Brite-Euram Project No.:	BE95-1426
Contract No.:	BRPR-CT95-0024
Task No.:	3
Sub-Task No.:	3.2
Date:	22.12.1997
Contributing Organisations:	VTT, TWI, British Steel, NEL and HSE
Document No.:	SINTAP/VTT/7

STRUCTURAL INTEGRITY ASSESSMENT PROCEDURES FOR EUROPEAN INDUSTRY

SINTAP

SUB-TASK 3.2 REPORT: METHODOLOGY FOR THE TREATMENT OF FRACTURE TOUGHNESS DATA: PROCEDURE AND VALIDATION

REPORT VAL A: SINTAP/VTT/7

FINAL REPORT

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Espoo, December 1997

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SUMMARY

METHODOLOGY FOR THE TREATMENT OF FRACTURE TOUGHNESS DATA: PROCEDURE AND VALIDATION

VTT Manufacturing Technology

The fracture toughness available for a fracture mechanics analysis can be based either upon K_{IC}, J or CTOD (δ). The data therefore usually appears in various forms which complicates structural integrity assessments. The treatment of toughness data, at present, varies depending on the type of the data that is available in each case, and this makes it impossible to apply any single, unified procedure.

In this report, a procedure is described for the unified treatment of various forms of toughness data for use in structural integrity assessments. Instead of applying various equations and routes for different types of toughness data in the assessment, the methodology is based on an approach, in which one material specific K_{mat} value, together with its probability density distribution $P\{K_{mat}\}$ is defined. All the other fracture toughness data types (parameters) are hence transferred into K_{mat}.

For brittle fracture, the evaluation procedure is based upon the maximum likelihood concept (MML) that uses a 'Master Curve' method to describe the temperature dependence of fracture toughness. The method makes the following assumptions: (i) specimen size adjustment, (ii) distribution of scatter and (iii) minimum toughness and temperature dependence. As a result of the procedure, a conservative estimate of the mean fracture toughness (and the distribution) is obtained.

The methodology can be easily applied to either fracture toughness data at a single temperature or the data at different temperatures. The procedure is further divided into three separate steps: (i) Normal Maximum Likelihood Estimation, (ii) Lower-Tail maximum Likelihood Estimation and (iii) Minimum Value Estimation. Depending on the characteristics of the data which is available in each case, the procedure guides the user to select the step that is most appropriate for the fracture toughness analysis to the particular case being assessed.

The treatment of data for ferritic steels on the upper shelf of fracture toughness, for materials which do not exhibit brittle cleavage fracture, or in the case that only ductile fracture data is available, is discussed separately in an informative manner.

For each section, details of validation are given in a corresponding Validation Section, providing details of aspects such as accuracy of the prediction and situations where the guidance may not be applicable.

The report brings together a number of published well validated equations applicable for statistical treatment of fracture toughness data into a single, user-friendly step-by-step methodology which allows an accurate fracture toughness assessment with quantified probability and confidence levels. Irrespective of the type of the original toughness data, one material specific K_{mat} value, together with its probability distribution $P\{K_{mat}\}$ is always obtained as a final result of the procedure. Thus, K_{mat} represents a unique parameter and its distribution describing material's toughness for the assessment.

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1. INTRODUCTION

In an ideal situation, appropriate fracture toughness data for use in structural integrity assessments are generated through the use of suitable fracture mechanics based toughness tests. In reality, however, the existing data can appear in various forms, as the fracture toughness used in a fracture mechanics analysis can be based either upon K_{IC}, J or CTOD (δ) [1]. Fracture toughness testing standards can not give any recommendations for the application of fracture toughness data for structural integrity assessment, since they are based on ensuring the correct test performance and the quality of the data rather than treatment of data. A number of methods and models are available today for the treatment of fracture toughness data, especially in the ductile-to-brittle transition regime [1], but very few comparative studies have been conducted to validate the results. As a result, treatment of toughness data, at present, varies depending on the type of the data (K, J, CTOD) that are available in each case.

Instead of applying various equations and routes for different types of toughness data in the fracture mechanics assessment, an approach is presented here, in which one material specific K_{mat} value, together with its probability distribution $P\{K_{mat}\}$ is defined, irrespective of the type of the original toughness data available. All other toughness data types are therefore transferred into K_{mat} which thereby represents a unique parameter and its distribution describing material's toughness for the assessment. The various treatments needed for the fracture toughness analysis, including e.g. specimen size adjustment, inclusion of strain rate effects, etc., are then applied to the K_{mat} data.

In the following sections, the basic principles and detailed procedure of the methodology for the treatment of toughness data for fracture toughness estimation is described, with the associated numerical equations.

For assessment against *brittle fracture*, the evaluation procedure is based upon the maximum likelihood concept (MML) that uses a 'Master Curve' method to describe the temperature dependence of fracture toughness. The results of the procedure will be a conservative estimate of the <u>mean</u> fracture toughness (together with the distribution). Section 2 outlines the general scientific background of the treatment of fracture toughness data, whilst the principles of the initial structure of the procedure are given in section 3, with the flow-chart describing hierarchy of the procedure. In section 4, the mathematical formulation of each step of the procedure is explained and guidance is given on the selection of a step that is most appropriate to the particular type of data available for material's fracture toughness estimation.

Section 5 discusses separately the treatment of data for ferritic steels on the upper shelf of fracture toughness, for materials which do not exhibit brittle cleavage fracture, or in the case that only ductile fracture data is available. This section is not meant to be a procedure, but explanatory, only.

Finally, additional guidance for correct use is provided and the limitations of the procedure are discussed in Section 6. The validation of the procedure is presented in a separate Validation Section (section 7).

2. BACKGROUND OF THE TREATMENT OF FRACTURE TOUGHNESS DATA

The present procedure is based on an approach, in which one material specific K_{mat} value, together with its probability distribution $P\{K_{mat}\}$ is defined, irrespective of the type of the original toughness data available. All other toughness data types are therefore transferred into K_{mat} which thereby represents a unique parameter and its distribution describing material's toughness for the assessment, see Fig. 1.
For assessment against *brittle fracture*, the evaluation procedure is based upon the maximum likelihood concept (MML) that uses a 'Master Curve method' which describes the temperature dependence of

fracture toughness. The Master Curve method makes the following assumptions: (i) specimen size adjustment, (ii) distribution of scatter and (iii) minimum fracture toughness (K_{min}) and temperature dependence. These are discussed in more detail in sections 2.1 and 2.2.

In the case that *Charpy data* is all that is available for the assessment, the treatment is carried out according to the flow-chart in Fig. 2. Preference is given to the use of brittle fracture data, since the approach can, in this case, be based on the comparatively well verified correlation between T28J and fracture toughness ($TK_{100MPa\sqrt{m}}$) following the 'Master Curve' concept [1,11]. All the other Charpy parameters are then correlated to T_{28J}. Why brittle fracture data is preferred here stems from the findings [11] that energy levels greater than 27/28 J tend to yield less reliable prediction of fracture toughness. Fracture toughness at the reference temperature should be low enough to preclude ductile tearing and to eliminate any effects of extensive plasticity. The Master Curve Method which is in accordance with Eurocode 3 is also used in the new ASTM standard for fracture toughness testing in the ductile-brittle transition region.

Apart from that above, if only *ductile Charpy data* is available, the approach should, instead, be based on some verified CVN - K -correlation [11] derived particularly from upper shelf results.

The assessment procedure based on available Charpy data is presented in Sub-Task 3.3 Procedure and Validation Report [11], whereas the assessments using fracture toughness data forms the scope of the present document.

In the case of *ductile J_{IC}, J_i, J-R and K_{IC} (ductile) data*, the treatment follows the flow-chart according to Fig. 3. Apart from the type of fracture toughness data available, say, ductile data, the philosophy of the design of a structure itself can be based either on *"design against brittle fracture"* or *"design against ductile fracture"*. In the former case, the approach is, again, based on the "Master Curve" prediction but, now, using the minimum data treated as brittle.

For (i) ferritic steels on the upper shelf of fracture toughness, or for (ii) materials which do not exhibit brittle cleavage fracture, design against brittle fracture is not realistic. In this case, treatment of *ductile fracture data* should follow a separate approach presented in Section 5. Due to insufficient knowledge of the extent of to which all the factors (e.g. constraint, mismatch, scatter, definition of "initiation", testing, etc.) influencing the ductile fracture behaviour should actually be taken into account in the prediction, the approach is suggested as explanatory only, see Fig. 3.

In the case of *CTOD data* in the form of δ or J, the treatment is conducted according to the flow chart in Fig. 4. With respect to the parameter δ, the procedure is based on the standard CTOD (BS 5762) and other non-standardised parameters, like δ_5, are given only as a reference.

In the case of *brittle K_{IC} or K_{JC} data*, the treatment continues according to the flow chart presented in Fig. 5. In the present procedure, the fracture toughness evaluation is based upon the maximum likelihood concept (MML) that uses a 'Master Curve' prediction method to describe the temperature dependence of fracture toughness. For obtaining a 'best estimate' - i.e. a conservative estimate of the mean fracture toughness - for various types of microstructures, the treatment also includes the homogeneity check , see Fig. 5. This is explained in more detail in the following sections.

The idea of the present procedure is to apply the various treatments needed for the fracture toughness analysis, including specimen size adjustment, inclusion of strain rate effects etc. directly to K_{mat} data. The procedure is initially structured in a way that the less sufficient or accurate the original data to be converted to K_{mat}, the more it will be penalised in the probabilistic fracture mechanics assessment. While this ensures that even the estimate derived from 'lowest quality data' is always 'safe', it brings a

benefit in that the more sufficient and accurate the original data, the less becomes the need for additional procedure-induced conservatism.

Structured this way, the procedure rewards the user that has the most accurate data but, on the other hand, permits the maximum benefit to be gained from any given data set by relating the penalty to the quality of the original data. Any additional data improving the accuracy of a previously existing data set can also be readily utilised in terms of reduced conservatism. The procedure thereby not only enables the quantification of probability and confidence levels of the K_{mat} estimate, but also guarantees the avoidance of multiple safety margins that could lead to unnecessary conservatism.

Because of the maximum likelihood concept (MML) chosen as a basis of the fracture toughness evaluation, the methodology allows the use of data sets consisting of both results ending in failure and those ending in non-failure. One distinct advantage of the procedure is therefore that the whole data set that is available in each case can always be fully utilised in the analysis, regardless of whether the results are ductile or brittle. The procedure can be applied as easily to either fracture toughness data at a single temperature or to the data at different temperatures.

2.1 Scatter and size effect of fracture toughness at cleavage instability

The fracture toughness to be used in a fracture mechanics analysis can be based upon K_{IC}, J, or CTOD. Regardless of parameter it is preferable to express the fracture toughness in terms of it's equivalent K-value, denoted here as K_{IC}.

The present procedure assumes the scatter to follow the statistical brittle fracture model of Wallin [1,13,16] which assumes a Weibull type distribution function for *scatter in fracture toughness as*:

$$P\left[K_{IC} \le K_I\right] = 1 - \exp\left(- \left[\frac{K_I - K_{min}}{K_0 - K_{min}} \right]^4 \right)$$

where $P[K_{IC} \le K_I]$ - i.e. P_f - is the cumulative failure probability at a K_I level, K_I is the stress intensity factor level, Kmin is the lower bound to the fracture toughness and K_0 is a temperature and specimen thickness dependent normalisation fracture toughness which corresponds to a 63.2 % cumulative failure probability (and is approximately 1.1 $\overline{K}_{IC}$, where $\overline{K}_{IC}$ is mean fracture toughness). Although "K_{min}" itself can be regarded as "theoretical" in nature, it has been found [1] that for structural steels, a fixed, experimental value of K_{min} = 20 MPa√m can be used.

The methodology also predicts a *statistical size effect of fracture toughness* test specimens of the form [1,7]:

$$K_{B2} = \left(K_{B1} - K_{min}\right)\left(B_1 / B_2\right)^{1/4} + \mathrm{Kmin}$$

where B_1 and B_2 correspond to respective specimen thickness (length of crack front).

Other statistical brittle fracture models [1,17] yield very similar equations, the main difference being essentially in the treatment of K_{min}.

The model applied here is based upon the assumption that brittle fracture is primarily initiation controlled, even though it contains a conditional crack propagation criterion, which among others results in the lower bound fracture toughness K_{min}. Close to the lower shelf of fracture toughness (K_{IC} < 50

MPa√m) the equations are expected to be inaccurate. On the lower shelf, the initiation criterion is no longer dominant, but the fracture is completely propagation controlled [1,18]. In this case there is no statistical size effect and also the toughness distribution differs slightly from the presented Weibull type distribution function according to [16].

In the ductile to brittle transition region the equations presented here should be valid as long as loss of constraint and/or ductile tearing do not play a significant role.

2.2 Temperature dependence of fracture toughness

For brittle fracture, the present procedure is based on the 'Master Curve' prediction that describes the temperature dependence of fracture toughness, with the data homogeneity check, see Fig. 5.

Generally, in the case of "homogeneous" data it is sufficient to consider only the toughness of the matrix microstructure and the estimate can be based on the mean value of the data. In the case of "inhomogeneous" data, where the "brittle microstructure" is substantially more brittle (e.g. 3 times) than the "matrix microstructure", the fracture behaviour will be dominated by the brittle microstructure alone [13] and, consequently, the estimate must be based on the minimum value of the data. This is explained in more detail in the context of the methodology description in section 3.

The 'Master Curve' is used in the new ASTM standard for fracture toughness testing in the ductile to brittle transition region. It describes the temperature dependence of fracture toughness K_0, which for ferritic structural steels is proposed [2] as:

$$K_0 = 31 + 77.\exp\left(0.019.\left[T - T_0\right]\right)$$

where T_0 (°C) is the transition temperature where the mean fracture toughness, corresponding to a 25 mm thick specimen, is 100 MPa√m and $K_0(T_0)$ which is a normalisation fracture toughness at 63.2 % cumulative failure probability, is 108 MPa√m.

The expression gives an *approximate* temperature dependence of the fracture toughness for ferritic structural steels and it is comparatively well verified [2-11]. The effect that possible outlier or invalid fracture toughness values may have upon the transition temperature T_0 decreases if the temperature dependence is fixed.

2.3 Parameter estimation

Depending whether the original data consist of results obtained at different temperatures or correspond to one single temperature, the parameters to estimate are either the transition temperature T_0 or the normalisation toughness K_0, respectively. As a result of the procedure, a conservative estimate the mean fracture toughness is obtained.

The maximum likelihood concept (MML) [12] which the present methodology uses for the toughness estimation, suits well to analysis of data sets which include both results ending in failure and non-failure. This is often the case in practice fracture mechanics testing, especially for welded joints.

Irrespective of the actual estimate of fracture toughness that is obtained from the present procedure, the "amount of safety", so to speak, depends - and should depend - on the particular application. This means that selecting a confidence level to be used in the structural integrity assessment depends on the criticality of the component / structural member in question. In other words, for the assessment suitable

confidence and probability levels should be chosen in terms of the final application. Consequently, for very critical structural parts, a more conservative confidence level should be chosen.

3. PRINCIPLES OF THE PROCEDURE

For assessment against *brittle fracture*, the evaluation procedure is based upon the maximum likelihood concept (MML) that uses a 'Master Curve' method to describe the temperature dependence of fracture toughness. The flowchart describing the initial structure of the procedure is shown in Fig. 6. As an output of the procedure, a conservative estimate of the mean fracture toughness at cleavage instability is being made.

Firstly, the available data is written in the form of K_{mat}. In the case that the original data appears in the form other than K (e.g. J, CVN etc.), the assessment procedures described in Sub-Task 3.3 Procedure and Validation Report [11] are used to convert the data in the form of K_{mat}. Otherwise, the procedure described in the present document should be followed, starting with size-adjustment [7] of the data according to Eq. (1). This size-adjustment of the original fracture toughness (K) data should be made whenever a given data set includes results from specimens having thickness other than 25 mm.

The procedure then progresses according to three separate steps: Step 1: *Normal Maximum Likelihood Estimation*, Step 2: *Lower-Tail Maximum Likelihood Estimation* and Step 3: *Minimum Value Estimation.* Depending on the characteristics of the original data which are available in each case, the procedure guides the user to select the toughness estimate K_{mat} (P, T, B) given by the step that is most appropriate for the fracture toughness analysis to the particular case being assessed.

The idea of the different steps in the procedure is that each step sets a different validity level for that part of the data that is to be censored. It should be emphasised here that censoring the data does not mean neglecting the data. The whole data set is thereby involved in the analysis and censoring only means that a certain pre-assumption is made concerning the nature of the data being censored. Consequently, censored data, e.g. non-brittle results that are above the censoring validity level, are recognised to be higher than the validity level (i.e. $\delta i = 0$), but the toughness value corresponding to the validity level in question is used in further estimation.

3.1 Step 1: Normal MML estimation

The principles of treatment of data according to Normal MML Estimation (Step 1) in the case of data at a single temperature and data at different temperatures are schematically presented in Figs 7a and 8a, respectively.

In Step 1 (Normal MML Estimation), all the available data is used for MML estimation of K_{mat} or $T_0(K_{mat})$, with the exception of test results which are affected by large-scale yielding and those ending in non-failure. In the case of large-scale yielding, the results are violated because the specimen measuring capacity is exceeded. As a result, the fracture mechanical parameters no longer describe the cleavage fracture process zone correctly. Therefore, these data need to be censored to obtain a valid and 'safe' estimate for fracture toughness.

The specimen measuring capacity limit depends on the specimen geometry and material properties and can be calculated according to the relevant test standards. The new ASTM standard for fracture toughness testing in the transition region defines the measuring capacity as: $K_{JC(limit)} = (E \times b_0 \times \sigma_{ys}/30)^{0.5}$.

3.2 Step 2: Lower-Tail MML estimation

The principles of treatment of data according to Lower Tail MML Estimation (Step 2) in the case of data at a single temperature and data at different temperatures are schematically presented in Figs. 7b and 8b, respectively.

In Step 2 (Lower-Tail MML Estimation), only the data corresponding to a cumulative probability of 50 % or lower, is used for MML estimation of K_{mat} or $T_0(K_{mat})$, whilst the data above this probability level is censored. In other words, it is recognised that the true value of each censored result is above the censoring validity limit (i.e. $\delta i = 0$), but the toughness value corresponding to this validity limit is used for further estimation of fracture toughness (i.e. $K_{MATi} = K_{CENSi}$). The purpose of this is to obtain an estimate which, besides large-scale yielding, would also be unaffected by such phenomena, as excessive ductile tearing or plasticity.

The Lower-Tail MML estimation therefore aims at obtaining a 'realistic' toughness estimate that would be descriptive of material properties only, without a risk of being influenced or violated by those results in the data set that can exhibit unrealistically high 'apparent' toughness values due to e.g. testing conditions rather than 'inherent' material properties.

In the case that the results above the 50 % probability level should exhibit unrealistically low 'apparent' toughness values, the procedure is mathematically constructed in a way that prevents 'false' iteration direction.

The Step 2 then proceeds as a continuous iteration process to obtain K_{mat} or $T_0(K_{mat})$ fracture toughness estimate. Following this, the procedure continues to Step 3, after which the estimates according to Step 1, 2 and 3 are compared with each other, in order to obtain a final characteristic toughness estimate to be further used in structural integrity assessment.

3.3 Step 3: Minimum Value Estimation

The principles of Minimum Value Estimation (Step 3) that uses single data for estimates of either K_{MAT} or $T_0(K_{MAT})$ are schematically presented in Figs. 7c and 8c, respectively.

The Step 3 (Minimum Value Estimation) uses only one toughness value, i.e. the minimum value in the data set, for the toughness estimation. Despite of this, it is equivalent to bias-corrected MML estimate where all the values are censored to the lowest value in a given data set.

In a way, Step 3 serves as material's inhomogeneity check, because it takes into account the possibility that a single minimum value in a data set can become significant (i.e. capable of triggering brittle failure) due to severe local microstructural inhomogeneity of the material. This can, for instance, be the case in the heat-affected zone of an otherwise tough steel exhibiting local brittle zones [4,13,14].

Provided that the thereby obtained K_{mat} or $T_0(K_{mat})$ estimate according to Step 3 is more than 10 % lower or 8 °C higher, respectively, than the corresponding estimate according to Step 1 or Step 2 - whichever of them is lower: K_{mat} (or higher: $T_0(K_{mat})$), this single minimum value is regarded as significant and the estimate according to Step 3 is taken as a final estimate of material's fracture toughness. Otherwise, the lowest (highest) one of the estimates given by Step 1 and Step 2 is taken as a final estimate.

4. FRACTURE TOUGHNESS ESTIMATION: THE PROCEDURE

In this section, the details of the various steps of the procedure are described, with the associated mathematical equations. The initial structure of the procedure at each step is presented in Figs 9-11.

The nomenclature of the mathematical equations used in the estimation procedure in section 4 is given in the following:

B	=	specimen thickness
P_f	=	cumulative failure probability
K_{CENS}	=	censoring value for individual fracture toughness
K_{limit}	=	specimen measuring capacity as defined in testing standards
K_{MAT}	=	individual fracture toughness
K_{MAT25}	=	size adjusted K_{MAT}
$\overline{K}_{MAT}$	=	median K_{MAT}
K_0	=	63.2 % failure probability KMAT
$P\{K_{MAT}\}$	=	probability distribution corresponding to the median KMAT estimate
N	=	total number of tests
T_0	=	100 MPa$\sqrt{m}$ $\overline{K}_{MAT}$ transition temperature
T	=	operating temperature
δ	=	censoring parameter δ = 1 (brittle), d = 0 (censored)

The procedure consists of three different steps, of whose mathematical formulation is given in the following sections 4.1 to 4.4.

4.1 Procedure according to Step 1: Normal MML Estimation

The flowchart describing the analysis according to Step 1: Normal MML Estimation is shown in Fig. 9 for both the cases of having data at a single temperature and data at various temperatures.

Firstly, all ductile results and those results in a given data set that exceed the specimen's measuring capacity limit are censored according to the methodology specified in the testing standards, e.g. according to: $K_{IC(limit)} = (E \times b_0 \times \sigma_{ys} / 30)^{0.5}$ defined by the new ASTM standard. The results associated with brittle and non-brittle failure modes are designated as $\delta i = 1$ and $\delta i = 0$, respectively. For each censored result with the true value above the censoring validity limit, i.e. $K_{MATi} > K_{limit}$, the toughness value corresponding to this validity limit is used for further estimation of fracture toughness (i.e. $K_{MATi} = K_{limit}$) and the result is designated as being non-brittle, i.e. $\delta i = 0$.

Secondly, the size adjustment is made to the K_{MAT} data according to Eq. (1), whenever the data set includes results from specimens having thickness other than 25 mm. The thickness adjustment for obtaining normalised, size-adjusted K_{MAT}, denoted as K_{MAT25}, is calculated as:

$$K_{MAT_{25}} = 20\,\text{MPa}\sqrt{m} + (K_{MAT} - 20\,\text{MPa}\sqrt{m}).\left(\frac{B}{25\text{mm}}\right)^{1/4} \quad \text{.....(1)}$$

where K_{MAT} is the individual fracture toughness and B is specimen thickness.

The procedure then has two alternative routes depending on whether test data is available (a) at a single temperature, or (b) at different temperatures.

4.1.1 Data at a single temperature

In the case of data at a single temperature, two fracture toughness parameters: K_0 corresponding to a 63.2 % cumulative failure probability K_{MAT} and median K_{MAT} (= $\overline{K}_{MAT}$) corresponding to the median (50 %) failure probability are calculated according to Eq. (5a) and Eq. (3), respectively, as:

$$K_0 = 20\text{MPa}\sqrt{\text{m}} + \left(\frac{\sum_{i=1}^{N} \left(K_{MAT_i} - 20\ \text{MPa}\sqrt{\text{m}} \right)^4}{\sum_{i=1}^{N} d_i} \right)^{1/4} \quad \text{.....(5a)}$$

where K_{MATi} is individual fracture toughness of a specimen and δ_i is censoring parameter for each individual result (brittle: δ_i = 1, non-brittle = censored: δ_i = 0). The thereby calculated K_0 value is then used to determine $\overline{K}_{MAT}$ corresponding to 50 % failure probability according to Eq. (3), as:

$$\overline{K}_{MAT} = 20\text{MPa}\sqrt{\text{m}} + \left(K_0 - 20\text{MPa}\sqrt{\text{m}} \right).0.91 \quad \text{.....(3)}$$

4.1.2 Data at different temperatures

In the case of having data at different temperatures, transition temperature T_0 corresponding to the 100 MPa√m median (50 %) K_{MAT} transition temperature is calculated iteratively from Eq. (5b) as:

$$\sum_{i=1}^{n} \frac{d_i.\exp\{0.019.[T_i - T_0]\}}{11 + 77.\exp\{0.019.[T_1 - T_0]\}} - \sum_{i=1}^{n} \frac{\left(K_{MAT_i} - 20\text{MPa}\sqrt{\text{m}} \right)^4.\exp\{0.019.[T_i - T_0]\}}{\left(11 + 77.\exp\{0.019.[T_i - T_0]\} \right)^5} = 0 \quad \text{(5b)}$$

where T_i is individual transition temperature of a specimen, T_0 is median K_{MAT} transition temperature corresponding to 100 MPa√m (= $T_0(\overline{K}_{MAT})$), δ_i is censoring parameter for each individual result (brittle: δi = 1, non-brittle = censored: δi = 0) and K_{MATi} is individual fracture toughness of a specimen.

After obtaining either $T_0(\overline{K}_{MAT})$ corresponding to the 100 MPa√m median (50 %) K_{MAT} transition temperature from Eq. (5b), or $\overline{K}_{MAT}$ corresponding to the median (50 %) failure probability from Eqs (5a) and (3), the procedure then continues to the analysis according to Step 2.

4.2 Procedure according to Step 2: Lower Tail MML Estimation

The flowchart describing the analysis according to Step 2: Lower Tail MML Estimation is shown in Fig. 10 for both the cases of having data at a single temperature and data at various temperatures. The Step 2 procedure itself is mathematically similar to Step 1 procedure in terms of equations used, the only difference being the criteria for the data to be censored.

The idea of the estimation according to Step 2 is to check whether the upper tail of a given data set has a significant influence on the estimated fracture toughness $\overline{K}_{MAT}$. In the case that this would lead to a deviation of the estimate calculated according to Step 1 towards unconservative direction, Step 2 avoids this by censoring the 50 % upper tail of the data set and the remaining 50 % lower tail is then used for the estimation. The Step 2 procedure proceeds as a continuous iteration process, until the 'constant' level for either K_0 or T_0 has been reached, that is, $K_{0i} \geq K_{0i-1}$ and $T_{0i} \leq T_{0i-1}$, respectively.

Firstly, the censoring value for an individual fracture toughness result, K_{CENSi}, is set either as (i) median K_{MAT} ($=\overline{K}_{MAT}$) or is calculated as (ii) $K_{CENSi} = 30 + 70 \cdot \exp\{0.019 \cdot (T_i - T_0)\}$ corresponding to the median (50 %) failure probability level, depending on whether data at a single temperature or data at different temperatures, respectively, are going to be used for the further Step 2 analysis.

In accordance with Step 1, the results associated with brittle and non-brittle failure modes are designated as $\delta i = 1$ and $\delta i = 0$, respectively. For each censored individual result with the true value above the censoring value, i.e. $K_{MATi} > K_{CENSi}$, the toughness value corresponding to this censoring value is used for further estimation of fracture toughness (i.e. $K_{MATi} = K_{CENSi}$) and the result is designated as being non-brittle, i.e. $\delta i = 0$.

The Step 2 procedure then proceeds according to two alternative routes, depending on whether test data is available (a) at a single temperature, or (b) at different temperatures.

4.2.1 Data at a single temperature

In the case of data at a single temperature, two fracture toughness parameters: K_{0i} corresponding to a 63.2 % cumulative failure probability K_{MAT} and median K_{MATi} ($=\overline{K}_{MAT}$) corresponding to the median (50 %) failure probability are calculated for the first iteration round 'i' according to Eq. (5a) and Eq. (3), respectively, see Step 1 procedure in section 4.1.1.

Provided that the fracture toughness of an individual result given by the last iteration round is still lower than that given by the previous round, i.e. $K_{0i} < K_{0i-1}$, the iteration process is continued and this last obtained value, K_{0i}, is thereby set as an input value for further calculation of the next iteration round. This way, the iteration process is continued as long as fracture toughness given by the last iteration round is equal to or higher than the value given by the second last iteration round, i.e. $K_{0i} \geq K_{0i-1}$.

The iteration process then stops, and the two $\overline{K}_{MAT}$ values obtained according to Eq. (5a) and Eq. (3) from Step 1 and Step 2 procedures are taken as reference values to be compared against the $\overline{K}_{MAT}$ estimate that will be obtained from Step 3 procedure in the next stage.

4.2.2 Data at different temperatures

In the case of data at different temperatures, transition temperature T_{0i} corresponding to the transition temperature of an individual result for an iteration round 'i' is calculated iteratively from Eq. (5b), see Step 1 procedure in section 4.1.2.

Provided that the transition temperature given by the last iteration round is still higher than that given by the previous round, i.e. $T_{0i} > T_{0i-1}$, the iteration process is continued and this last obtained value, T0i , is thereby set as an input value for further calculation of the next iteration round. This way, the iteration is continued as long as the transition temperature of an individual result given by the last iteration round is equal to or lower than the value given by the second last iteration round, i.e. $T_{0i} \leq T_{0i-1}$.

The iteration process then stops, and the two $T_0(\overline{K}_{MAT})$ values corresponding to the 100 MPa√m median (50 %) K_{MAT} level and obtained according to Eq. (5b) from Step 1 and Step 2 procedures are taken as reference values to be compared against the $T_0(\overline{K}_{MAT})$ estimate that will be obtained from Step 3 procedure in the next stage.

4.3 Procedure according to Step 3: Minimum Value Estimation

The flowchart describing the analysis according to Step 3: Minimum Value Estimation is shown in Fig. 11. In this procedure, single data is used for estimate of either median K_{MAT} $(=\overline{K}_{MAT})$ or $T_0(\overline{K}_{MAT})$ in the cases of data at one single temperature and at different temperatures, respectively. Thus, only the minimum test result corresponding to one single temperature is taken as an input value for the estimation.

The idea of minimum value estimation according to Step 3 is to check material inhomogeneity in a given data set. This is to avoid unconservative fracture toughness estimates which may arise if median (50 %) fracture toughness is used for a material expressing significant inhomogeneity.

Therefore, a criteria is set to the allowable difference between the median (50 %) fracture toughness and the lower-bound (5 %) fracture toughness level, for both data at a single temperature and data at different temperatures. This is to assess the significance of a single minimum fracture toughness test result in a given data set.

4.3.1 Data at a single temperature

In the case of data at a single temperature, two fracture toughness parameters: K_0 and $\overline{K}_{MAT}$ are calculated, similarly to Step 1 and Step 2 procedures, see sections 4.1.1 and 4.2.1.

Of these two, K_0 corresponding to a 63.2 % cumulative failure probability K_{MAT} is calculated according to Eq. (6a) as:

$$K_0 = 20\text{MPa}\sqrt{m} + \left(K_{MAT_{min}} - 20\text{MPa}\sqrt{m}\right).\left(\frac{N}{\text{In } 2}\right)^{1/4} \quad \text{.....(6a)}$$

where K_{MATmin} is a minimum individual K_{MAT} value in a given data set and N is the total number of tests.

It is seen that Eq. (6a) is basically similar to Eq. (5a), with the exception of now using the minimum individual K_{MAT} value, K_{MATmin}, instead of a number of different individual values (K_{MATi}). Parameter

N, in turn, takes into account the influence of the total number of results in a given data set on K_0 estimate, increasing number of tests having a positive influence on K_0.

Using K_0 obtained from Eq. (6a), $\overline{K}_{MAT}$ corresponding to the 50 % failure probability is calculated according to Eq. (3), similarly to that according to Step 1 and 2 procedures in sections 4.1 and 4.2.

Provided that the fracture toughness K_0 according to Step 3 and calculated from Eq. (6a) now is more than 10 % lower than the fracture toughness according to Eq. (5a) in Steps 1 and 2 - whichever of them is lower, i.e. $K_{0step3} < 0.9\ K_{0step1\&2}$, the single minimum test result in a given data set that was used to calculate K_0 is considered as significant. Thus, the Step 3 estimate for K_0 is taken for further calculations of the final fracture toughness estimate, i.e. $\overline{K}_{MAT}$ fracture toughness, together with its probability distribution $P\{K_{MAT}\}$, see section 4.4.

In the case that the fracture toughness K_0 according to Step 3 and calculated from Eq. (6a) remains equal to or less than 10 % below the fracture toughness according to Eq. (5b) in Steps 1 and 2, the single minimum test result in a given data set is considered as non-significant. Consequently, the lower one of the Step 1 and Step 2 estimates for K_0 is taken for calculating the final fracture toughness estimate, i.e. $\overline{K}_{MAT}$ fracture toughness, together with its probability distribution $P\{K_{MAT}\}$, see section 4.4.

4.3.2 Data at different temperatures

In the case of data at different temperatures, transition temperature T_0 corresponding to the 100 MPa√m median (50 %) K_{MAT} transition temperature is taken as a maximum of the individual values calculated according to Eq. (6b) as:

$$T_0 = \max\left| T_i - \frac{\mathrm{In}\left\{\dfrac{\left(K_{MAT_i} - 20\mathrm{MPa}\sqrt{m}\right).\left(\dfrac{N}{\mathrm{In}\ 2}\right)^{1/4} - 11\mathrm{MPa}\sqrt{m}}{77}\right\}}{0.019}\left(d_i = 1\right)\right. \quad \text{.....(6b)}$$

where T_i is individual transition temperature of a specimen, K_{MATi} is individual fracture toughness of a specimen and N is the total number of tests. The expression assumes the use of brittle test result by designating $\delta_i = 1$.

Provided that the transition temperature T_0 according to Step 3 and calculated from Eq. (6b) now is more than 8 °C above the transition temperature according to Eq. (5b) in Steps 1 and 2 - whichever of them is higher, the single minimum test result in a given data set that was used to calculate T_0 is considered as significant. Thus, the Step 3 estimate for T_0 is taken for further calculations of the final fracture toughness estimate, i.e. $\overline{K}_{MAT}$ fracture toughness, together with its probability distribution $P\{K_{MAT}\}$, see section 4.4.

In the case that the transition temperature T_0 according to Step 3 and calculated from Eq. (6b) remains equal to or less than 8 °C above the transition temperature according to Eq. (5b) in Steps 1 and 2, the single minimum test result in a given data set is considered as non-significant. Consequently, the higher one of the Step 1 and Step 2 estimates for T_0 is now taken for the calculation of the final fracture toughness estimate, i.e. $\overline{K}_{MAT}$ fracture toughness, together with its probability distribution $P\{K_{MAT}\}$, see section 4.4.

4.4 Determination of final K_{MAT} estimate ($\overline{K}_{MAT}$) and its probability distribution $P\{K_{MAT}\}$

In the last stage of the procedure, the final $\overline{K}_{MAT}$ fracture toughness estimate, together with its probability distribution $P\{K_{MAT}\}$ is calculated. For this, the calculation procedure uses the estimates obtained either according to Step 1, 2 or 3 procedure ($T_{0(step1-3)}$, $K_{0(step1-3)}$) and which hence are chosen according to the criteria given in the context of each step.

4.4.1 $\overline{K}_{MAT}$ for data at a single temperature

In the case of data at a single temperature, the median K_{MAT} fracture toughness estimate ($\overline{K}_{MAT}$) is simply calculated according to Eq. (3) by using $K_{0(step1-3)}$ as an input value, see sections 4.1.1 - 4.1.3, as:

$$\overline{K}_{MAT} = 20\text{MPa}\sqrt{m} + \left(K_0 - 20\text{MPa}\sqrt{m}\right).0.91 \quad \text{.....(3)}$$

4.4.2 $\overline{K}_{MAT}$ for data at different temperatures

In the case of data at different temperatures, the median K_{MAT} fracture toughness estimate ($\overline{K}_{MAT}$) is calculated according to Eq. (4b) by using $T_{0(step1-3)}$ as an input value, as:

$$\overline{K}_{MAT} = 30 + 70.\exp\left\{0.019.\left(T - T_0\right)\right\} \quad \text{.....(4b)}$$

Alternatively, $\overline{K}_{MAT}$ can also be approximated by using Eq. (4a) and Eq. (3) in combination, as:

$$K_0 \approx 31 + 77.\exp\left\{0.019.\left(T - T_0\right)\right\} \quad \text{.....(4a)}$$

$$\overline{K}_{MAT} = 20\text{MPa}\sqrt{m} + \left(K_0 - 20\text{MPa}\sqrt{m}\right).0.91 \quad \text{.....(3)}$$

4.4.3 Probability distribution of K_{MAT} estimate

The probability distribution corresponding to the median K_{MAT} estimate, $P\{K_{MAT}\}$, is calculated according to Eq. (2) as:

$$P\{K_{MAT}\} = 1 - \exp - \left\{\frac{K_{MAT} - 20\text{MPa}\sqrt{m}}{K_0 - 20\text{MPa}\sqrt{m}}\right\}^4 \quad \text{.....(2)}$$

4.4.4 Size-re-adjustment of $\overline{K}_{MAT}$ estimate

For the assessment, the hereby obtained median K_{MAT} estimate corresponding to 'normalisation' fracture toughness (B = 25 mm), K_{MAT25}, is size-re-adjusted to correspond to an estimate related to any required crack size (=> specimen size) by using Eq. (1) given in section 4.1.

5. TREATMENT OF DUCTILE FRACTURE DATA

Even in the case that ductile fracture data is all that is available for the assessment, the philosophy of design of a structure can, apart from the type of the available data, be based either on (i) "design against brittle fracture" or (ii) "design against ductile fracture". As shown in the flow chart in Fig. 3, for structures with their operating temperature in the transition regime or close to the lower shelf, the recommended practice is the former, in the case which the approach is, again, based on the "Master Curve" prediction but, now, using the minimum data treated as brittle.

For ferritic steels (i) on the upper shelf of fracture toughness, or for (ii) materials which do not exhibit brittle cleavage fracture, design against brittle fracture is, of course, not realistic. Nevertheless, for these cases, it is also necessary to specify the correct treatment of data for obtaining a reliable fracture toughness estimate [19].

5.1 General characteristics of ductile fracture

The ductile fracture process which consists of micro-void formation, growth and coalescence, is usually characterised, in terms of J integral or crack opening displacement, with the associated amount of stable crack extension, Δa. Consequently, a single value of fracture toughness is not appropriate. The resistance curve, J - Δa say, is often measured in so-called single specimen tests with the crack extension Δa deduced by an indirect method such as the elastic unloading compliance method or by electrical potential drop techniques [19].

Ductile crack growth has usually a much smaller scatter than brittle cleavage fracture. The main source of uncertainty and scatter in ductile fracture is the test performance and data analysis, not the behaviour or macroscopical inhomogeneity of the material. This is true especially for single specimen tests.

Here, as discussed in Section 1, it is assumed that, irrespective of the type of the original toughness data available, it has been converted into a stress intensity factor equivalent, K_{mat} . However, in contrast to Sections 2-4, a single value of K_{mat} with an associated probability distribution is not defined. Instead, it is assumed that values of K_{mat} are available at an engineering definition of initiation and at a number of values of crack growth, Δa. Initiation may be determined according to a recognised standard and K_{mat} would then be equal to $K_{0.2}$ or $K_{0.2/BL}$, say, as defined by the standard. Note that subsequent data are assumed to be defined by values $K_{mat}(\Delta a)$ at specified amounts of crack extension rather than by the slope of a resistance curve. Bounds to the latter in conjunction with bounds to an initiation value can lead to unrepresentative results when there are correlations between initiation toughness and the slope of the resistance curve [19].

5.2 Approaches for treatment of ductile fracture data

The approach adopted for the treatment of ductile fracture data depends on the design philosophy of a structure, as well as the number of specimens tested.

5.2.1 Design against brittle fracture

If the possibility of brittle cleavage fracture in the actual structure cannot be excluded, the minimum initiation value should be treated as a cleavage fracture event. Consequently, the Step 3 brittle fracture analysis procedure should be followed (see section 4.3).

Due to insufficient knowledge of the extent to which all the factors (e.g. constraint, mismatch, scatter, definition of "initiation", testing, etc.) influencing the ductile fracture behaviour should actually be taken into account in the prediction, this approach is considered to be informative, only, see Fig. 3.

5.2.2 Design against ductile fracture

For ferritic steels (i) on the upper shelf of fracture toughness, or for (ii) materials which do not exhibit brittle cleavage fracture, design against brittle fracture is not realistic. Therefore, a different approach must be chosen. The approach here follows the methodology proposed by NEL [19].

5.2.2.1 *Limited amount of material - three specimens*

When limited material is available, the minimum value of K_{mat} obtained from three (3) normally identical test specimens may be used as a lower bound estimate to the fracture toughness. For values beyond initiation, $K_{mat}(\Delta a)$ must be evaluated from the test specimen data at the same amount of crack growth in each test.

Scatter in the data should be assessed by comparing the maximum and minimum values with the average value from each set. Where the minimum value is less than 0.7 times the average of the three results or the maximum value is greater than 1.4 times the average, then more specimens should be tested.

5.2.2.2 *Adequate amount of material - more than three specimens*

For more than three specimens, the following procedure is proposed: (i) evaluate the *mean toughness* ($\overline{K}_{mat}$), (ii) evaluate the *distribution of toughness* (S) and (iii) evaluate the *confidence limit to the mean toughness*.

The mean toughness ($\overline{K}_{mat}$) is simply given as:

$$K_{mat} = \frac{\sum_{i=1}^{n} K_{mat,i}}{n} \qquad \text{.....(7)}$$

where n is the number of individual $K_{mat,i}$ data points, at initiation or for a specific value of Δa.

To evaluate the distribution of toughness, the variance to the data (S) can be defined as:

$$S^2 = \frac{\sum_{i=1}^{n} \left(K_{mat,i} - \overline{K}_{mat}\right)^2}{(n-1)} \qquad \text{.....(8)}$$

where n is the number of individual $K_{mat,i}$ data points, at initiation or for a specific value of Δa, $K_{mat,i}$ is an individual data point and $\overline{K}_{mat}$ is the mean toughness.

Confidence limits to the data ($K_{mat'\propto}$) are then given by:

$$K_{mat\propto} = \overline{K}_{mat} \pm t_{\propto} S \qquad (9)$$

where $\propto$ is the confidence limit and $t_{\propto}$ is the corresponding value of Student's distribution at (n - 1) degrees of freedom.

The scatter in ductile fracture toughness data has been found to be broadly independent of the level of crack extension, Section 7. Therefore, when only limited data are available, the standard deviation at one value of Δa, 1 mm say, may be used to estimate scatter at other values of K_{mat}. The expected scatter in the J-R curve is best described as a normally distributed absolute scatter in J-integral values. For a range of materials, the scatter has been found to be typically less than 10 % of the mean value corresponding to a crack extension of 1 mm. The standard deviation therefore is conservatively described as 10 % of the mean J-integral corresponding to a crack growth of 1 mm, see Fig. 12.

In some cases, confidence limits to the mean of the data are required. These are obtained in a similar manner to Eq. (9) as:

$$\overline{K}_{mat'\propto} = \overline{K}_{mta} \pm t_{\propto} S / \sqrt{n} \qquad (10)$$

Clearly, wide bounds to the data are obtained when only few specimens have been tested, see Fig. 12. While more vigorous statistical treatments of data may be attempted, it is preferable to test more specimens to increase confidence [19].

6. ADDITIONAL GUIDANCE AND LIMITATIONS

As will be demonstrated in the Validation Section, the present procedure for treatment of brittle fracture data consisting of three different steps, enables a reliable fracture toughness estimate to be obtained for various forms of data sets containing results from both homogeneous and inhomogeneous material. Thus, the procedure is expected to work well not only for base materials but also in the case of welded joint's weld metals and heat-affected zones. Therefore, there are no major limitations that need to be taken into account.

Some additional guidance, however, can be given. First of all, one must make sure that the data which is used for the analysis, is really representative to the application of the structure or a component being assessed. When it comes to welded joints, this means, for instance, that the data should include valid results from all 'critical' zones of a weldment: i.e. weld metal, heat-affected zone and base material. This, of course, is more or less a prerequisite of all structural integrity assessment methods, and hence not a limitation of this particular procedure, only. Nevertheless, if some microstructurally brittle region has not been sampled in the experimental fracture toughness testing, the procedure cannot overcome this lack of essential data. To overcome this may call for detailed post-test sectioning and metallography of tested specimens, which, of course, is already a demand which is included in many current testing standards.

On the other hand, it is also a question of criteria which is set to a 'valid' result. A current practice is to require some minimum amount of coarse-grained HAZ, say, 15...20 % to be sampled by the fatigue

pre-crack in the CTOD test, in order for a result to be valid. The idea is naturally to increase the probability to sample the most brittle zones with the associated minimum values. The experience [15], however, has shown that although this may apply to a sufficiently large data set, when testing approximately 3 parallels - as many standards do not require more - the one giving the lowest dc -value is not necessary associated at all to the largest amount of coarse-grained HAZ in a specimen in a data set. In fact, rejecting those having less than 15 % coarse-grained HAZ ahead of a fatigued pre-crack as invalid, would have led to the rejection of the minimum value in a data set [15]. Obviously, the question of how to determine these kind of criteria, as well as of how relevant they actually are, should be carefully considered, but is perhaps a matter of testing standards rather than the present procedure.

Attention should also be paid to the difference between the intended operating temperature of a structure and the testing temperature of the results in a given data set. This is not a problem, if ductile fracture data is used for failure assessment of a structure intended for low service temperatures, because in that case the data is advised to be treated as brittle. In the opposite situation, however, problems may rise - that is, if only brittle fracture data is available for the assessment of a structure that is going to be used at high temperatures close to the material's upper-shelf, i.e. in the ductile fracture regime. In such a case, it is advised to do additional testing in order to obtain relevant ductile fracture data for the assessment.

From a design viewpoint, the advantage of the procedure is that it enables the fracture toughness of an inhomogeneous material to be assessed, as well as can quantify the significance of a single minimum value in a given data set. From a metallurgical viewpoint, it can be claimed that this allows for ignoring the metallurgical reason for this low individual value, unless the findings of post-test sectioning metallography from the experimental data that is going to be used, are available in the assessment stage.

Finally, it is important to realise that for the final structural integrity assessment, suitable confidence and probability levels should be chosen bearing in mind the criticality of the component/structural member in question. Therefore, for very critical structural parts, a more conservative confidence level is advised to be chosen.

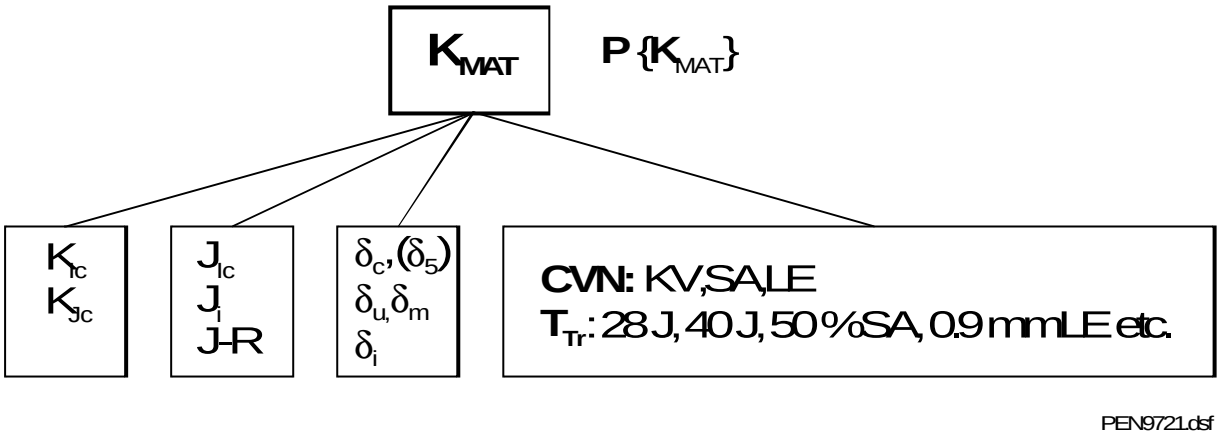

Fig. 1 - Schematic illustration of the different types of toughness data for obtaining K_{mat} and $P\{K_{mat}\}$.

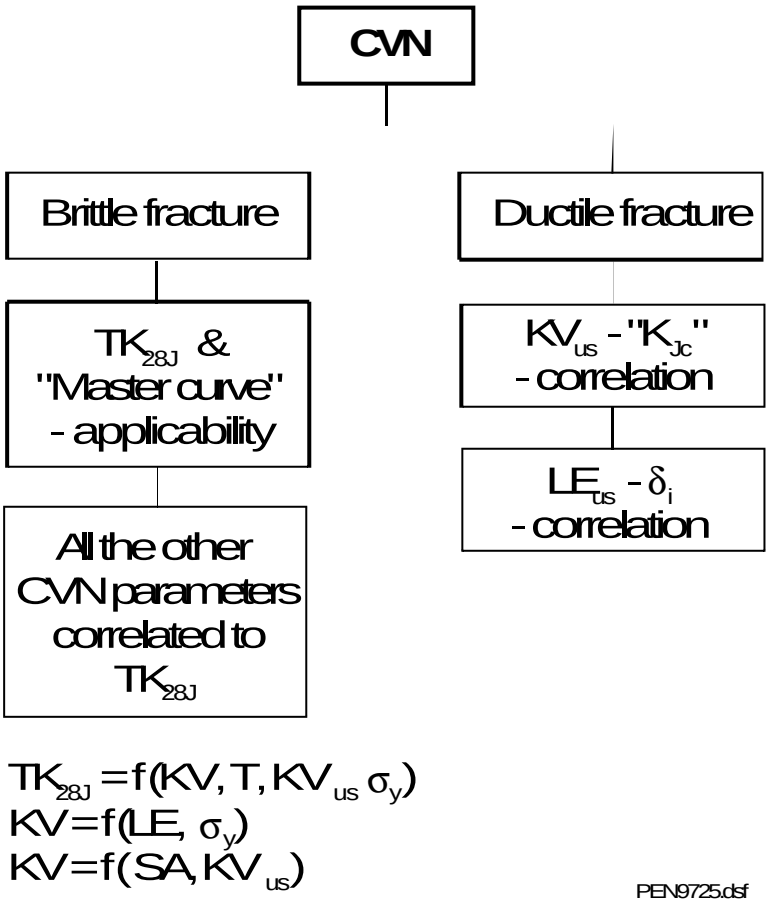

Fig. 2 - Treatment of Charpy-V based data.

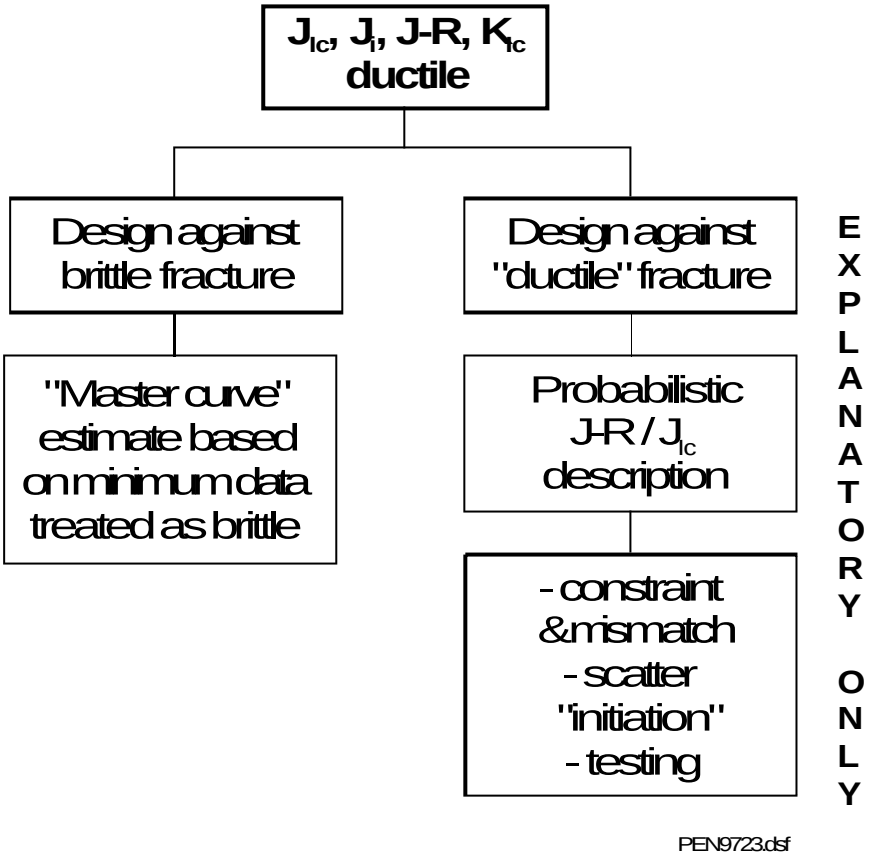

Fig. 3 - Treatment of ductile fracture toughness data depending on design philosophy.

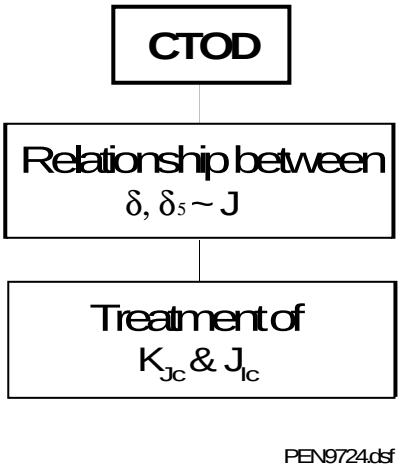

Fig. 4 - Treatment of CTOD based data.

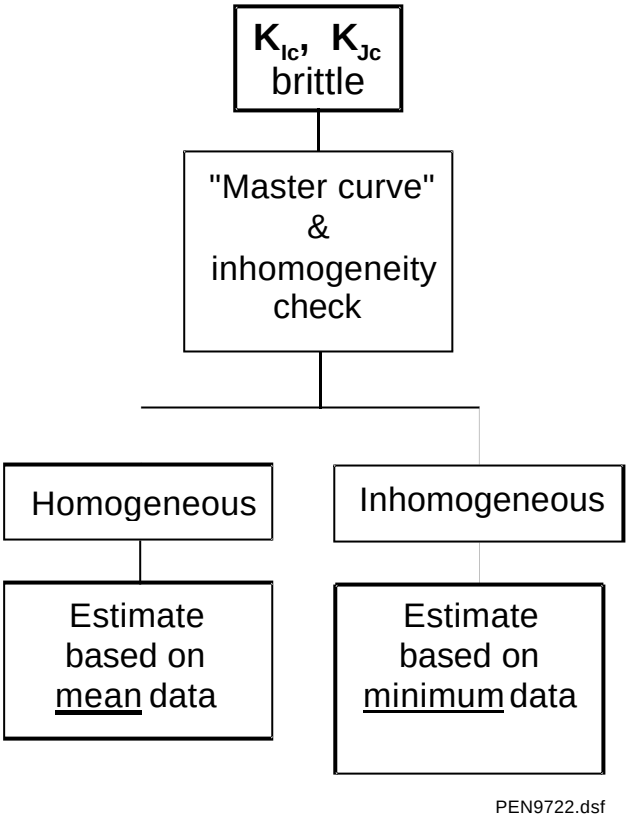

Fig. 5 - Treatment of brittle fracture toughness (K_{IC} , K_{JC}) data.

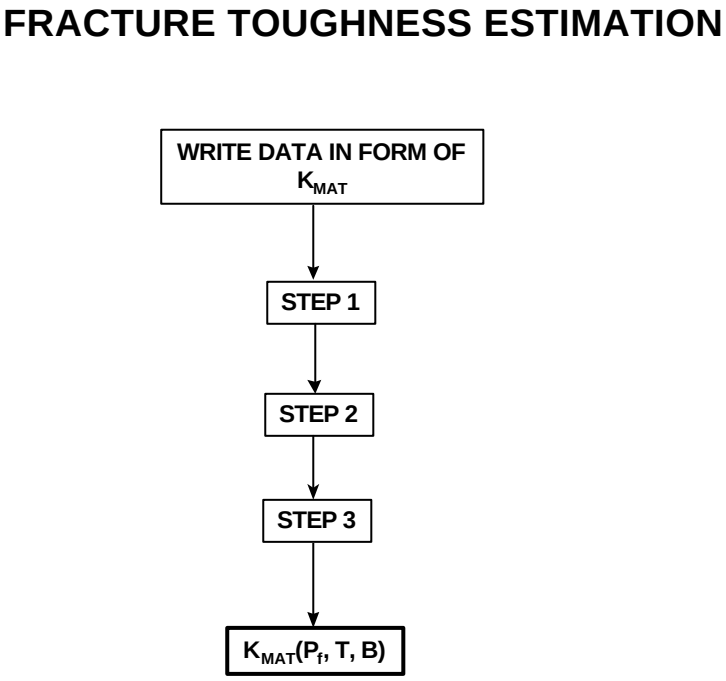

Fig. 6 - Flowchart of the Fracture Toughness Estimation Procedure for obtaining K_{MAT}.

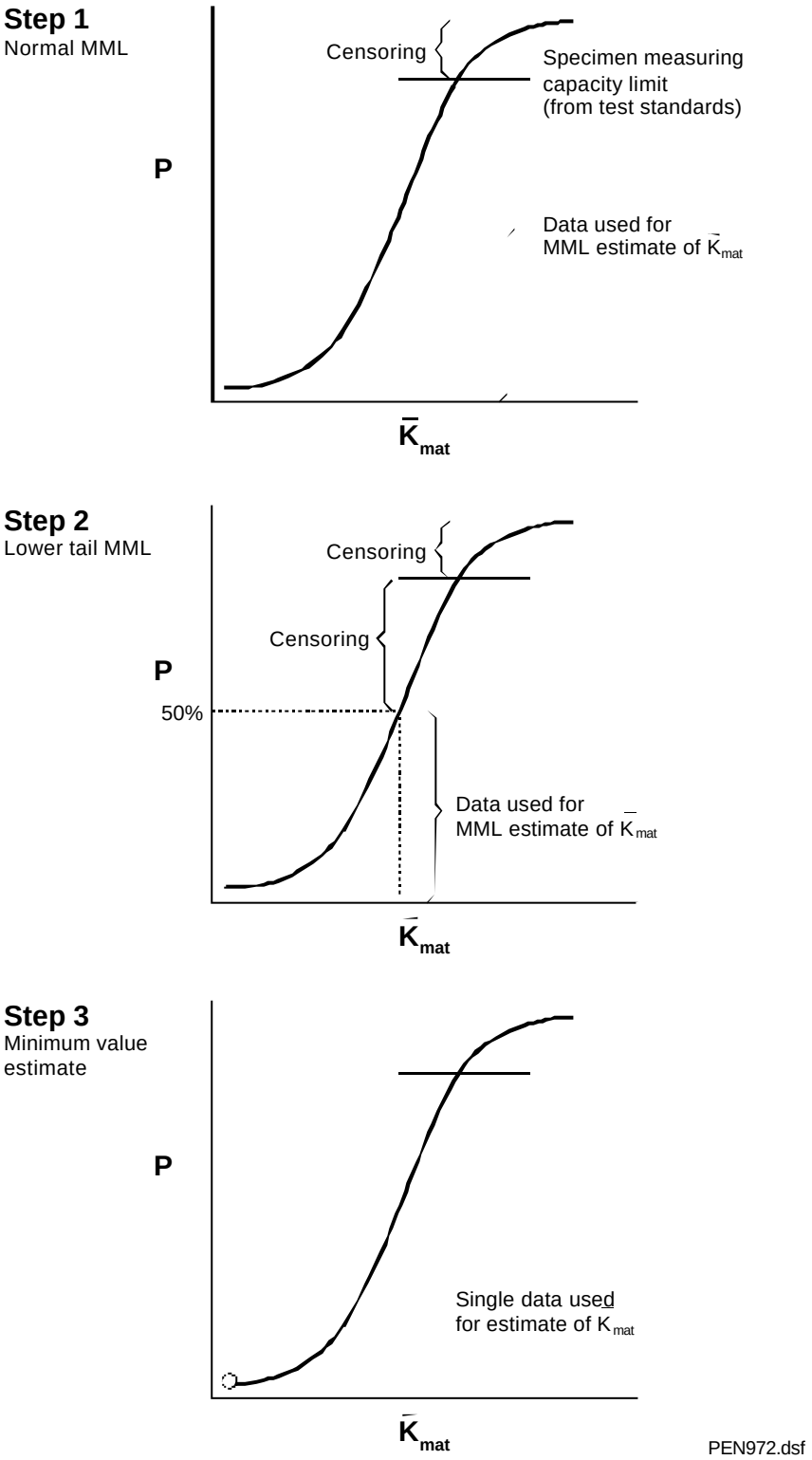

Fig. 7 - Principles of the treatment of fracture toughness data in the case of data at a single temperature - a) *Step 1*: Normal MML Estimation, b) *Step 2*: Lower-Tail MML Estimation and c) *Step 3*: Minimum Value Estimation.

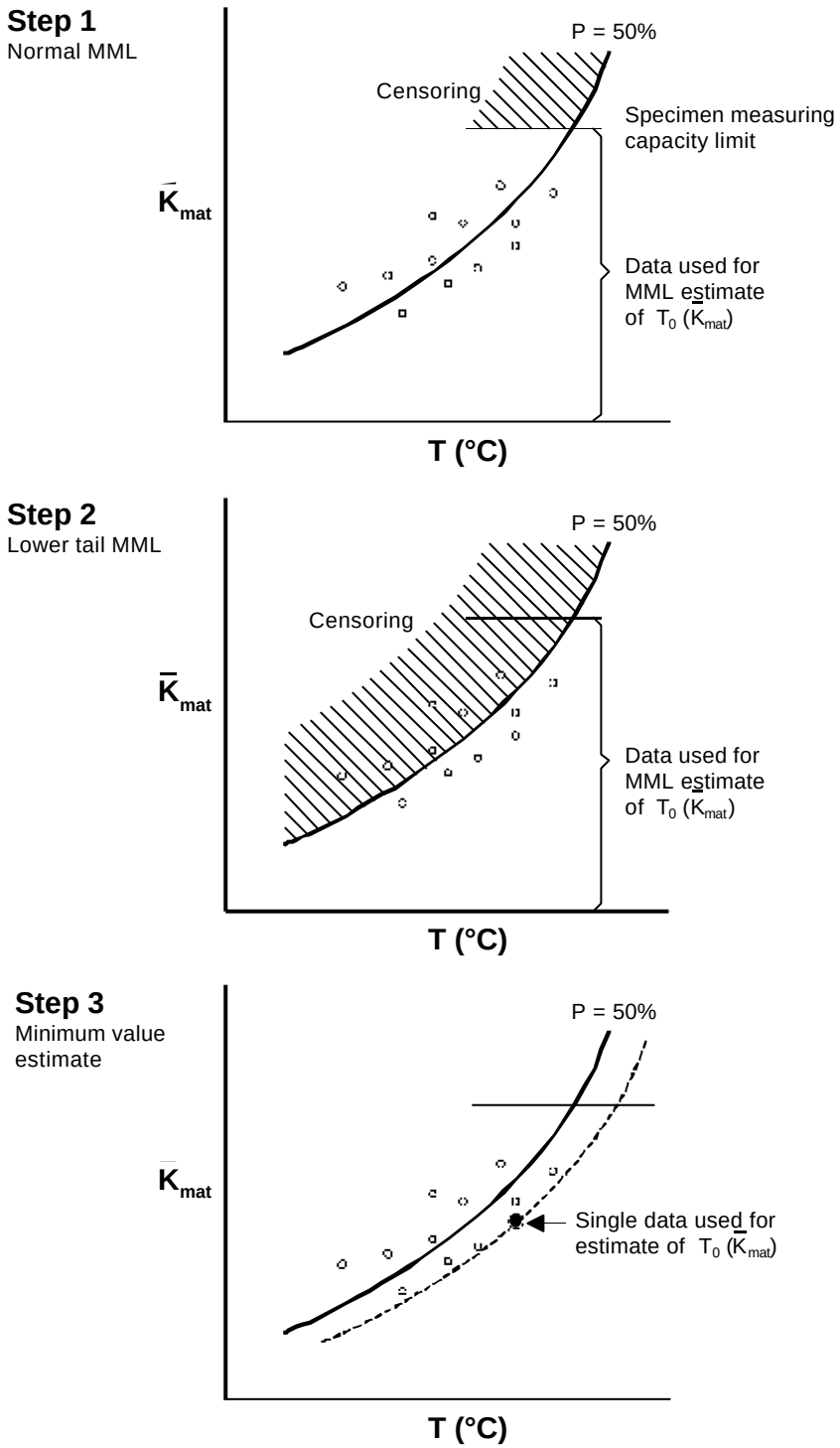

Fig. 8 - Principles of the treatment of fracture toughness data in the case of data at different temperatures - a) *Step 1*: Normal MML Estimation, b) *Step 2*: Lower-Tail MML Estimation and c) *Step 3*: Minimum Value Estimation.

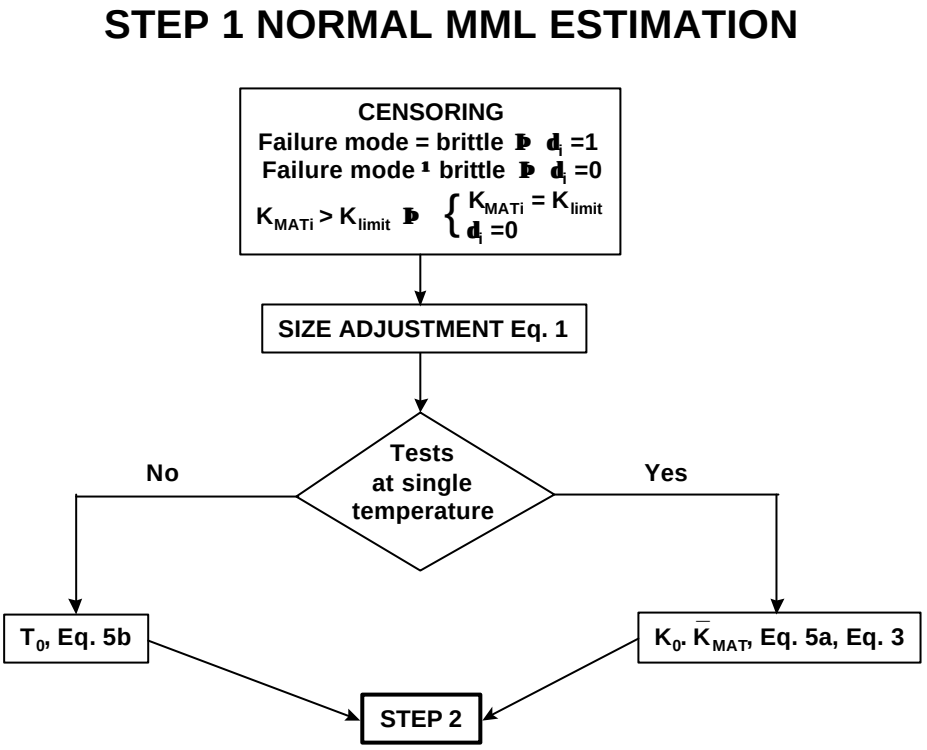

Fig. 9 - Fracture Toughness Data Treatment Procedure according to Step 1: Normal MML Estimation.

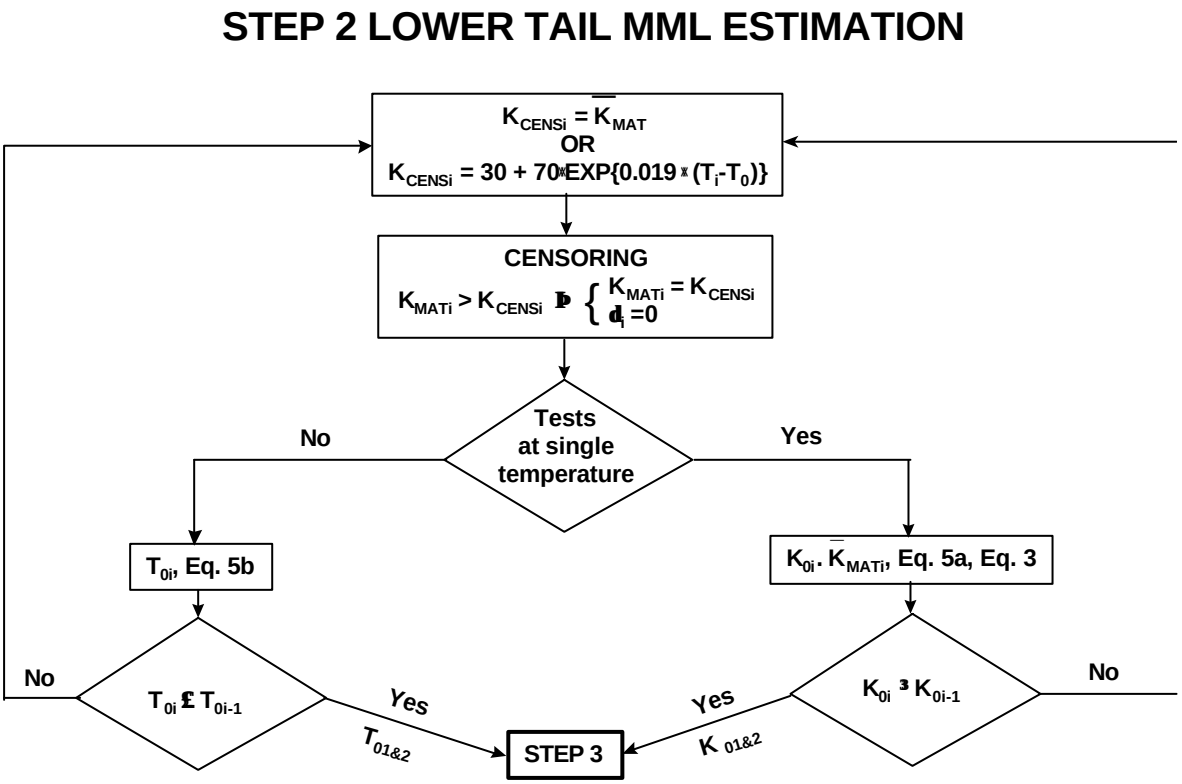

Fig. 10 - Fracture Toughness Data Treatment Procedure according to Step 2: Lower-Tail MML Estimation.

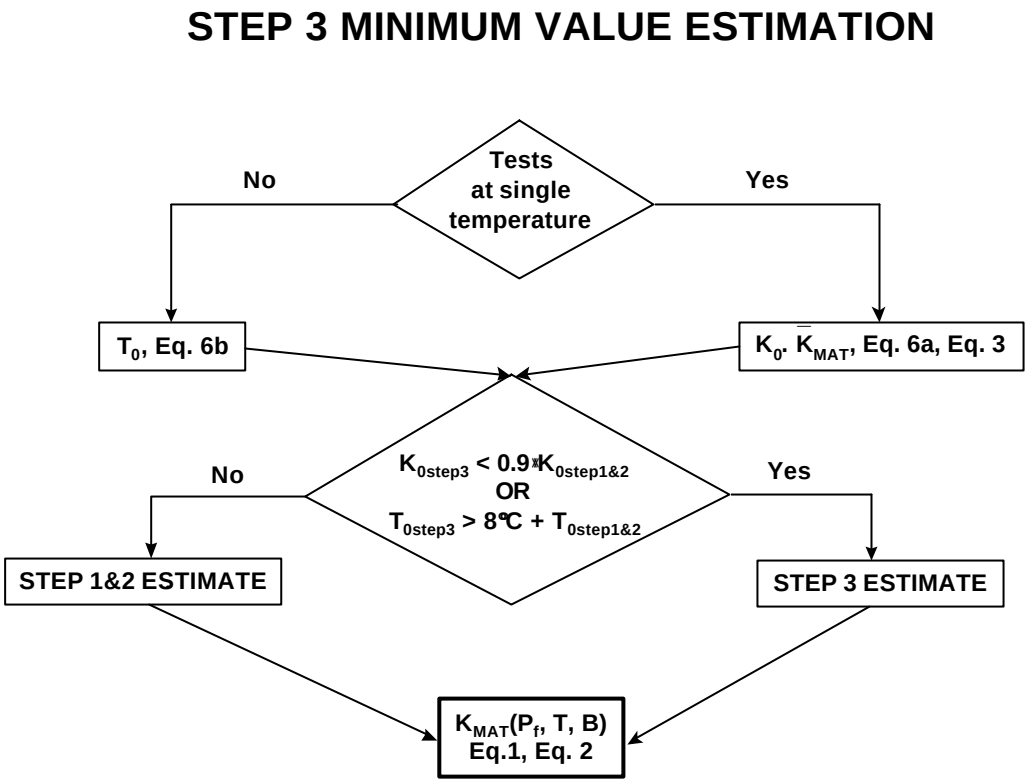

Fig. 11 - Fracture Toughness Data Treatment Procedure according to Step 3: Minimun Value Estimation.

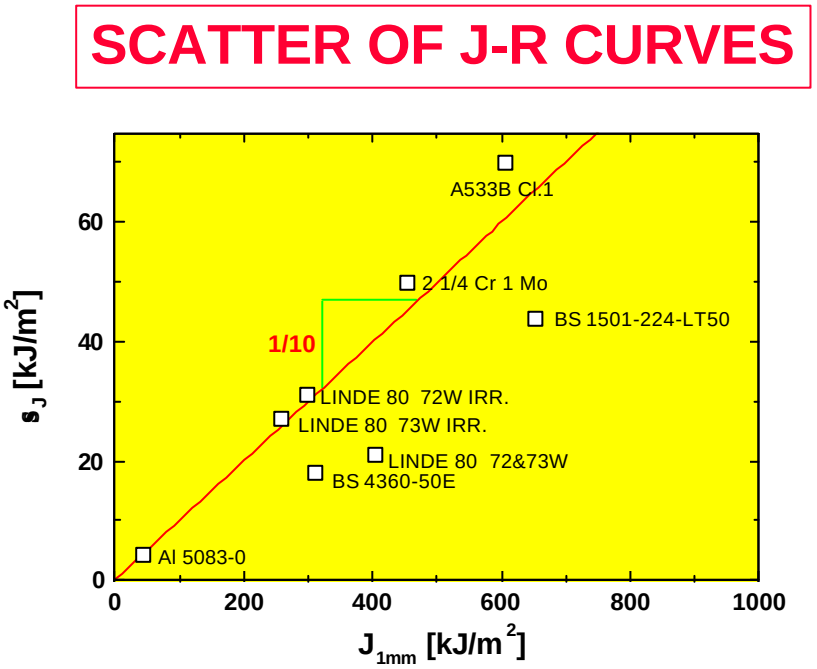

Fig. 12 - Scatter in J-R curve data, based on multispecimen test results.

7. VALIDATION SECTION

The Validation Section consists of three parts:

(i) Validation of each Step (1 to 3) of the procedure using experimental parent plate and weld metal data from three TWI Round Robins

(ii) Numerical check of accuracy of the procedure using Monte-Carlo simulation for both homogeneous and inhomogeneous (arbitrary) data - i.e. 'sensitivity analysis'

(iii) Validation of scatter in VTT's ductile fracture data presented in the form of J-R -curves

Part 1 Validation

The first part of this section covers validation of the three different Steps of the Procedure using experimental data from three TWI Round Robins and data from the OakRidge ORNL 1+SST - program. The data consist of results from both weld metals and parent plates. Only the PTSE-2 data in Figs 17-18 correspond to a macroscopically homogeneous material. The validation of Steps 1 to 3 for data at a single temperature (K_0) and data at different temperatures $T_0(K_{JC})$ are presented in Figs. 14-16 and 17-19, respectively.

Fig. 13 shows the coordinates of the s.c. 'Master Curve Failure Probability Diagram', which is used to present the results of the validation according to Steps 1 to 3. The advantages of the use of 'K_{IC} [MPa]' versus 'Probability $[\{\ln 1 / (1 - P_f)\}^{1/4}]$' coordinates are (i) a clear description of K_{min}, (ii) linear toughness representation and (iii) nearly symmetric rank probability confidence bounds.

Examples of the validation of the TWI data for one parent plate and weld metals at two different temperatures (-60 and -20 °C) are shown in terms of K_0 in Figs 14-16.

It is seen that for the parent plate data in Fig. 14, Step 3 produces a K_0 estimate of more than 10 % below that of Steps 1 and 2. Thus, the Step 3 estimate is taken for final analysis. Accordingly, the data for weld metals in Figs 15 and 16 yield Step 3 and Step 2 estimates, respectively. Thus, in all cases, performing only Step 1: Normal MML Estimation without censoring of the upper-Tail data would have been insufficient by producing higher estimate than what was finally taken, i.e. a probably unconservative estimate of fracture toughness.

Figs. 17-19 show the validation of the OakRidge (B = 25 mm) and VTT (B = 10 mm) data for two parent plates PTSE-1 A508 and PTSE-2 A387 are shown in terms of T_0 (versus K_{JC}). The data consists of results associated with two specimen sizes (B): 25 mm (PTSE-2 A 387, PTSE-1 A508) and 10 mm (PTSE-2 A 387).

In the case of PTSE-2 A387 data (B = 25 mm) in Fig. 17, Steps 1 and 2 yield equivalent T_0 estimates, whilst Step 3 produces and estimate below that of Steps 1 and 2. Thus, Step 2 (= Step 1) estimate is taken for final analysis. Accordingly, the data for PTSE-2 A387 (B = 10 mm) and PTSE-1 A508 (B = 25 mm) in Figs 18 and 19 yield Step 2 and Step 3 estimates.

The result of going for Step 3: Minimum Value Estimate in the case of the data in Fig. 19 is in accordance with a pronounced inhomogeneity and resulting large scatter (and a large number of ductile fracture results) of the data in Fig. 19, as compared to the data in Fig. 17 or 18. It is also worth

highlighting that despite of the two different specimen sizes of 25 and 10 mm, they both yield almost identical T_0 estimates of 27 and 30 °C, respectively.

Part 1 Validation thereby demonstrates that the adoption of three different steps in the procedure enables a reliable fracture toughness estimate to be obtained for various forms of data sets containing results from both relatively homogeneous and severely inhomogeneous material. Thus, the procedure is expected to work well not only for base materials but also in the case of welded joint's weld metals and heat-affected zones.

Part 2 Validation

The second part of the validation section comprises a numerical check of accuracy of the procedure using Monte-Carlo simulation for arbitrary data, see Figs 20-24. This check also serves as a kind of 'sensitivity analysis' of the procedure.

Fig. 20 presents the accuracy check of normal MML K_0 estimate, whereas Fig. 21 shows the accuracy check of 'conservative' MML K_0 estimate, both for 'homogeneous' distribution and plotted as a function of the total number of tests (N). It is seen that replacing the 'normal' estimate with a 'conservative' one increases the confidence level to obtain a conservative estimate of the mean toughness from about 50 % up to 75 %. It is worth noticing that in both cases, the confidence lines appear to be relatively flat. This means that unless the total number of tests remains very low, say, 1 to 2, increasing the number of tests has a relatively small influence on the confidence level of the data. Particularly in the case of a 'conservative' MML estimate, it is seen that the 75 % confidence level is reached already with a minimum of 4-5 tests.

Fig. 22 presents an optimised fitting for 'inhomogeneous' K_0 distribution according to Steps 1 to 3 using a large data set of 10 000 arbitrary tests and assuming equal probabilities (i.e. 50 %) of having either "low toughness" material/result (K_{01} = 100 MPa√m) or "high toughness" material/result (K_{02} = 200 MPa√m). It is seen that Step 2: Lower-Tail MML Estimation produces the lowest and hence 'correct' estimate of K_0, with Step 3: Minimum Value Estimation coming pretty close to Step 2 estimate.

In Fig. 23a-d, Monte Carlo simulation has been performed for four different arbitrary data sets of 'inhomogeneous' distribution, with same assumptions for K_{01} and K_{02}, but now using a substantially smaller data set of 50 tests. It is seen that reducing the number of tests does not impair the accuracy of the procedure to any significant extent. In all four cases, either Step 2: Lower-Tail MML Estimation (Figs. 23b, 23d) or Step 3: Minimum Value Estimation (Figs. 23a, 23c) produces a significantly lower K_0 estimate than would have been obtained by applying Step 1: Normal MML Estimation alone. The estimates according to Steps 2 and 3 also come very close to the K_{01} assumption of 100 MPa√m, i.e. "low toughness" material, whereas the estimates according to Step 1: Normal MML Estimation lie close to the K_{02} assumption of 200 MPa√m, i.e. "high toughness" material.

Finally, Fig. 24 shows the accuracy of 'conservative' K_0 estimate of 'inhomogeneous' distribution as a function of the total number of tests (N), again assuming equal probabilities (i.e. 50 %) of having either "low toughness" material/result (K01 = 100 MPa√m) or "high toughness" material/result (K_{02} = 200 MPa√m). It is seen that now taking 125...130 MPa√m level as K_0 estimate - as suggested by the optimised fitting of 'inhomogeneous' K_0 distribution in Fig. 22, a 75 % probability of having a 'conservative' estimate can be obtained with a minimum of 6 tests.

As a result, Part 2 validation clearly demonstrates that with a confidence of 75 %, a conservative and hence 'safe' estimate of the mean toughness is obtained. The procedure thereby produces a realistic description of the lower tail probabilities. The verification calculations show that with as few as six tests

(i.e. 6 parallel specimens), the probability of having a conservative, 'safe' estimate is approximately 75 %. This can be considered quite adequate for structural integrity assessment.

Part 3 Validation

The third part of the validation section comprises validation of scatter in ductile fracture data, presented in the form of multispecimen J-R -curves for 7 different steels and one aluminium in Figs 25-32. The data is formulated in a way that the upper figures present absolute J values as a function of crack growth (Δa) - with some of the data including also the predicted 5 % and 95 % confidence limits, whilst the lower figures show the scatter in J values (J_{error}) at different crack growth (Δa) levels, together with 5 % and 95 % scatter bands and absolute σ_{error} -values.

It is seen that the mathematical relationship between absolute J -integral values and crack growth (Δa) can be approximated as a power law function of a form: $J = a \cdot (\Delta a)^b$, where 'a' is material dependent and 'b' obtains values between 0.4 - 0.6, i.e. it is quite close to the square root.

Part 3 Validation demonstrates that the scatter in J values which is actually quite small does not appear to depend on the absolute crack growth value and is best described as a normally distributed absolute scatter in J-integral values.

For the cases where only ductile fracture data is available, but the possibility of brittle fracture in the structure cannot be excluded, the Step 3 brittle fracture analysis procedure: Minimum Value Estimation that treats the initiation value as a cleavage fracture event can be reliably used for fracture toughness estimation in the case of macroscopically homogeneous material.

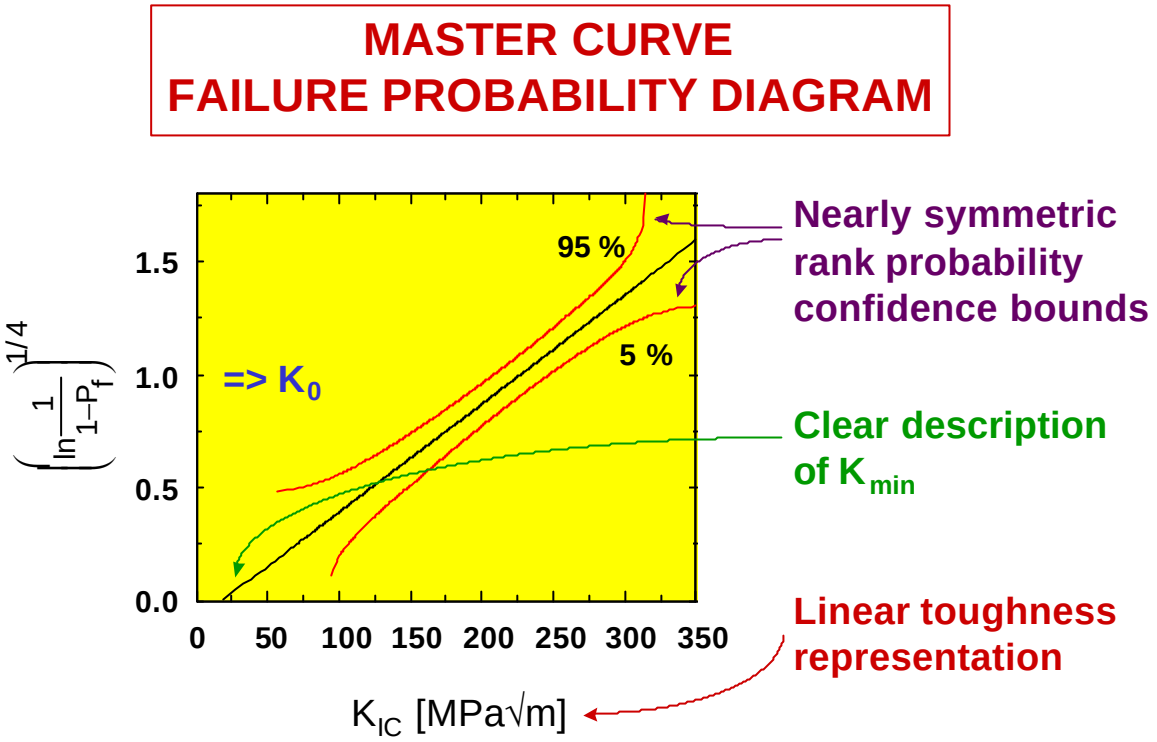

Fig. 13 - Master-Curve Failure Probability Diagram.

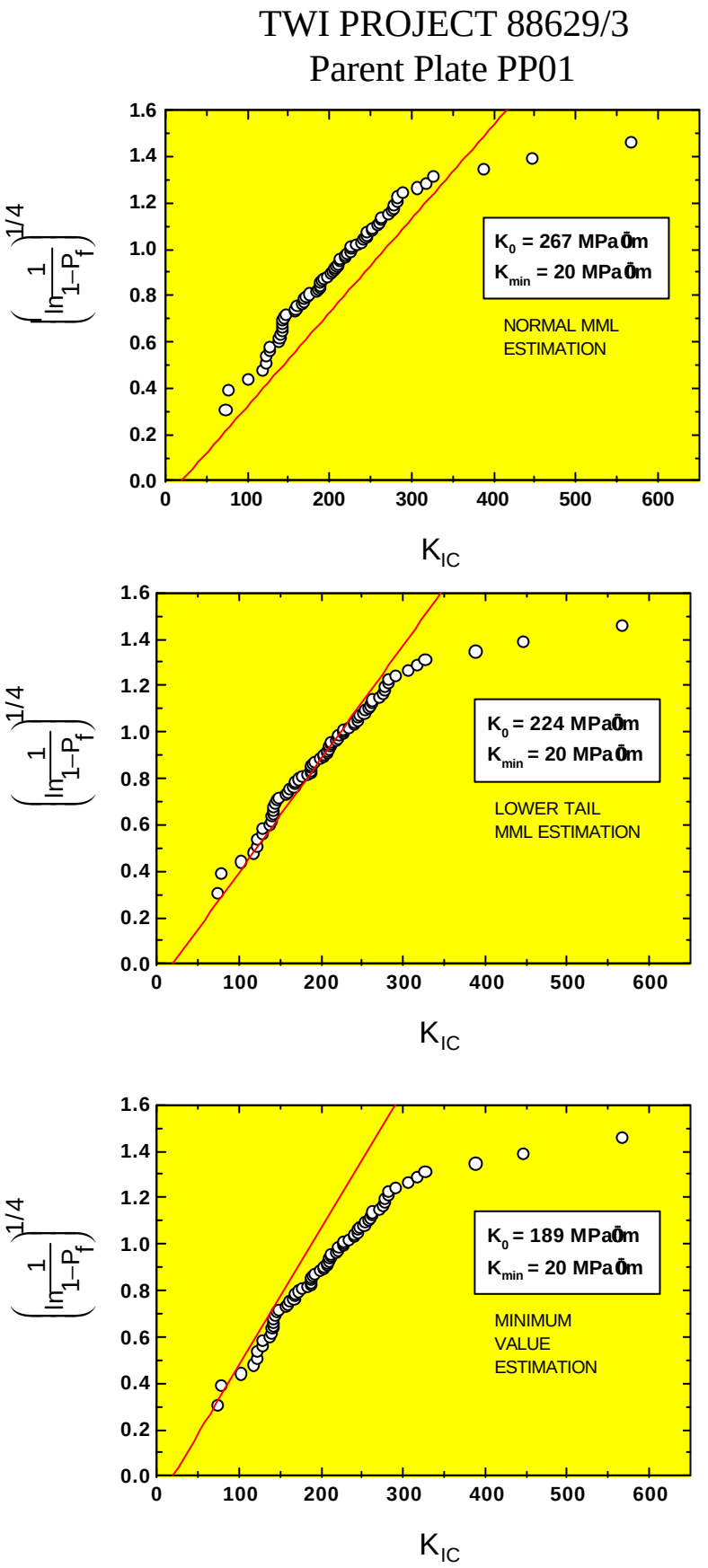

Fig. 14 - Validation of TWI Data for parent plate PP01 - Steps 1, 2 and 3.

TWI PROJECT 88629/3
-60 TTN WM01

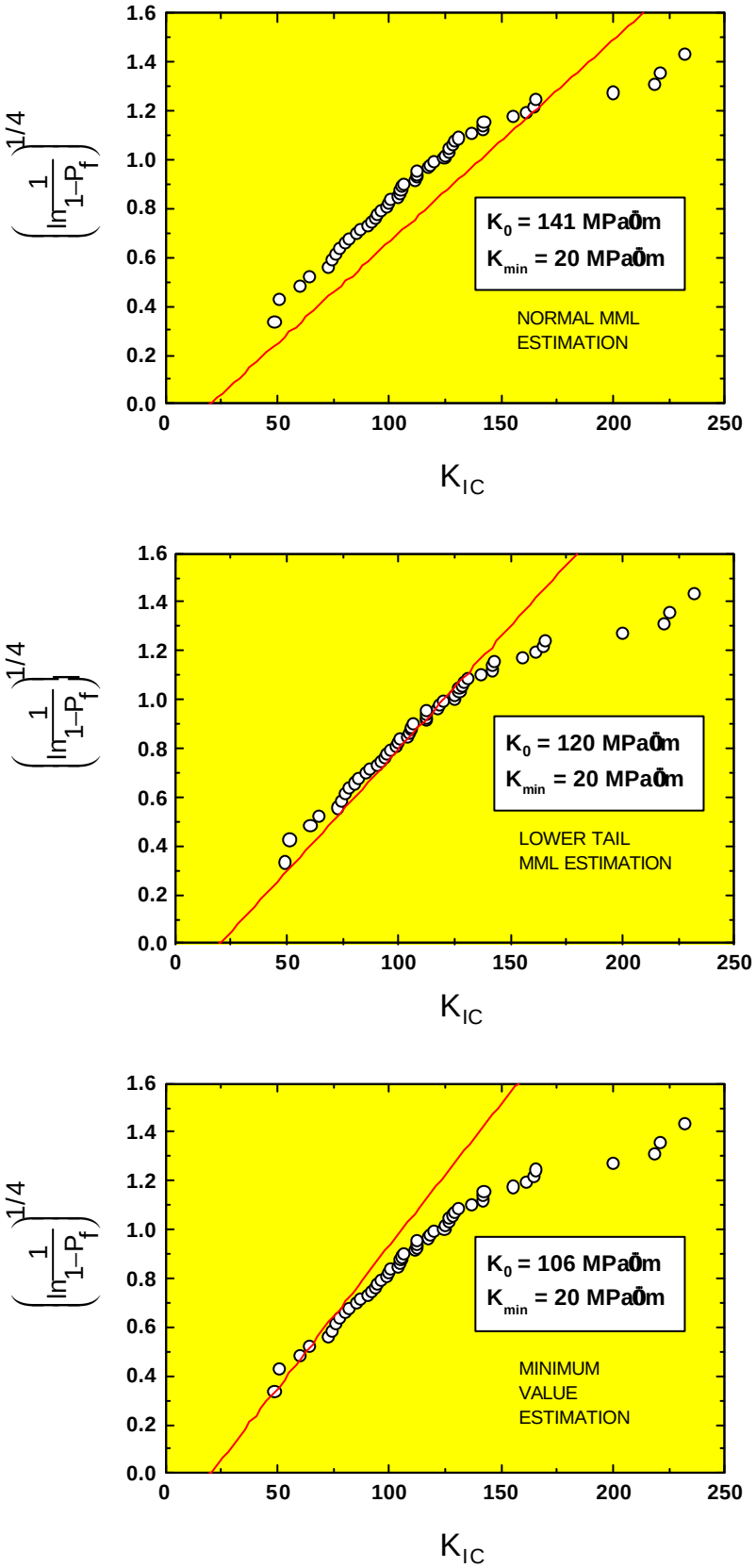

Fig. 15 - Validation of TWI Data for weld metal WM01 (at -60 °C) - Steps 1, 2 and 3.

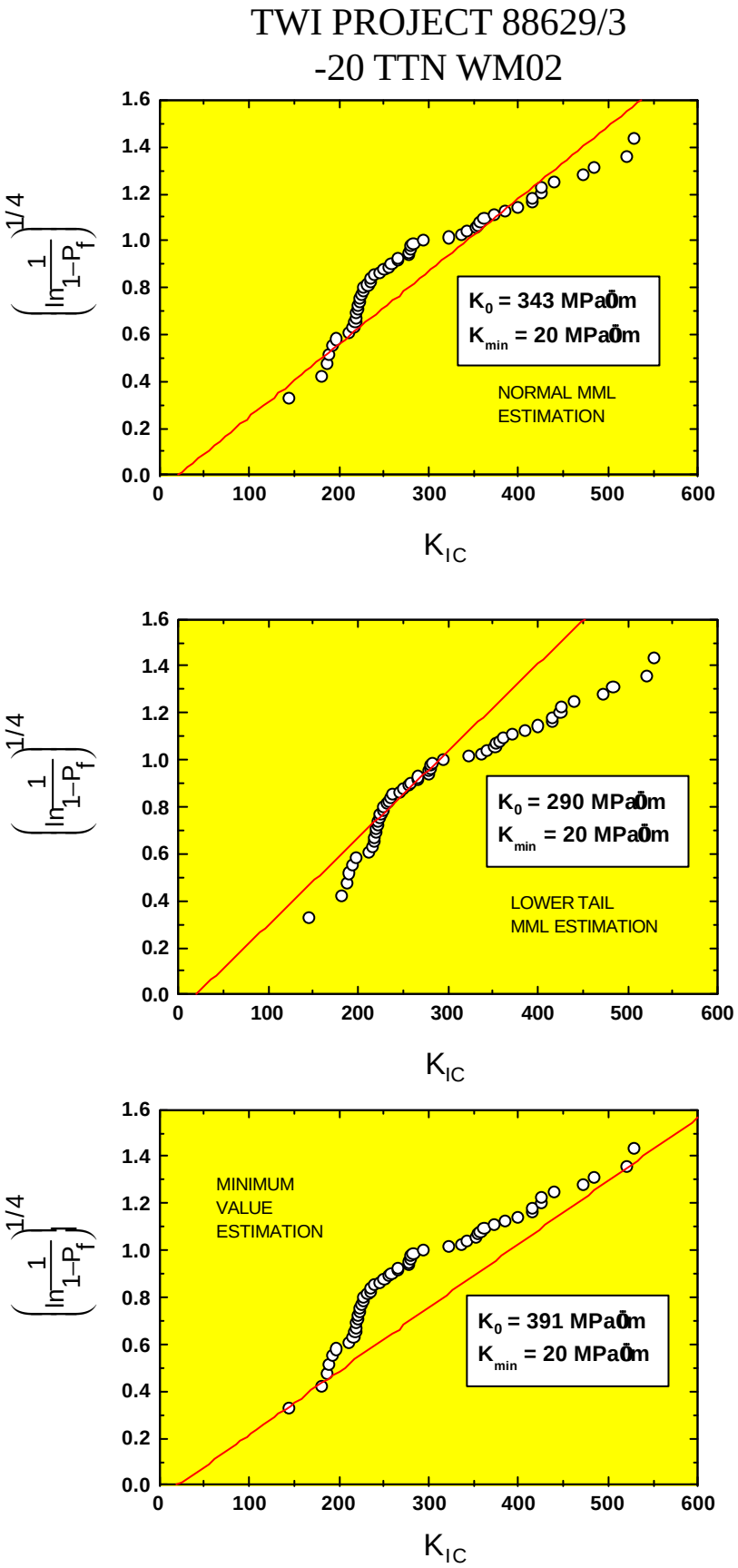

Fig. 16 - Validation of TWI Data for weld metal WM02 (at -20 °C) - Steps 1, 2 and 3.

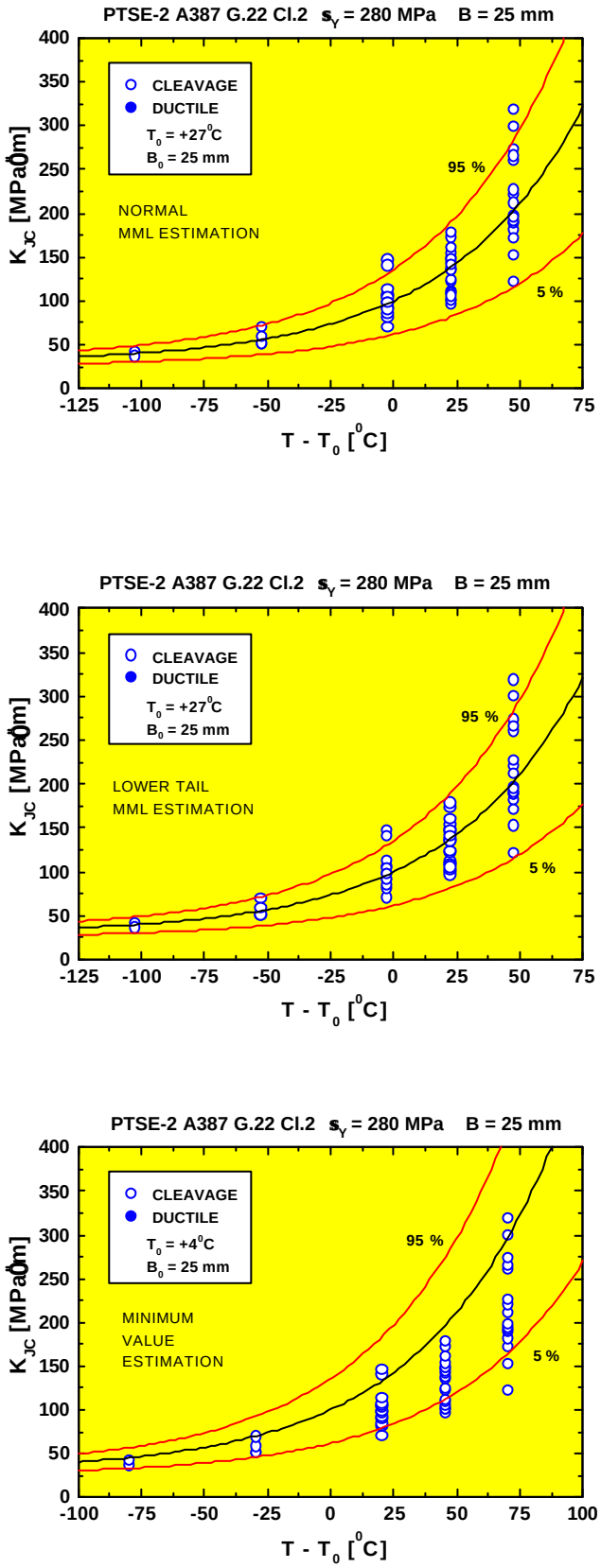

Fig. 17 - Validation of OakRidge Data for parent plate PTSE-2 A387 (B = 25 mm) - Steps 1, 2 and 3.

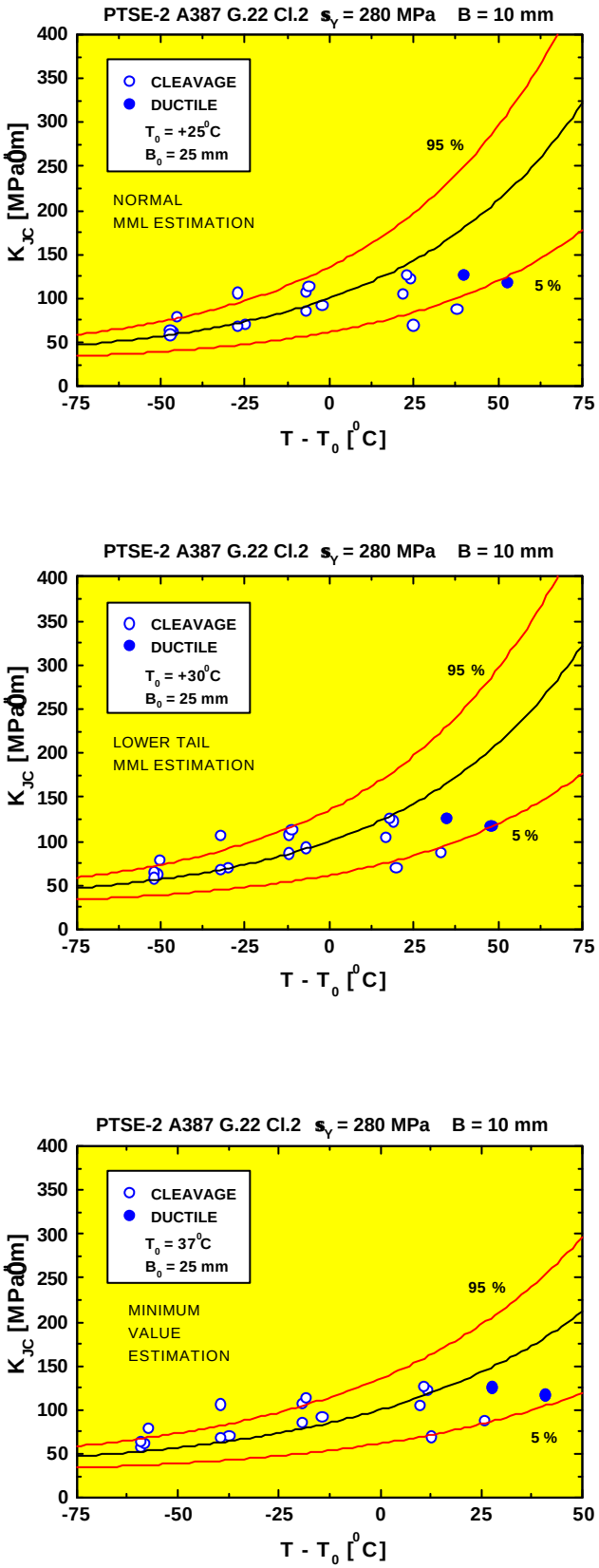

Fig. 18 - Validation of VTT Data for parent plate PTSE-2 A387 (B = 10 mm) - Steps 1, 2 and 3.

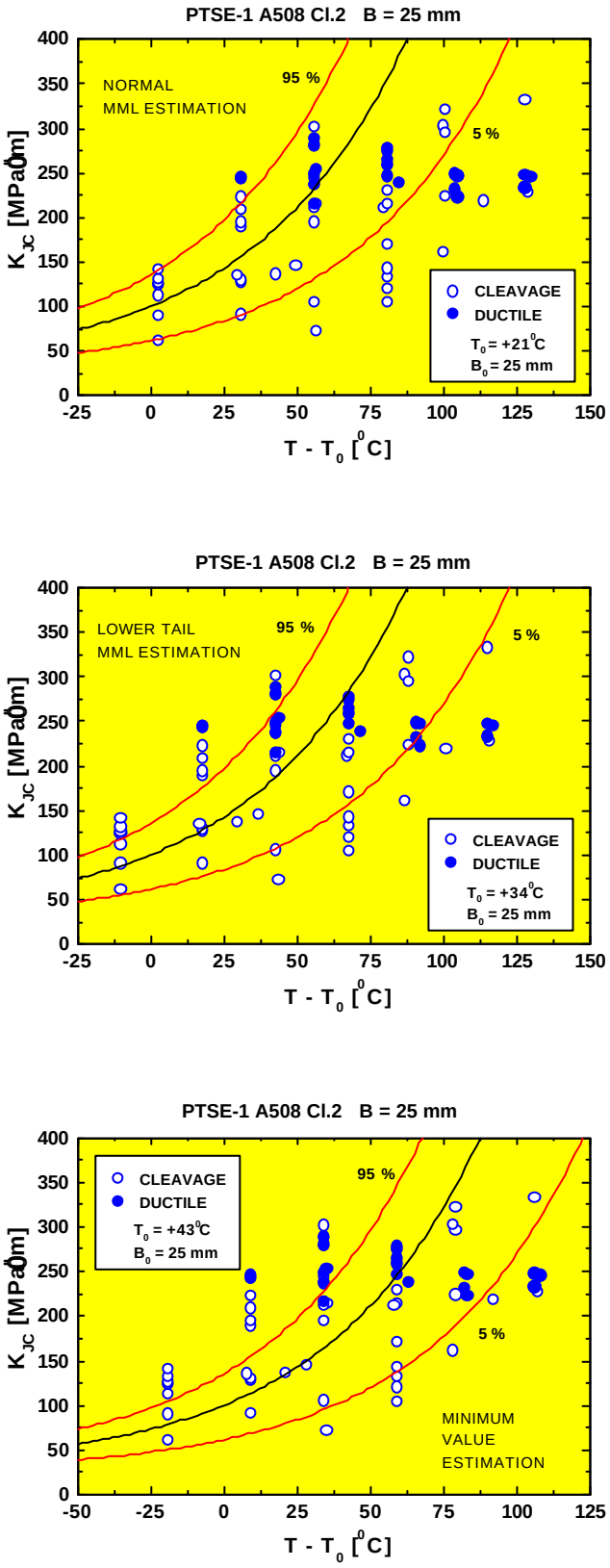

Fig. 19 - Validation of OakRidge Data for parent plate PTSE-1 A508 (B = 25 mm) - Steps 1, 2 and 3.

ACCURACY OF NORMAL MML K_0 ESTIMATE

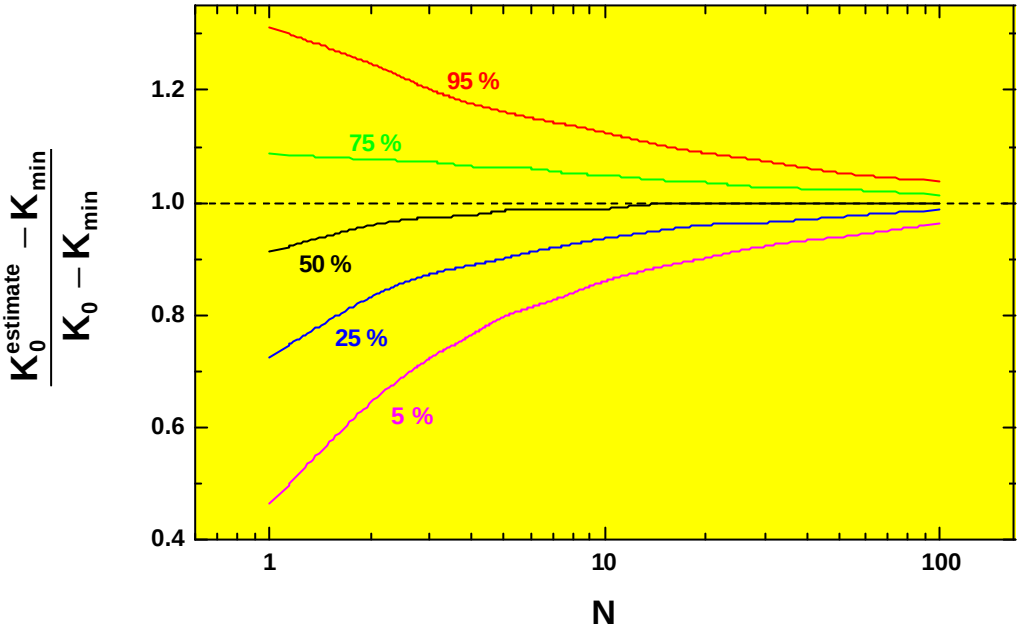

Fig. 20 - Accuracy check of normal MML K_0 estimate.

ACCURACY OF "CONSERVATIVE" K_0 ESTIMATE

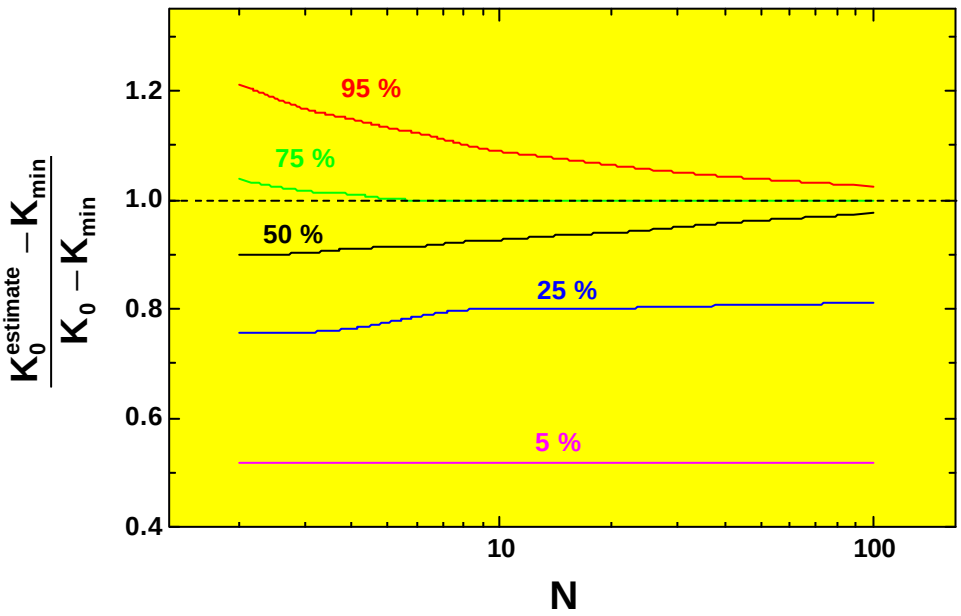

Fig. 21 - Accuracy check of ‘conservative’ MML K_0 estimate.

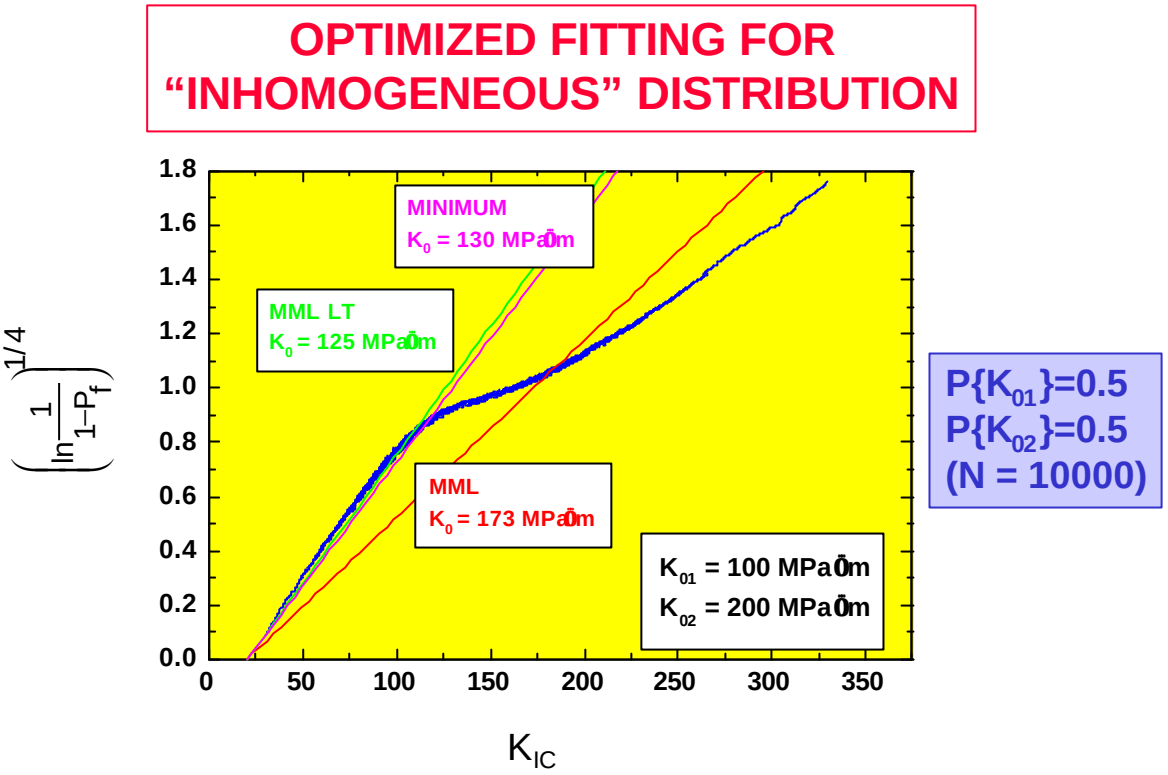

Fig. 22 - Optimised fitting for 'inhomogeneous' K distribution - Steps 1, 2 and 3.

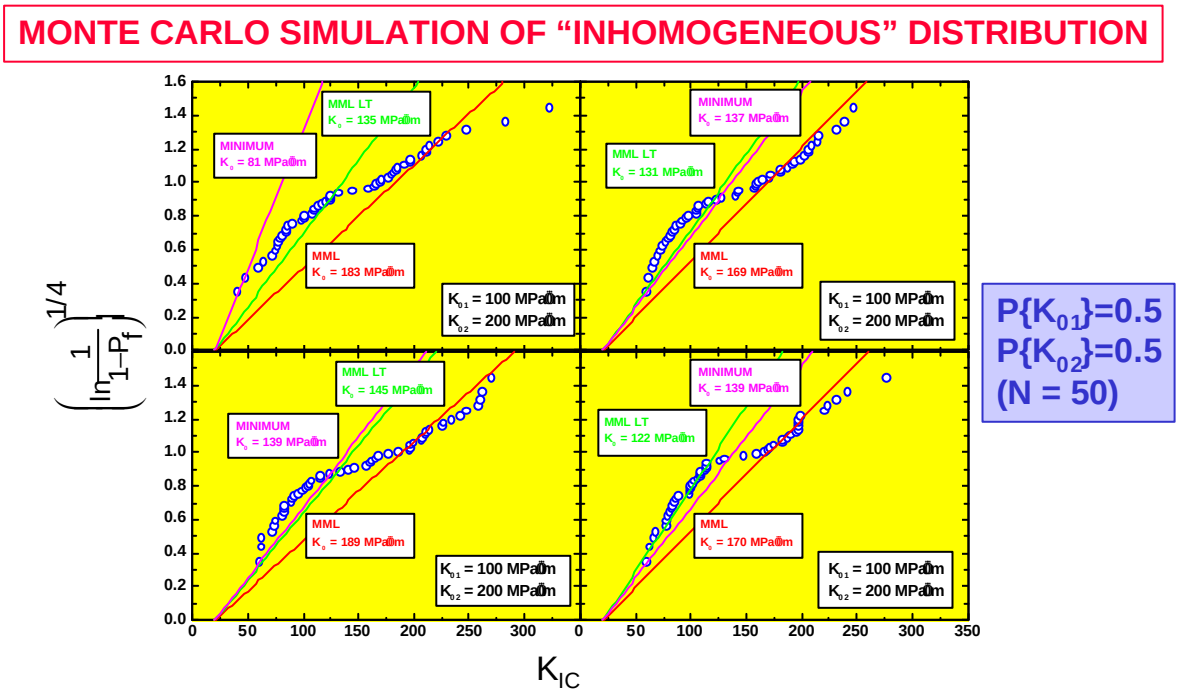

Fig. 23 - Monte-Carlo simulation for four different data data sets of 'inhomogeneous' K distribution - Steps 1, 2 and 3.

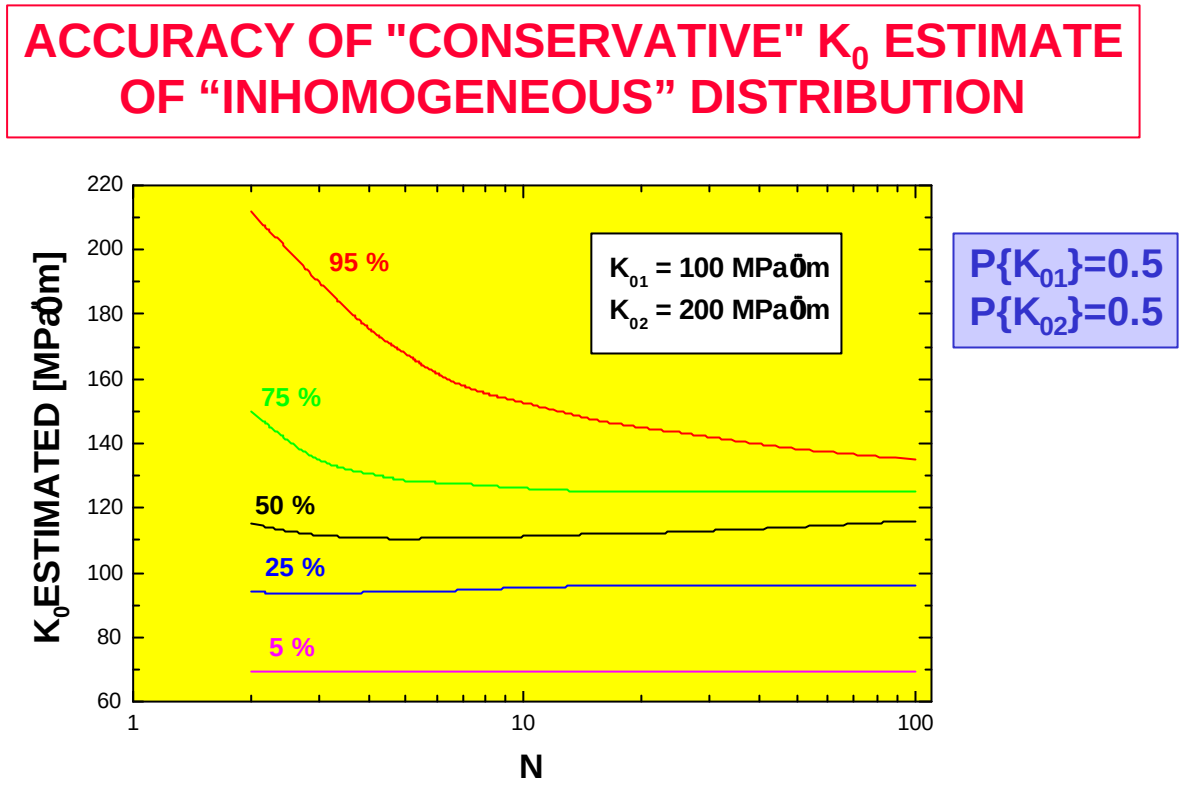

Fig. 24 - Accuracy check of 'conservative' K_0 estimate of 'inhomogeneous' distribution.

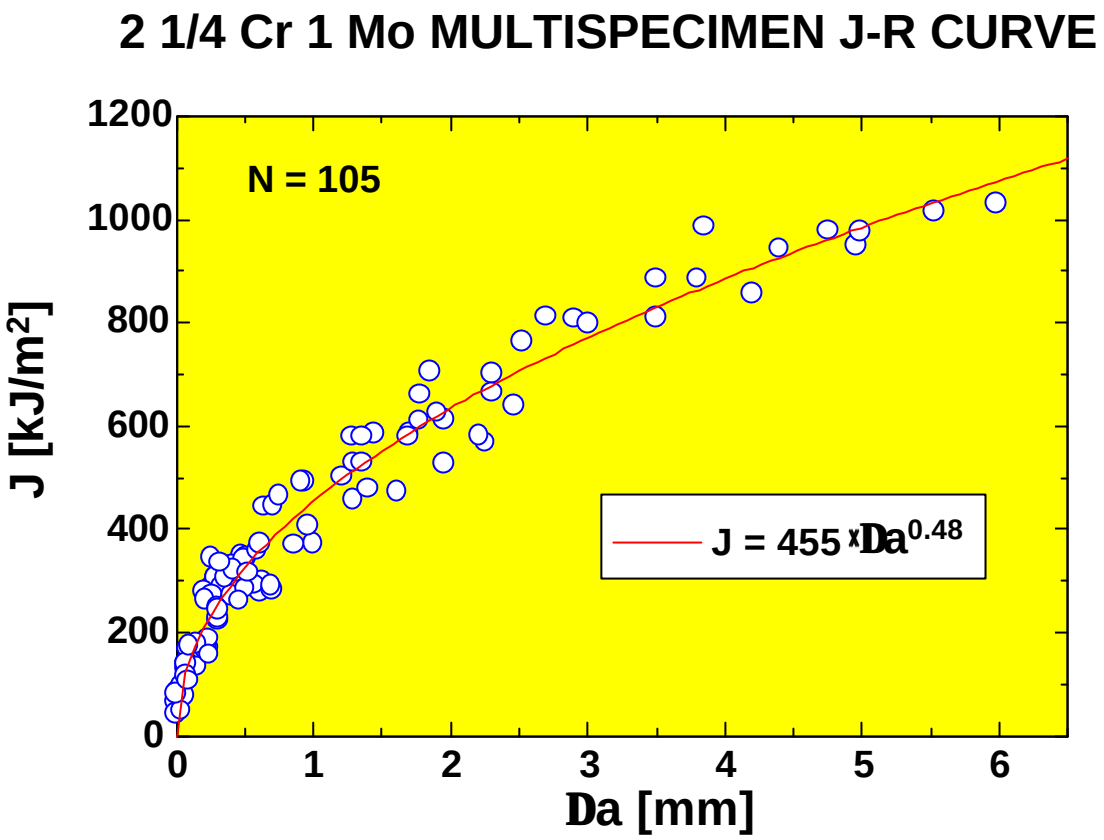

Fig. 25a

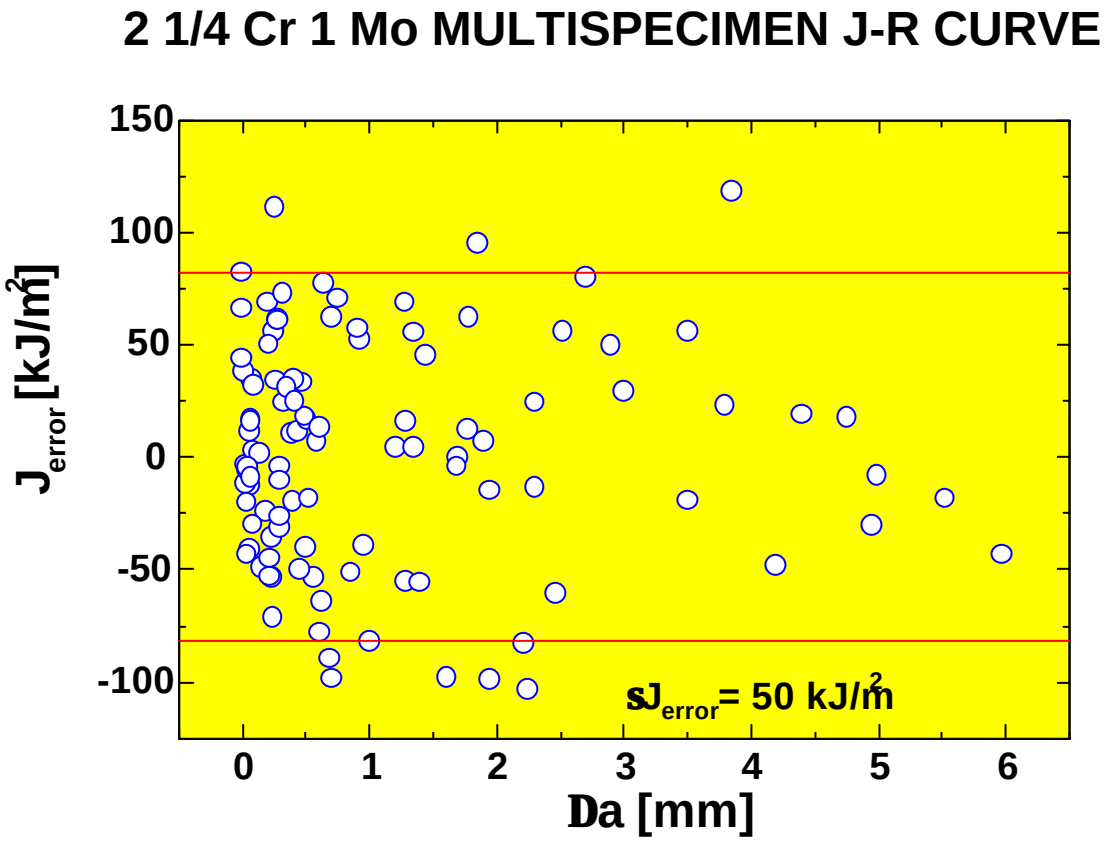

Fig. 25b

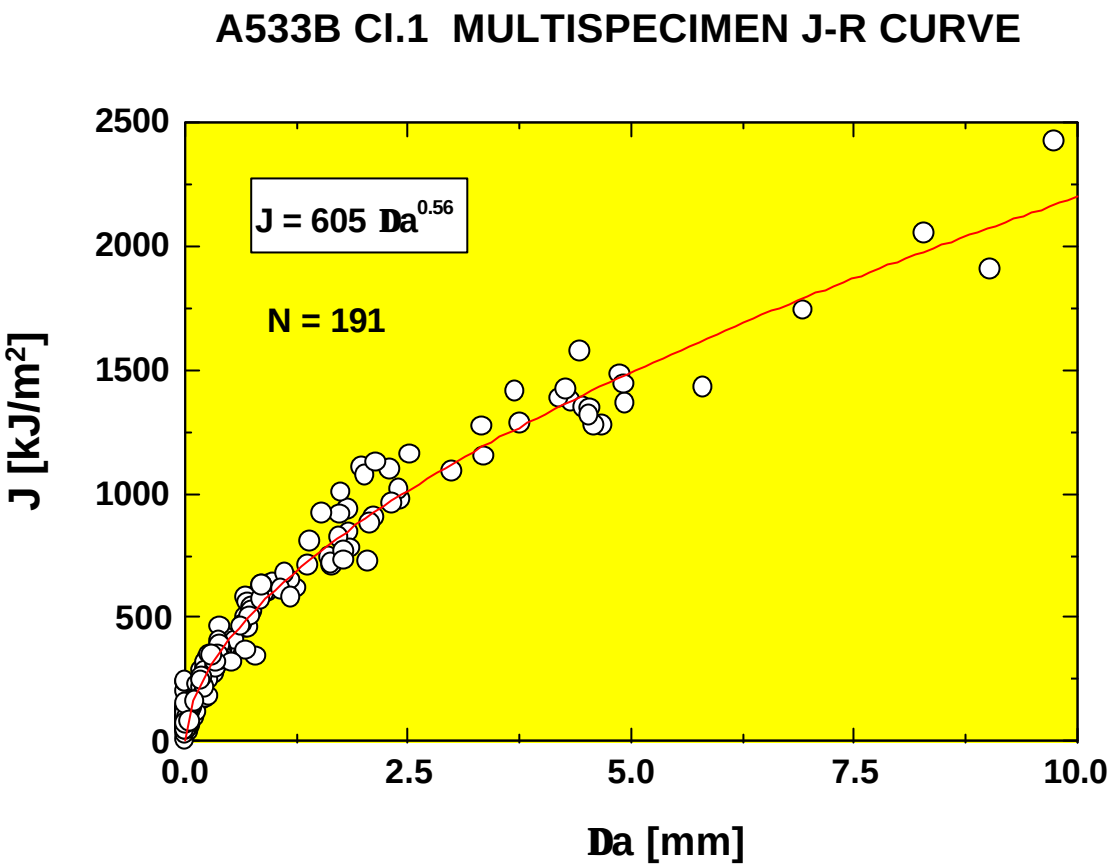

Fig. 26a

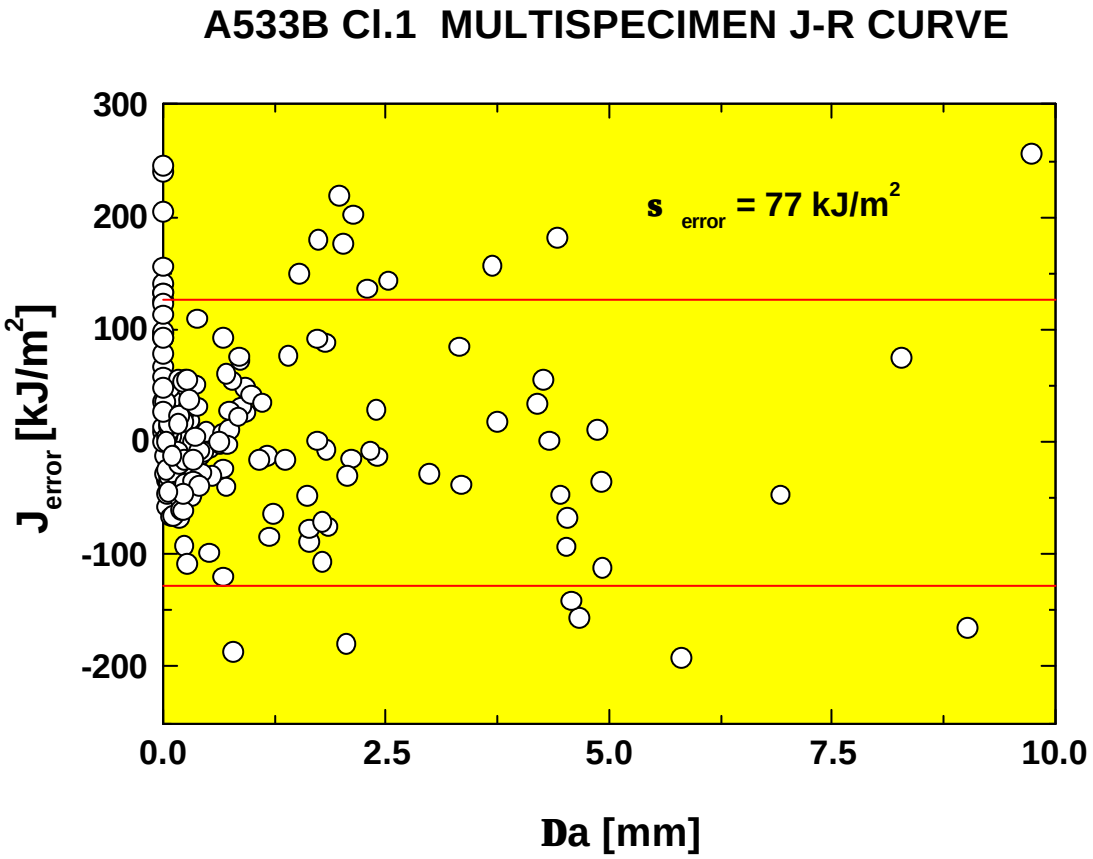

Fig. 26b

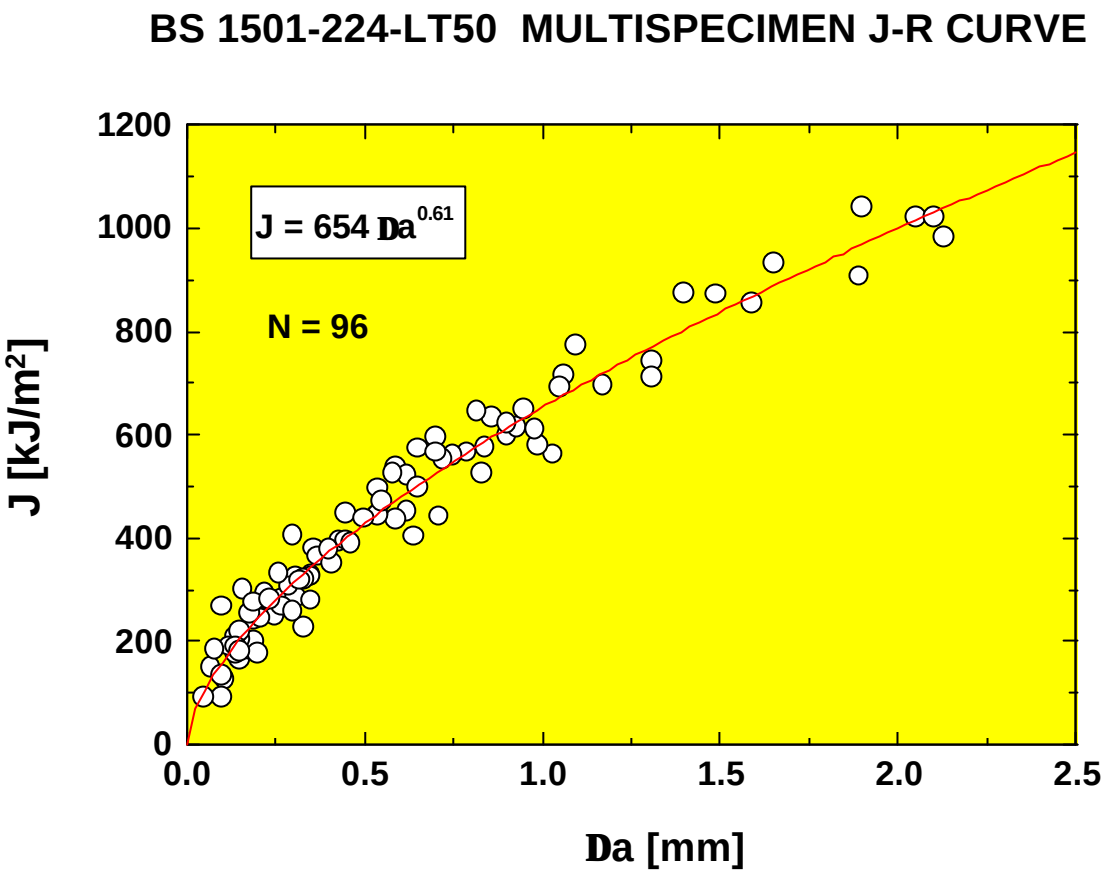

Fig. 27a

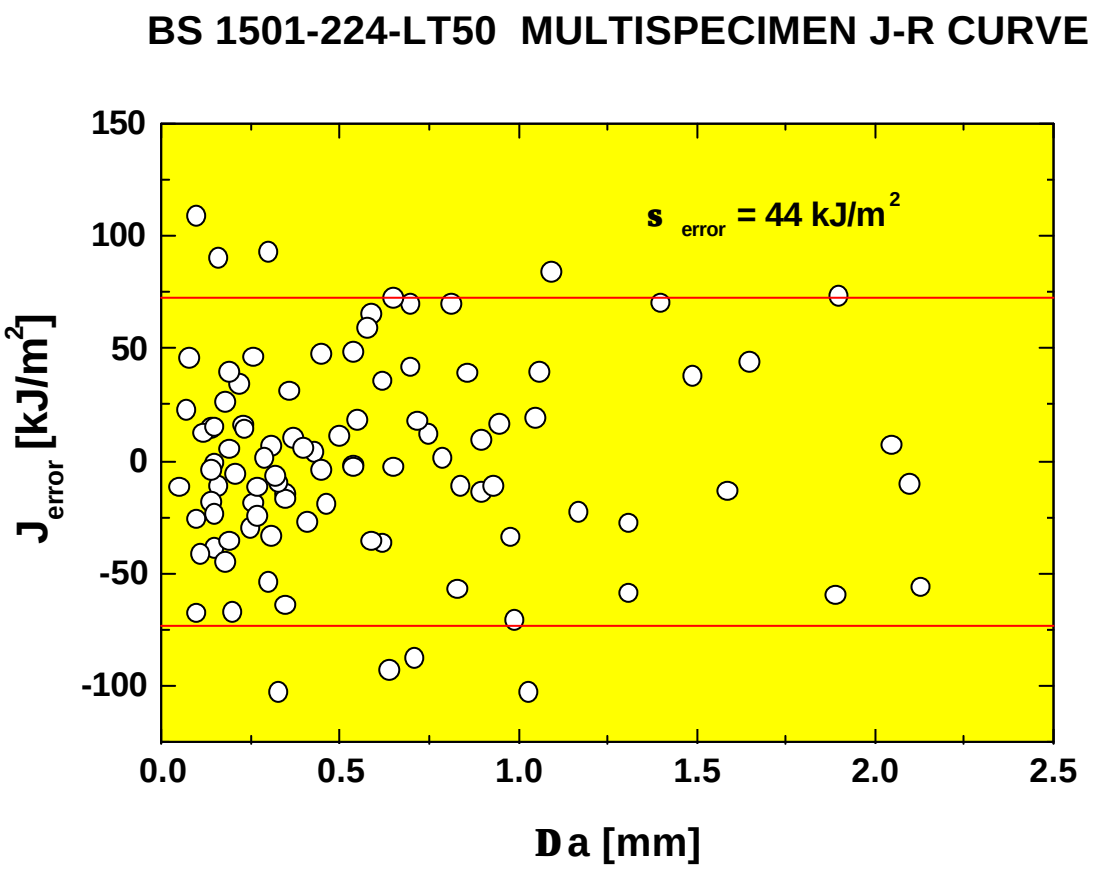

Fig. 27b

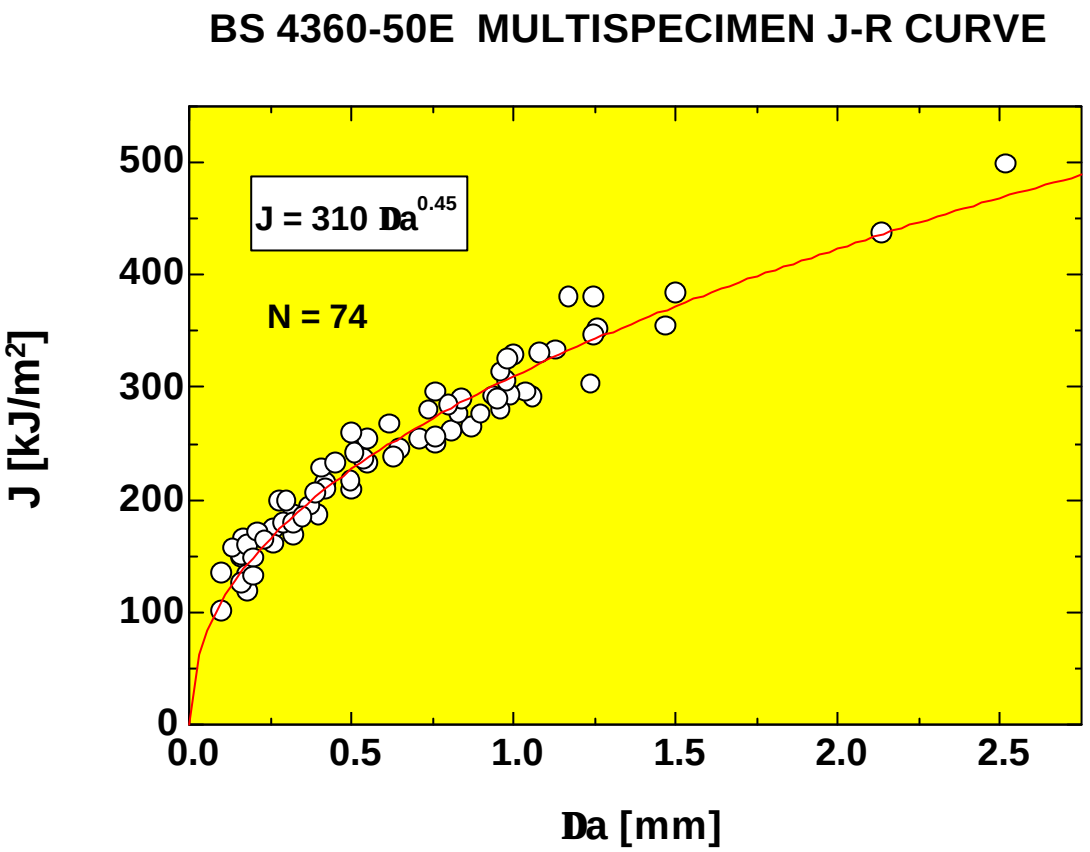

Fig. 28a

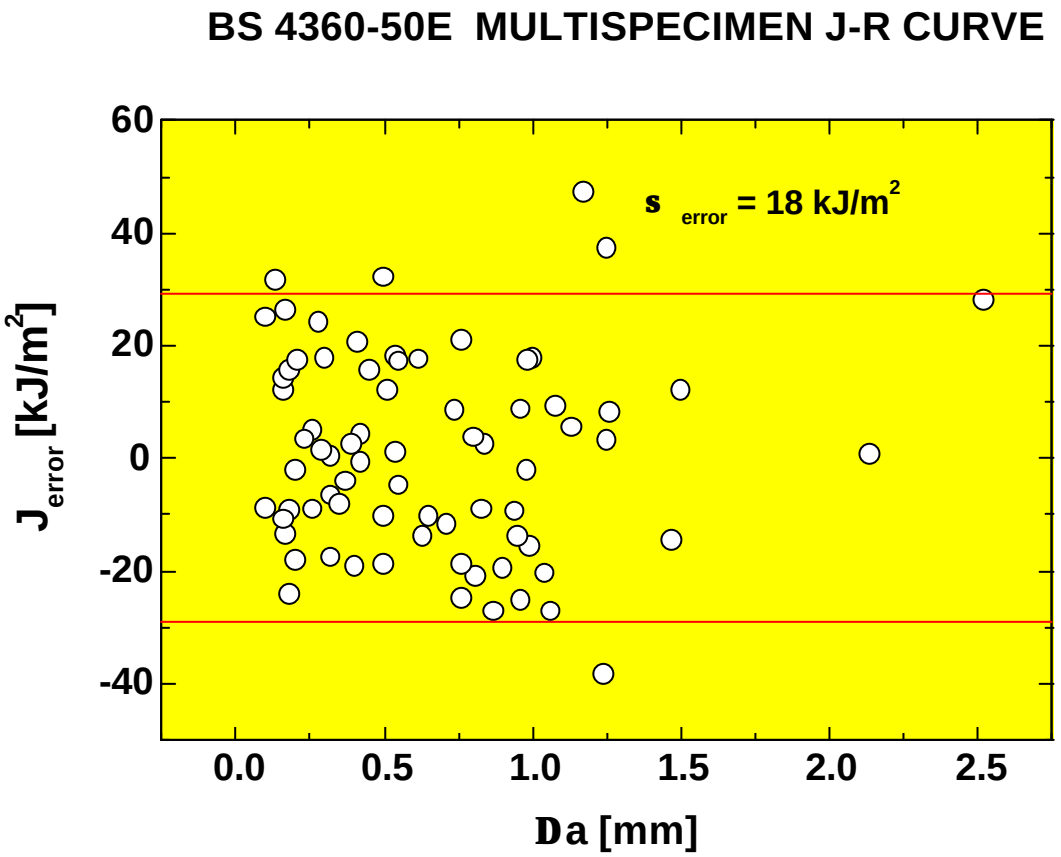

Fig. 28b

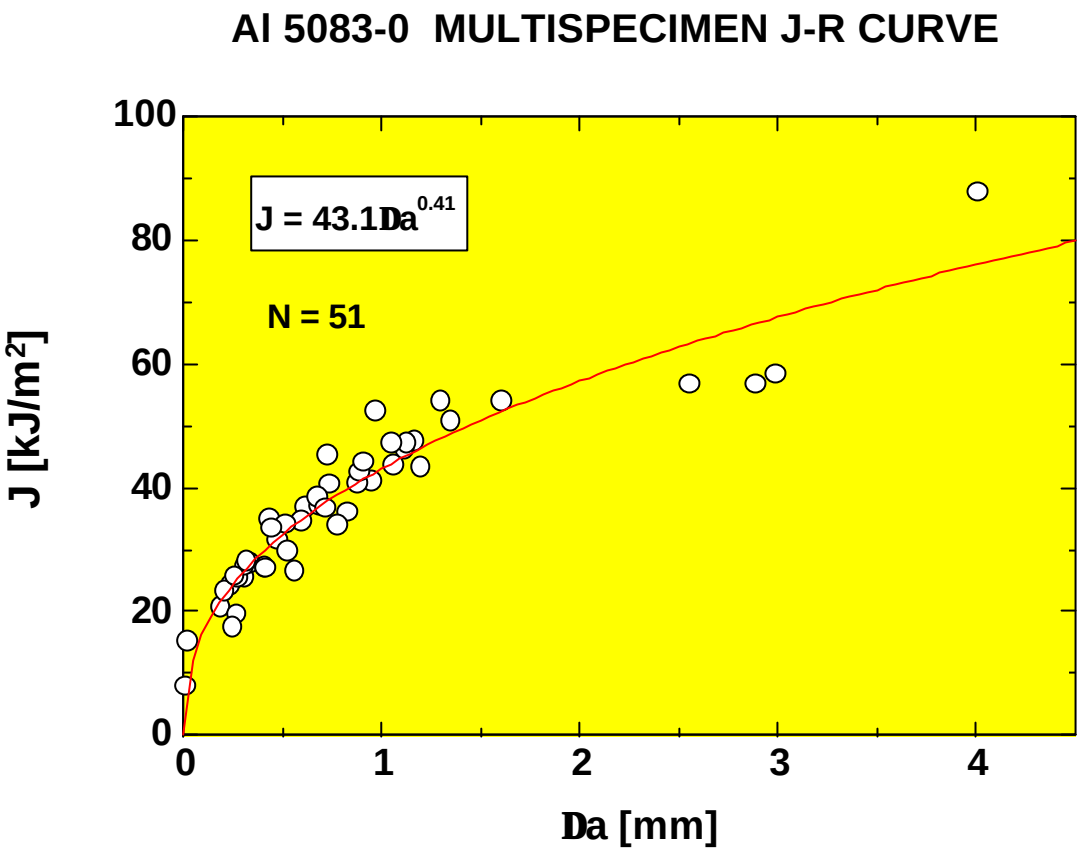

Fig. 29a

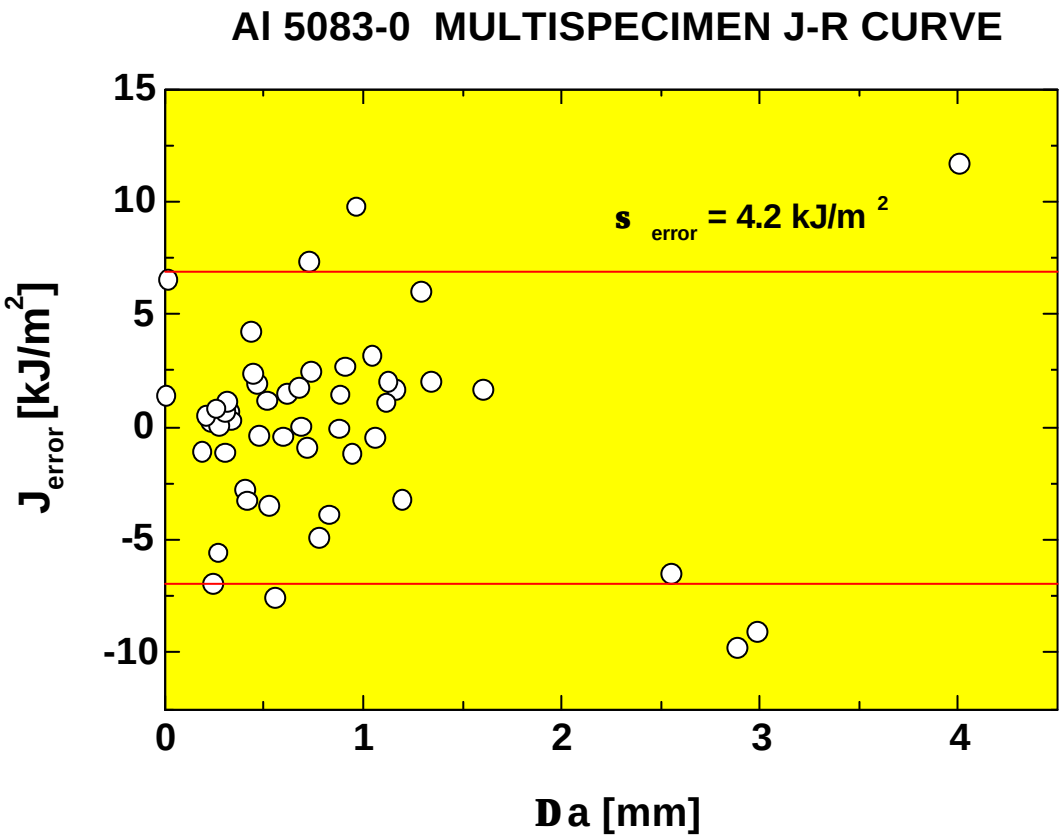

Fig. 29b

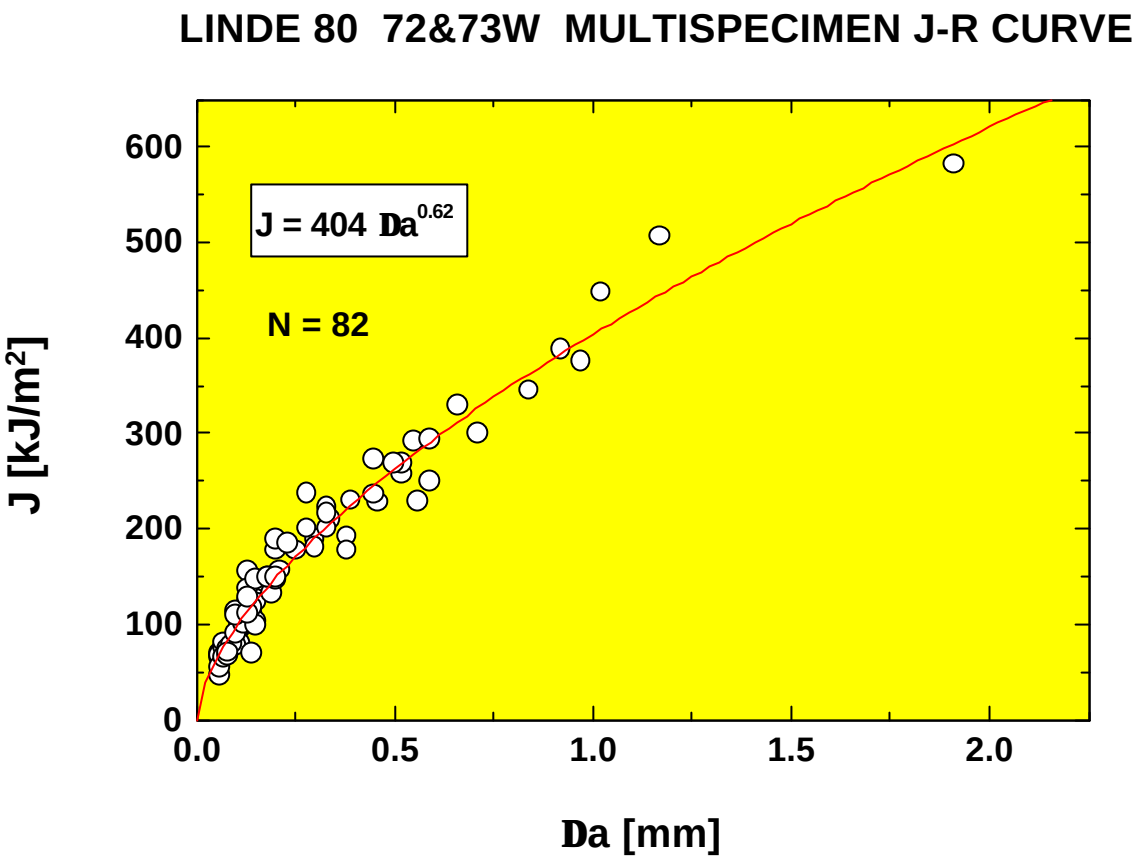

Fig. 30a

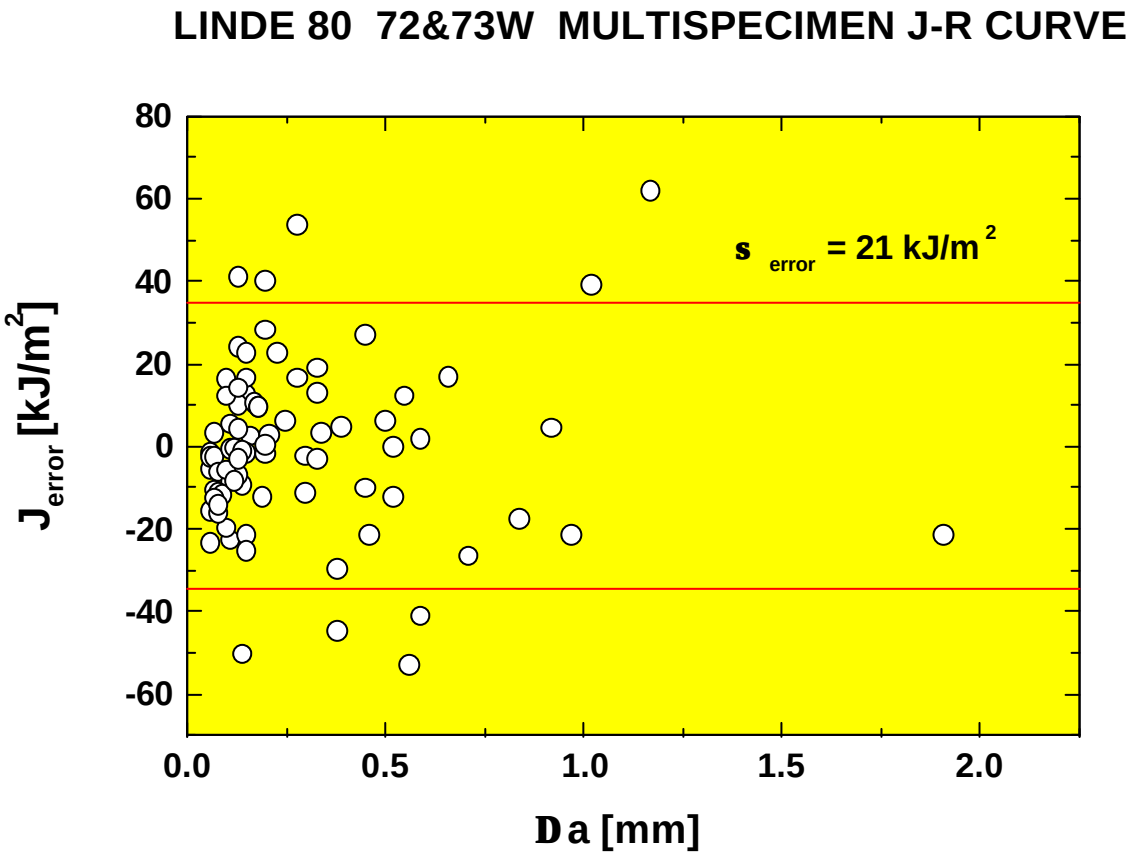

Fig. 30b

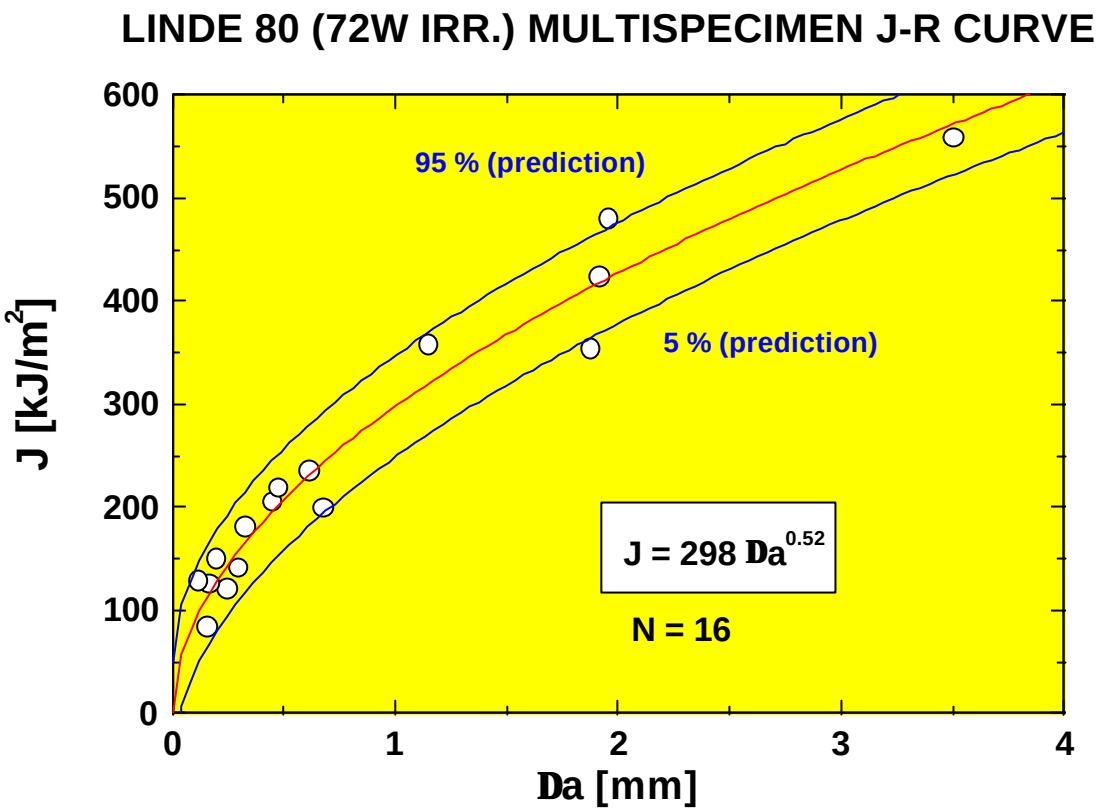

Fig. 31a

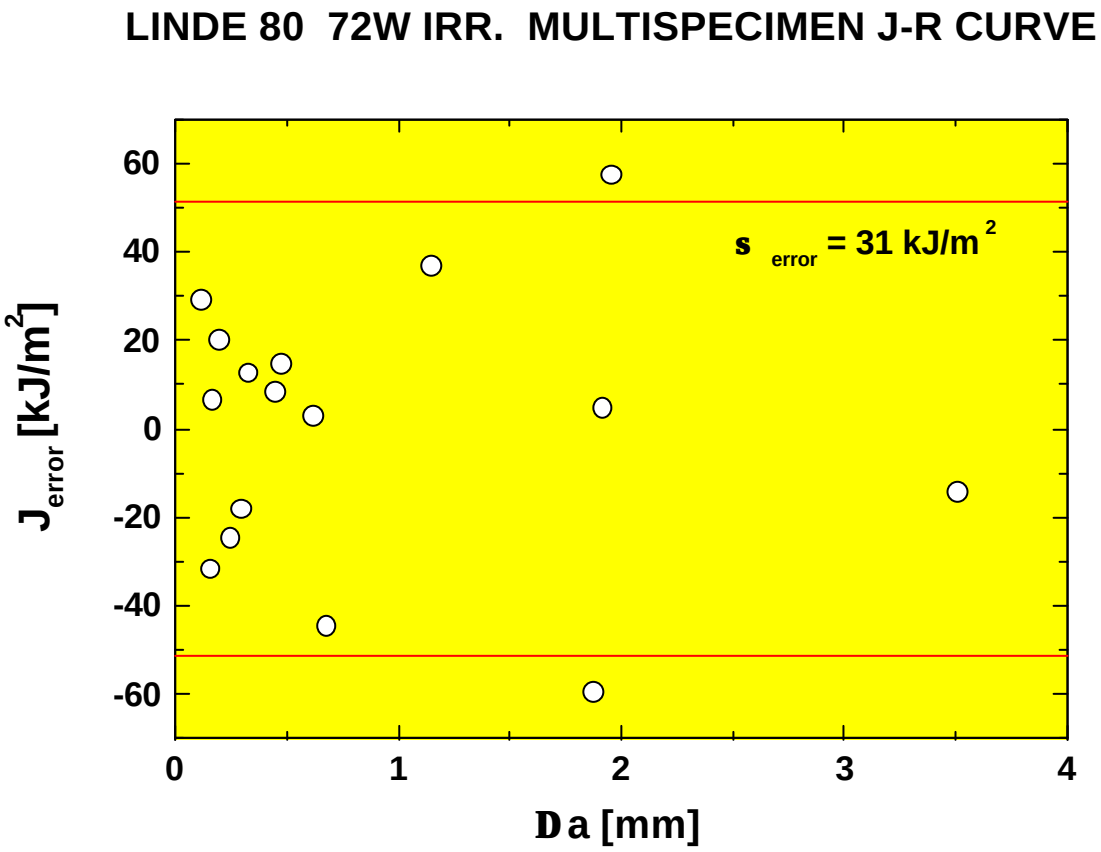

Fig. 31b

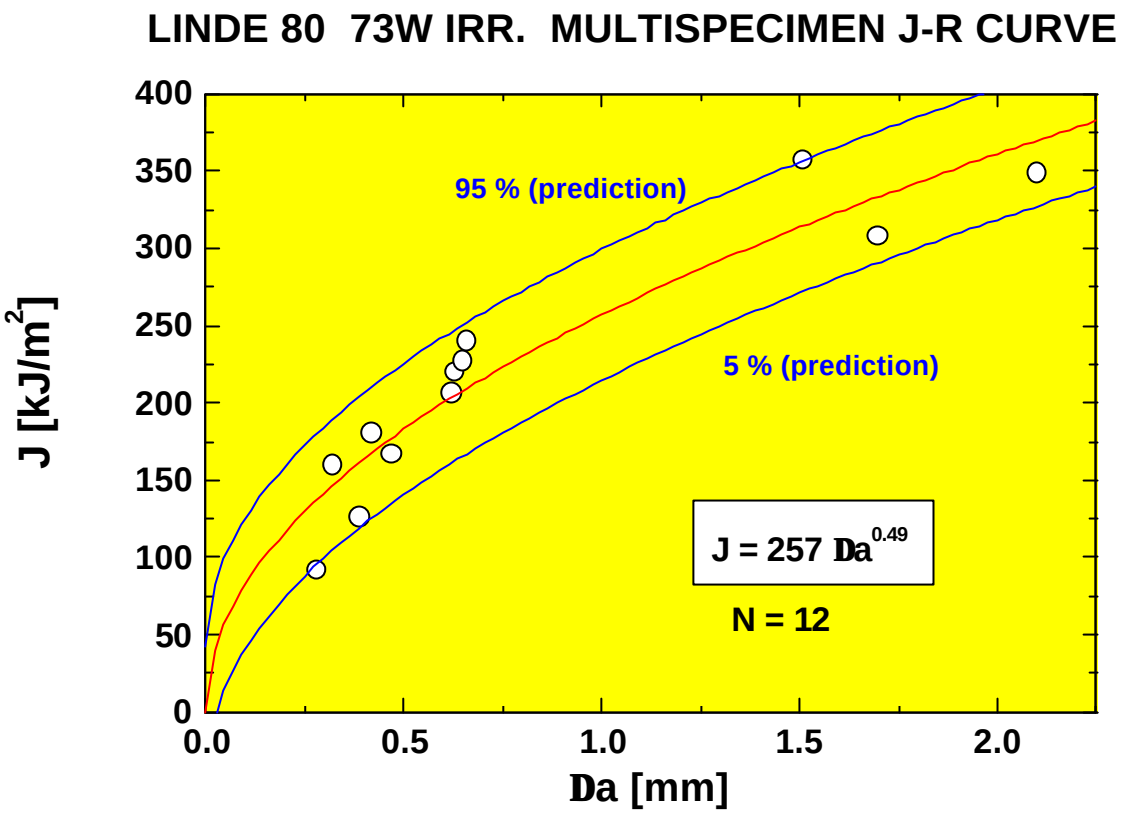

Fig. 32a

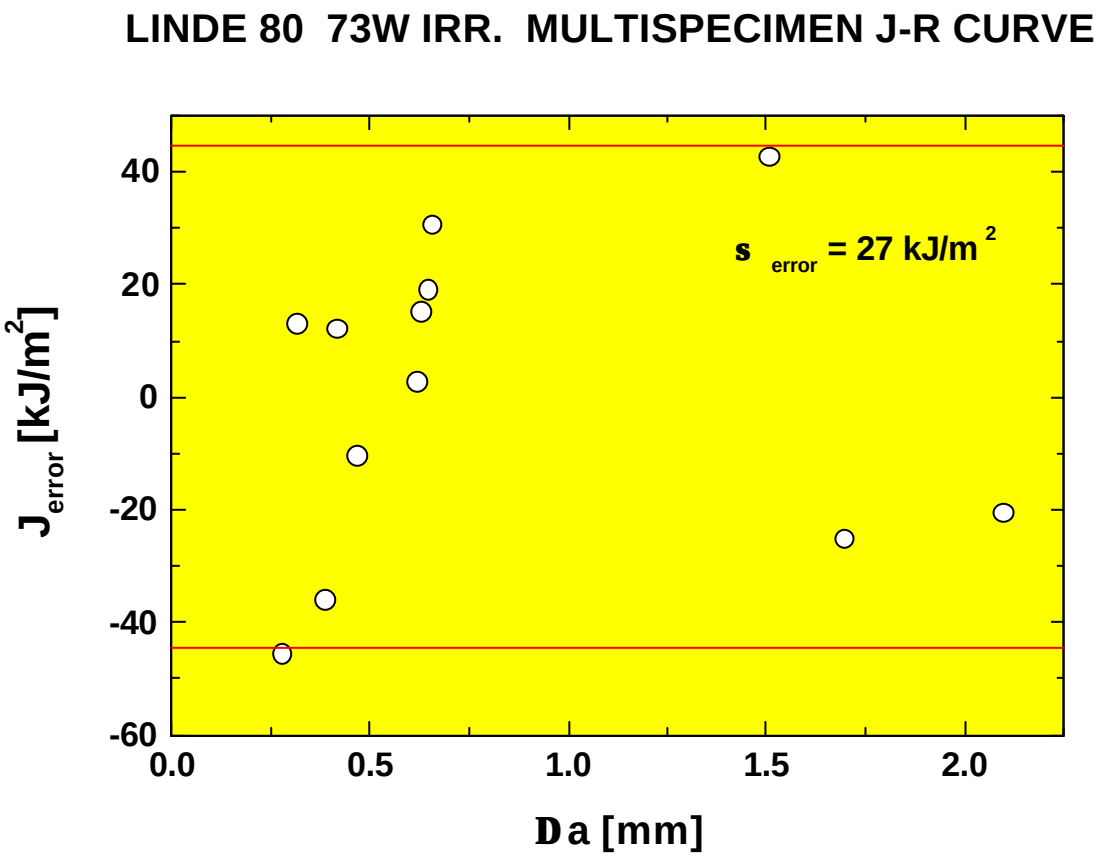

Fig. 32b

CONCLUSIONS

This report presents a procedure for the treatment of various forms of toughness data for use in structural integrity assessments. It uses an approach, in which one material specific K_{mat} value, together with its probability density distribution $P\{K_{mat}\}$ is defined. All the other fracture toughness data types (parameters) are hence transferred into K_{mat}.

For assessment against *brittle fracture*, the evaluation procedure is based upon the maximum likelihood concept (MML) that uses a 'Master Curve' method to describe the temperature dependence of fracture toughness. The method makes the following assumptions: (i) specimen size adjustment, (ii) distribution of scatter and (iii) minimum toughness (K_{min}) and temperature dependence. As a result of the procedure, a conservative estimate of the mean fracture toughness - either $T_0(\overline{K}_{MAT})$ or $\overline{K}_{MAT}$ - is obtained.

The methodology can be easily applied to either fracture toughness data at a single temperature or the data at different temperatures. The procedure is further divided into three separate steps: (i) Step 1: Normal Maximum Likelihood Estimation, (ii) Step 2: Lower-Tail maximum Likelihood Estimation and (iii) Step 3: Minimum Value Estimation. Depending on the characteristics of the data which is available in each case, the procedure guides the user to select the step that is most appropriate for the fracture toughness analysis to the particular case being assessed.

The validation of the procedure using experimental data has shown that the adoption of three different steps in the procedure enables a reliable fracture toughness estimate to be obtained for various forms of data sets containing results from both homogeneous and inhomogeneous material. Thus, the procedure is expected to work well not only for base materials but also in the case of welded joint's weld metals and heat-affected zones.

The numerical check of the accuracy of the three steps of the prediction was made by performing Monte-Carlo simulation (for arbitrary data). It demonstrates that with a probability of 75 %, a conservative and hence 'safe' estimate is obtained. The procedure thereby produces a realistic description of the lower tail probabilities. The verification calculations show that with as few as six tests (i.e. 6 parallel specimens), the probability of having a conservative, 'safe' estimate is approximately 75 %. This can be considered quite adequate for structural integrity assessment purposes.

The treatment of data for ferritic steels on the upper shelf of fracture toughness, for materials which do not exhibit brittle cleavage fracture, or in the case that only ductile fracture data is available, is discussed separately. For the cases where the design of a structure against brittle fracture is not realistic, an approach for the treatment of *ductile fracture* data, contributed by NEL, is presented. The scatter which is actually quite small depends on the absolute crack growth value and is best described as a normally distributed absolute scatter in J-integral values.

For the cases where only ductile fracture data is available, but the possibility of brittle fracture in the structure cannot be excluded, the Step 3 brittle fracture analysis procedure that treats the initiation value as a cleavage fracture event can be reliably used for fracture toughness estimation in the case of macroscopically homogeneous material.

It is concluded that the present procedure represents a user-friendly step-by-step methodology which allows a reliable fracture toughness assessment with quantified probability and confidence levels. Irrespective of the type of the original toughness data, one material specific K_{mat} value representing a conservative estimate of the mean fracture toughness ($\overline{K}_{MAT}$), together with its probability distribution $P\{K_{MAT}\}$ is always obtained as a final result of the procedure. The K_{mat} hence represents a unique

parameter and its distribution describing material's toughness to be further used for structural integrity assessments. For the assessment, suitable confidence and probability levels should be chosen in relation to the criticality of the component.

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