamma$  to be defined as a function of yield strength and the transition temperature  $T_0$ , the two effects being independent of each other. The predictions of this equation compared to experimentally determined  $\Gamma$  values are shown in Fig. A5.2.

## REFERENCES

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- A5.2 A.H. Priest: 'Influence of Strain Rate and Temperature on the Fracture and Tensile Properties of Several Metallic Materials', Dynamic Fracture Toughness (Abington, Cambridge, UK: The Welding Institute, 1977), pp 95-111.
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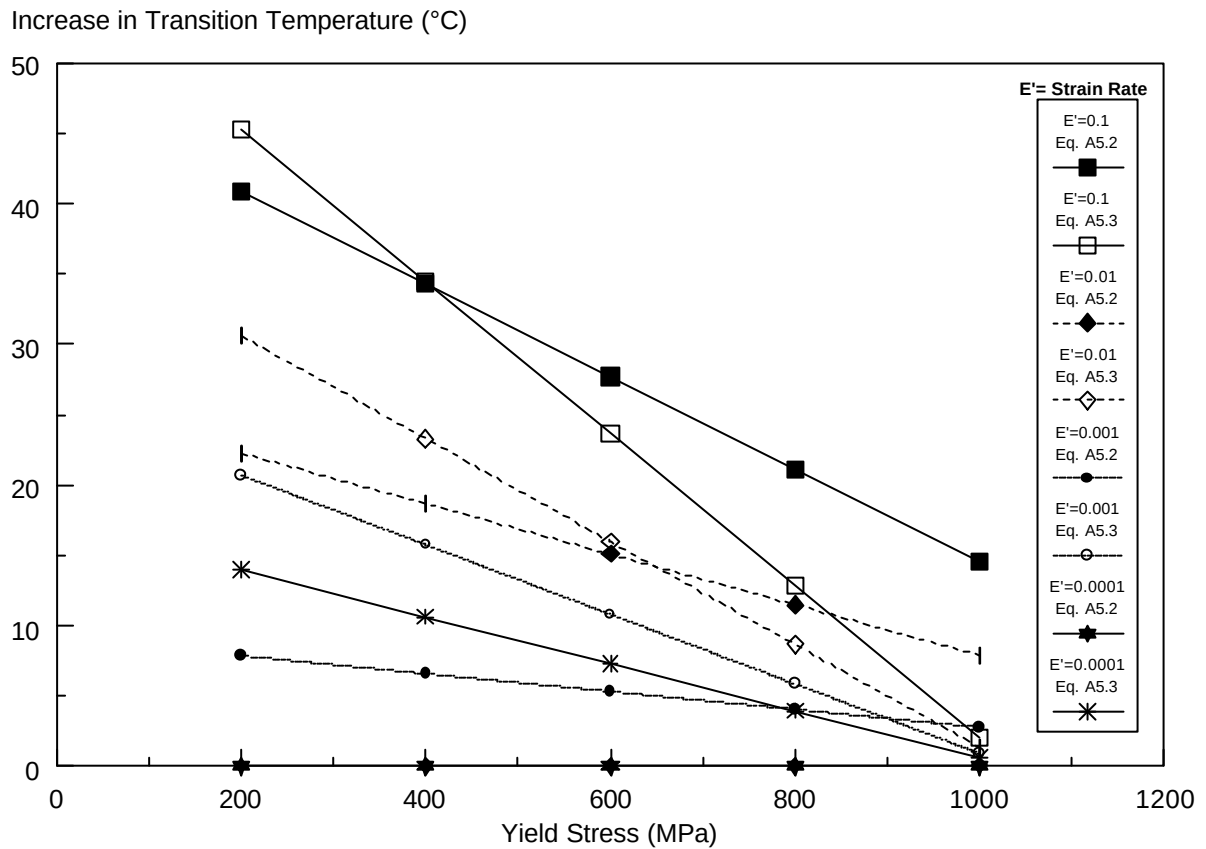


FIG. A5.1

PREDICTED INCREASE IN TRANSITION TEMPERATURE  
WITH YIELD STRENGTHS FOR VARIOUS STRAIN RATES

(D0643D19)

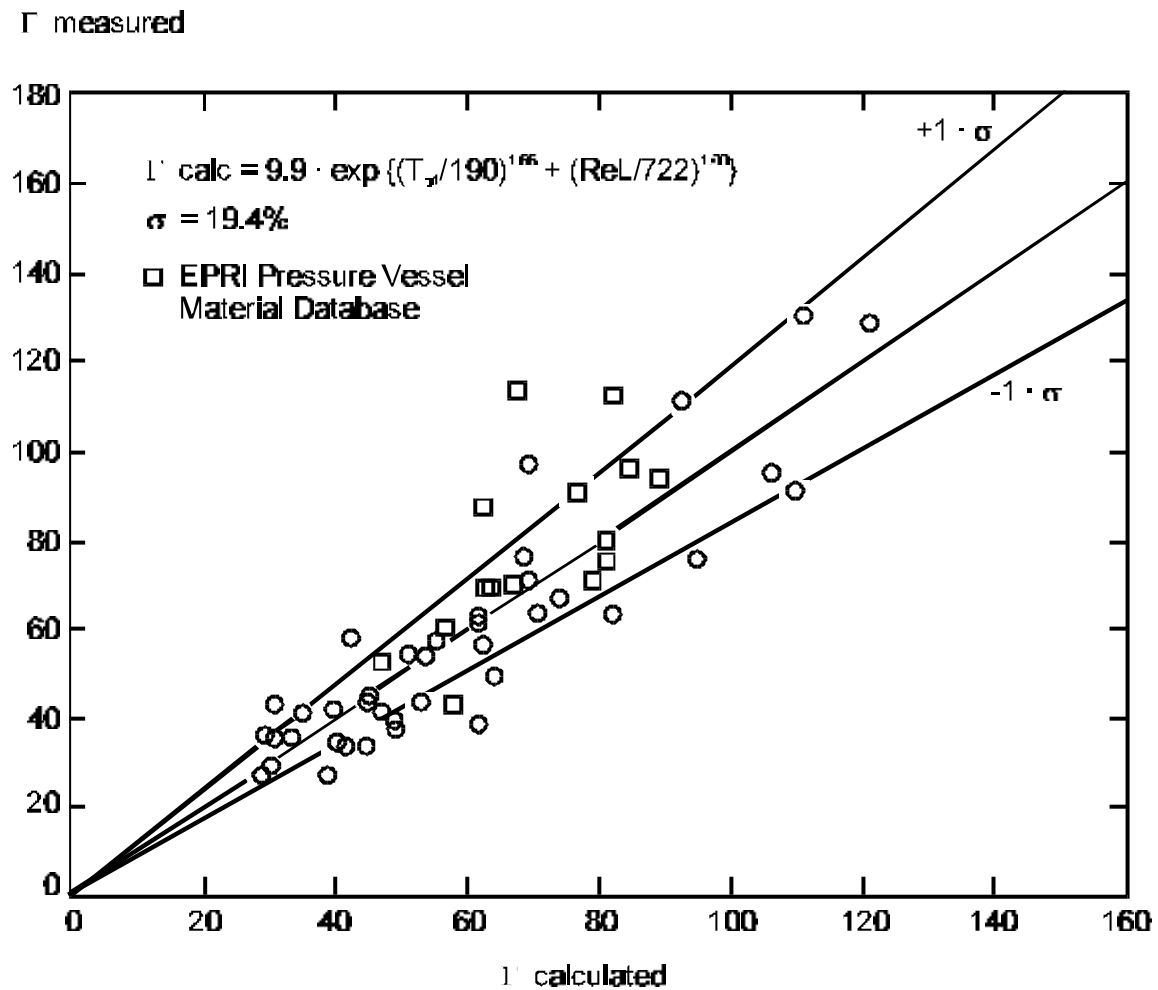


FIG. A52

COMPARISON OF MEASURED AND CALCULATED  
STRAIN RATE PARAMETER  $\Gamma$  (A5.5)

(D0643D19)

## APPENDIX 6

### UPPER SHELF CORRELATIONS

#### A6.1 APPROACH USED IN PD6493, 1991

Equation (19) in the main text represents the lower bound fit to upper shelf Charpy data used in BS PD6493<sup>(A6.1)</sup>. Figure A6.1 shows the results of a comparative exercise<sup>(A6.2)</sup> in which actual fracture toughness values for a range of thirty structural steels (determined from CTOD data) were compared with the correlation. The correlation is generally conservative although certain modern plate steels with low carbon and sulphur levels can give unconservative results. This usually arises when the Charpy transition temperature lies below the fracture toughness transition temperature. This effect was only observed at temperatures below -50°C and for cases where [% C + 10(% S)] was less than 0.16%. Figure A6.2 shows this effect and while extensive scatter is present, the general trend is that the 40 J Charpy temperature decreases at a faster rate than the 0.25 mm CTOD temperature as (% C + (10% S)) decreases. This composition parameter was identified by Graville in Ref. A6.3 for the purpose of correlations. It should however be noted that the toughness regime in the cases where non-conservative results were obtained was in a temperature range far below the typical design temperature of those steels.

#### A6.2 APPROACH OF ROBERTS & NEWTON

The correlation given as Equation (20) in the main text is a lower bound to data and was derived by Roberts & Newton<sup>(A6.4)</sup>. This correlation is shown in comparison with data in Fig. A6.3. The metric and imperial equivalents to this line, which represents a 95% confidence lower bound are:

$$\left(\frac{K_{IC}}{\sigma_y}\right) = a\left(\frac{CV}{\sigma_y} - b\right) \quad \dots (A6.1)$$

where for MPa  $\sqrt{m}$ , MPa and J,  $a = 0.52$  and  $b = 0.02$   
while for ksi  $\sqrt{in}$ , ksi and ft lb,  $a = 4.0$  and  $b = 0.1$

The correlation of Ault et al, shown in Fig. A6.3, is felt to be very conservative.

The lower bound relationship suggested (A6.1 above) was determined by taking all data shown in Fig. A6.3, excluding  $J_{IC}$  and invalid data points<sup>(A6.4)</sup>, and fitting a lower bound.

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$$K_{\delta(Nmm)^{-3/2}}$$

**FIG. A6.1**

**COMPARISON OF ACTUAL DATA WITH BSPD 6493  
UPPER SHELF CORRELATION<sup>(A6.2)</sup>**

**(D0643D21)**

**FIG. A6.2**

**RELATIONSHIP BETWEEN CHARPY 40 J AND CTOD 0.25 mm  
TRANSITION TEMPERATURES AS A FUNCTION OF COMPOSITION**

**(D0643D21)**

**FIG. A6.3**

**COMPARISON OF ROLFE-NOVAK-BARSOM AND  
AULT ET AL CORRELATIONS WITH THE  
LOWER BOUND RELATIONSHIP<sup>(A6.4)</sup>**

**(D0643D21)**

## APPENDIX 7

### TREATMENT OF SUB-SIZE CHARPY DATA

#### A7.1 DEFINITION OF PROBLEM

The ideal situation would be to be able to extrapolate directly the impact energies from sub-sized specimens to correspond to standard size specimens. Unfortunately, even though some simple equations for the purpose have been developed, they are not as reliable as one could desire. The problem with direct extrapolation lies in the fact that the specimen thickness yields different effects in different regions of the transition. On the lower shelf, sub-sized specimens yield proportionally higher impact energies as compared to standard size specimens. On the upper shelf the behaviour is reversed so that sub-sized specimens give either proportionally equal or even lower impact energies than standard sized specimens. The reason for this is that the different fracture micromechanisms result in different specimen thickness effects. In the transition region there is a competition between ductile and brittle fracture micromechanisms thus yielding a very complex combined thickness effect. A much more reliable extrapolation can be obtained by considering some transition temperature criterion.

#### A7.2 TOWERS CORRELATION

The shift in the 0.25 J/mm<sup>2</sup> and 0.5 J/mm<sup>2</sup> normalised Charpy energy transition temperatures has been assessed by Towers<sup>(A7.1)</sup>. These normalised energies correspond to 27 J and 40 J in a full size Charpy specimen. For situations that do not involve splitting, the reduction in the transition temperature is given by:

$$\Delta T = 0.7 (10-t)^2 \quad \dots (A7.1)$$

where t = specimen thickness in mm. The predicted relationship is shown in comparison with data at the two normalised energy levels in Fig. A7.1.

#### A7.3 WALLIN CORRELATION

An alternative expression has been derived by Wallin<sup>(A7.2)</sup> based on steels in the yield strength range 200-1000 MPa with thickness in the range 1.25-10 mm. The derived equation for a normalised energy of 0.35 J/mm<sup>2</sup> is given below:

$$\Delta T = 51.4 \cdot \ln \left[ 2 \cdot \left( \frac{B}{10} \right)^{0.25} - 1 \right] \quad \dots (A7.2)$$

The normalised Charpy energy of 0.35 J/mm<sup>2</sup> corresponds to 28 J in a full size Charpy specimen, the Charpy value used for correlation of the original Sanz approach.

Data for the full range of steels and for high strength steels only (YS > 500 MPa) are shown in comparison with the prediction in Figs. A7.2 and A7.3 respectively.

#### A7.4 COMPARISON

A comparison of the prediction of the two expressions is given in Fig. A7.4. For the thickness range of practical interest (2.5-10 mm) there is little difference between the two predicted relationships. The two studies were carried out on different materials at different instants and with a time gap of eight years and, although both equations are empirical and take different forms, the predicted effect is very similar.

The expression given in A7.2 (Equation 21) has therefore been recommended since this incorporates an inherent statistical confidence level.

#### A7.5 UPPER SHELF EFFECTS

When the material behaves in a fully ductile, upper shelf manner, the absorbed energy per unit ligament area is usually less for thin specimens, although the effect is minimal or even reversed for materials with a low resistance to crack propagation<sup>(A7.3)</sup>.

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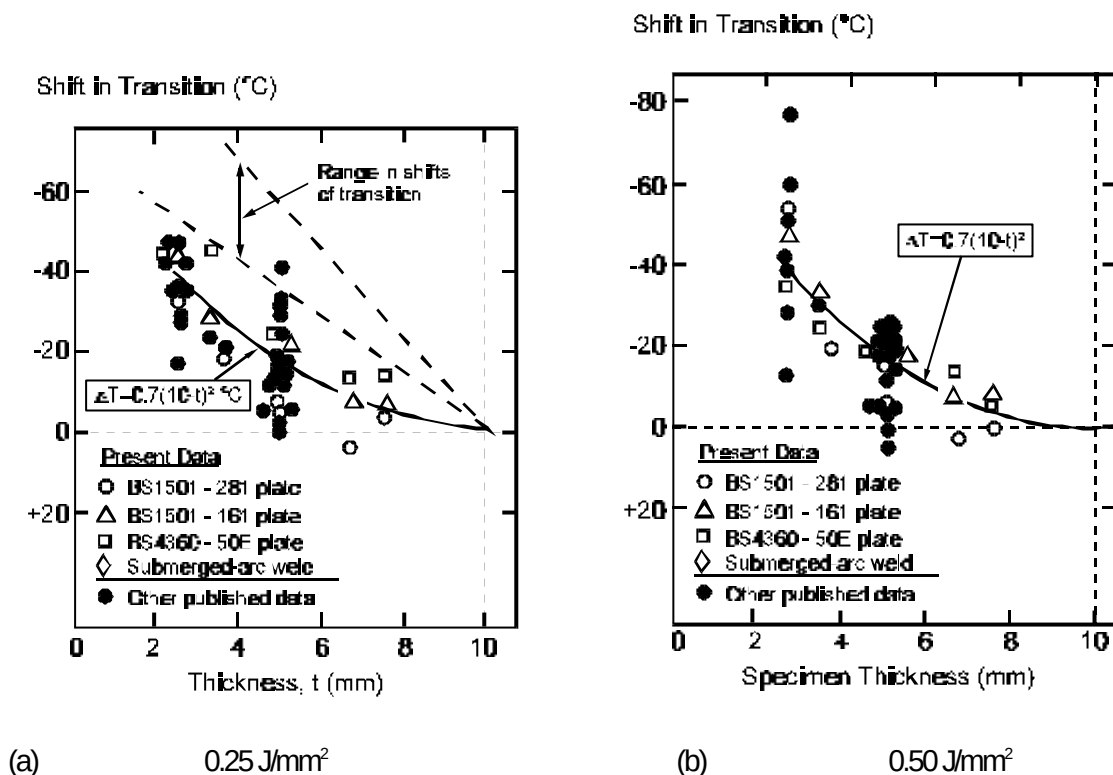


FIG. A7.1(a and b)

TRANSITION TEMPERATURE SHIFT FOR  
SUB-SIZE SPECIMENS RELATIVE TO FULL SIZE  
BASED ON NORMALISED ENERGY  
(STEELS, UTS RANGE 334-685 N/mm<sup>2</sup>)<sup>(A7.1)</sup>

(D0643D23)

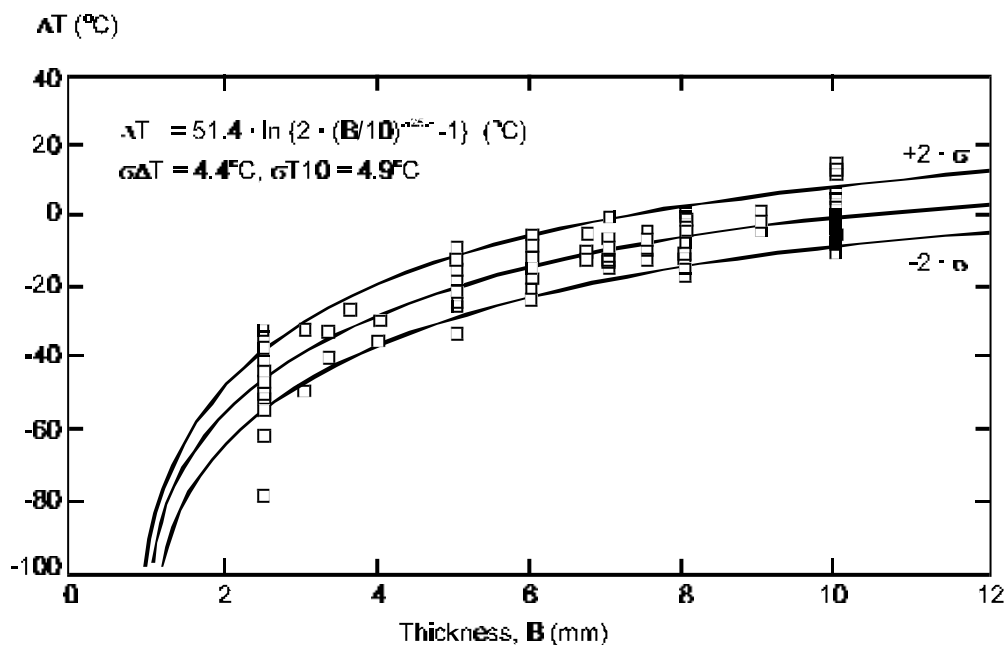


FIG. A7.2

TRANSITION TEMPERATURE SHIFT FOR SUB-SIZE SPECIMENS  
RELATIVE TO FULL SIZE BASED ON A NORMALISED ENERGY OF  
0.35 J/mm<sup>2</sup> (STEELS, YS RANGE 200-1000 N/mm<sup>2</sup>)<sup>(A7.2)</sup>

(D0643D23)

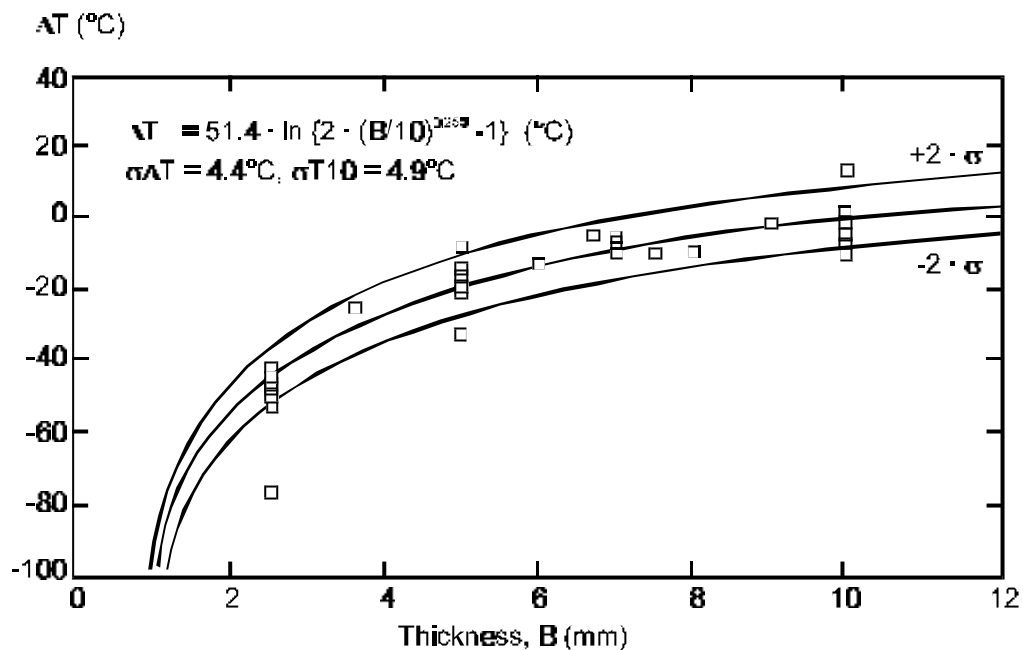


FIG. A73

TRANSITION TEMPERATURE SHIFT FOR SUB-SIZE SPECIMENS RELATIVE TO FULL SIZE BASED ON A NORMALISED ENERGY OF  $0.35 \text{ J/mm}^2$  (STEELS,  $Y_S$  RANGE  $500\text{-}1000 \text{ N/mm}^2$ )<sup>(A7.2)</sup>

(D0643D23)

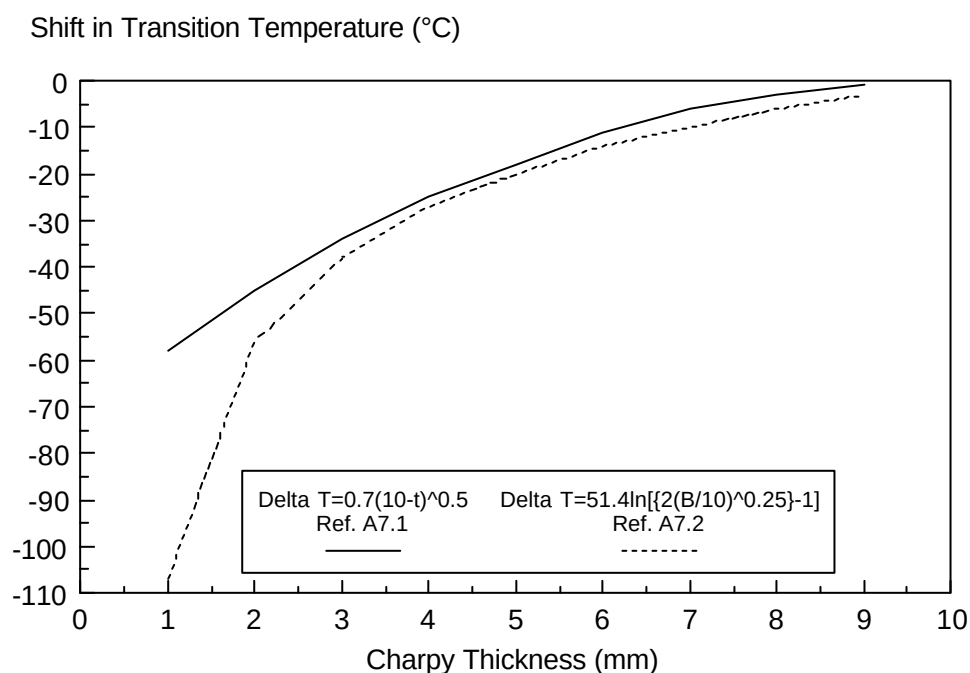


FIG. A74

COMPARISON OF PREDICTIONS OF THICKNESS EFFECT ACCORDING TO REFS. A7.1 AND A7.2

(D0643D23)