Overview of NIST Activities on Sub-size and Miniaturized Charpy Specimens: Correlations with Full-Size Specimens and Verification Specimens for Small-Scale Pendulum Machines

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ABSTRACT

NIST in Boulder Colorado investigated the correlations between impact test results obtained from standard, full-size Charpy specimens (CVN) and specimens with reduced thickness (sub-size Charpy specimens, SCVN) or reduced or scaled cross-section dimensions (miniaturized Charpy specimens, MCVN).

A database of instrumented impact test results was generated from four line pipe steels, two quenched

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Correlations between specimen types were established and compared with previously published relationships, considering absorbed energy, ductile-to-brittle transition temperature, and upper shelf energy. Acceptable correlations were found for the different parameters, even though the uncertainty of predictions appears exacerbated by the expected significant experimental scatter. Furthermore, we report on the development of MCVN specimens for the indirect verification of small-scale pendulum machines (with potential energies between 15 J and 50 J), which cannot be verified with full-size verification specimens. Small-scale pendulum machines can now be verified at room temperature with certified reference specimens of KLST type (3 mm × 4 mm × 27 mm), supplied by NIST at three certified absorbed energy levels (low energy, 1.59 J; high-energy, 5.64 J; super-high energy, 10.05 J). These specimens can also be used to verify the performance of instrumented Charpy strikers through certified maximum force values. Certified reference values for both absorbed energy and maximum force were established by means of an interlaboratory comparison (Round-Robin), which involved nine qualified and experienced international laboratories.

INTRODUCTION

Charpy V-notch testing is extensively used in the industry for ensuring that materials exhibit adequate toughness and resistance to brittle fracture. Typically, specifications require that a certain level of absorbed energy be achieved at a specified test temperature (either room temperature, or minimum design temperature).

A practical difficulty is encountered for small section thicknesses, or components with complicated shapes, when standard full-size Charpy V-notch specimens (CVN) cannot be extracted. Under these circumstances, Charpy specimens with reduced
thicknesses\textsuperscript{3} are typically machined and tested. Typical thickness values for sub-size Charpy specimens (SCVN) are 7.5 mm (3/4-size), 6.67 mm (2/3-size), 5 mm (1/2-size), and 2.5 mm (1/4-size). An alternative approach is to reduce both cross section dimensions (thickness and width), rather than just the thickness, as well as the remaining dimensions: in this case, specimens are denominated miniaturized Charpy-V notch (MCVN). The most popular MCVN specimen type is designated KLST (from the German Kleinstprobe), and has thickness $B = 3$ mm, width $W = 4$ mm, notch depth $N = 1$ mm and length $L = 27$ mm. Another MCVN specimen configuration considered in this study is designated RHS (Reduced Half-Size), and has $B = W = 4.83$ mm, $N = 0.97$ mm, and $L = 24.13$ mm. The main difference between KLST and RHS is that only the latter is proportionally scaled with respect to CVN.

Although it would seem logical that a Charpy specimen with reduced cross-section would absorb less energy than a full-size CVN and that energy reduction should be proportional to the reduction in the area of the remaining ligament below the notch, the situation is more complex for ferritic steels. The reduction in specimen thickness (and also specimen width for MCVN specimens) causes a loss in through-thickness constraint, leading to a decrease in the ductile-to-brittle transition temperature. Therefore, in order to correlate the results obtained from CVN and SCVN/MCVN specimens, one needs to both account for the transition temperature shift and factor the absorbed energy by an amount appropriate to the reduced cross-sectional area. This

\textsuperscript{3} In this paper, we will call “thickness” ($B$) the dimension parallel to the machined notch, in accordance with fracture mechanics terminology. In current Charpy standards, this dimension is referred to as specimen width ($W$).
approach is generally adopted by North American standards, while European standards tend to require a higher absorbed energy per unit cross-sectional area (absorbed energy density) for a SCVN/MCVN specimen tested at the same temperature [1].

The study presented here attempts to correlate Charpy results obtained from CVN, SCVN, and MCVN specimens of seven ferritic steels tested at NIST in Boulder Colorado. The results will be compared to previously published correlations.

MATERIALS AND EXPERIMENTAL

Among the seven ferritic steels characterized at NIST, four were commercial line pipe steels (X52, X65, X70, X100), and three were materials used to produce NIST Charpy verification specimens at low-, high-, and super-high-energy levels (two quenched and tempered AISI 4340 steels with different heat treatments, and a 18 % Ni maraging steel designated T200). The chemical composition of the seven steels is provided in Table . Additional information can be found in [2,3].

The four investigated line pipe steels represent a variety of different material behaviors and manufacturing processes. X52 was produced in the early 60s and put in service in 1964 in a natural gas pipeline, which was extracted from the ground after 40 years of operation. X65 and X70 represent more modern and very high ductility and toughness materials. X100, although of recent production, exhibits a lower ratio between ductility and mechanical strength [2]. Three of the four line pipe steels (X52 is the exception) are microalloyed with Nb and Ti, which results in grain refinement during steel processing. The remaining three steels (4340 and T200) correspond to three
batches of NIST Charpy verification specimens: LL141 (low energy), HH143 (high energy),
and SH38 (super-high energy) [3].

The type of Charpy specimens tested for each of the seven steels is summarized in Table 1.

Charpy tests on CVN and SCVN specimens were performed on an instrumented pendulum with capacity of 953.6 J and impact speed of 5.5 m/s. When testing SCVN specimens, shims were placed on the machine supports in order to maintain the position of the center of strike. MCVN specimens were tested by means of an instrumented small-scale pendulum with capacity of 50.8 J and impact speed of 3.5 m/s.

The instrumented striker used for CVN and SCVN specimens had a striking edge with 8 mm radius, compliant with ASTM E23 [4]. The instrumented strikers used for MCVN tests had a radius of the striking edge of 3.86 mm and 2 mm for RHS and KLST specimens, respectively.

For tests above room temperature, specimens were heated by means of an electric plate. Below room temperature, specimens were cooled in an ethyl alcohol bath down to -90 °C; for lower temperatures, liquid nitrogen (LN2) was used. To mitigate the temperature gradient for MCVN specimens after removal from the cooling medium, the anvils and supports of the machine were maintained at low temperature (between -30 °C and -60 °C).

Additional details on the experimental setup can be found in [2,3].
DATA ANALYSIS

For each impact test performed, absorbed energy ($KV$), lateral expansion ($LE$), and shear fracture appearance ($SFA$) were measured and reported. Each parameter was then fitted as a function of test temperature by means of the commonly used hyperbolic tangent model [5], expressed as:

$$Y = A + B \tan h \left( \frac{T - DBTT}{C} \right)$$

(1)

where $T$ is test temperature ($^\circ$C), $Y$ is $KV$ (J), $LE$ (mm), or $SFA$ (%), and $A$, $B$, $DBTT$, and $C$ are fitting coefficients that are calculated by the least-square method. Note that:

- $(A + B)$ corresponds to the upper shelf value, or the asymptotic level approached by $Y$ when $T \to +\infty$;

- $(A - B)$ corresponds to the lower shelf value, or the asymptotic level approached by $Y$ when $T \to -\infty$;

- $2C$, in $^\circ$C, is the width of the transition region (portion of the curve between lower and upper shelf);

- $DBTT$ (Ductile-to-Brittle Transition Temperature), in $^\circ$C, is the temperature at the midpoint between lower and upper shelf;

- $B/C$ is the slope of the fitted curve at $T = DBTT$.

The following constraints were applied when fitting results:

(a) the upper shelf for $KV$ and $LE$ $(A+B)$ was set as the average for all specimens with $SFA \geq 95\%$;  

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$^4$ This upper shelf definition is given in ASTM E185 (Standard Practice for Design of Surveillance Programs for Light-Water Moderated Nuclear Power Reactor Vessels).
(b) for SFA, A = B = 50 %, so that DBTT (designated as FATT$^{50}$) always corresponds to 
SFA = 50 %.

Between 9 and 13 specimens were tested to obtain Charpy transition curves. 
Test temperatures were chosen in order to achieve a clear definition of lower shelf, 
upper shelf, and transition region.

As far as instrumented test results are concerned, the following parameters 
were determined and reported:

- force at general yield ($F_{gy}$), maximum force ($F_m$), force at the initiation of brittle 
  fracture ($F_{bf}$), force at crack arrest ($F_a$);
- corresponding absorbed energy$^6$ values ($W_{gy}, W_m, W_{bf}, W_a$), as well as total absorbed 
  energy ($W_t$).

The analysis of the instrumented force/displacement test records was performed 
in accordance with ASTM E2298 [6] and ISO 14556:2000 [7]. The results of these 
analyses are not reported here, and will be the subject of a future publication.

**PRELIMINARY EXAMINATION OF TEST RESULTS**

Detailed test results of the instrumented Charpy tests performed are not reported here 
for the sake of conciseness, and can be found in [2,3]. We report however in Table the 
values of $DBTT_{KV}$, $DBTT_{LE}$, $FATT_{50}$, and $USE$ (Upper Shelf Energy) for all the materials and 
specimens tested.

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$^5$ FATT stands for Fracture Appearance Transition Temperature.

$^6$ For an instrumented impact test, absorbed energy $W$ is calculated from the force/displacement curve, 
whereas $KV$ is provided by the machine encoder.
The following remarks concerning some of the transition curves of the NIST reference materials (LL141, HH143, SH38) will be provided below, since they are relevant to the analyses detailed hereinafter.

1. For LL141, both $KV$ and $LE$ transition curves do not show a plateau and appear to increase beyond the maximum test temperature ($300 \, ^\circ\text{C}$), see Fig. 1. Hence, values of $DBTT$ and $USE$ are associated with significant uncertainty and should be treated with caution.

2. LL141, HH143, and SH38 exhibit relatively high lower shelf levels for all measured quantities. In the case of SH38, $SFA$ values above 25 % were measured down to the lowest test temperature ($-198 \, ^\circ\text{C}$), thus increasing the uncertainty of $FATT_{50}$ (Fig. 2).

   Particularly for LL141, the uncertainties in $DBTT$ values for the different specimen types produce results which deviate from the typical pattern of transition temperatures decreasing with specimen size, which has been reported by many investigators [8-16]. See for example the comparison between $DBTT_{KV}$ values for X52 and LL141 in Fig. 3.

   Another indication of the significant uncertainties associated with some of the transition temperatures for LL141 and SH38 is illustrated in Fig. 4, which compares $DBTT_{KV}$, $DBTT_{LE}$, and $FATT_{50}$ values for the three NIST reference steels.

   Under normal circumstances, the three definitions of transition temperature are expected to agree within $\pm 25 \, ^\circ\text{C}$. As seen in Fig. 4, this is often not the case for LL141 and to a lesser degree for SH38. We therefore decided to exclude from further analyses all material/specimen combinations corresponding to points falling outside the $\pm 25 \, ^\circ\text{C}$
tolerance bounds in Fig. 4. Even though arbitrary, this decision appeared to us a reasonable approach to deal with excessive scatter in experimental data.

CORRELATIONS BETWEEN CHARPY SPECIMEN TYPES

Ductile-to-Brittle Transition Temperatures

Figure 5 shows the average values calculated for the transition temperature shifts \( (DBTT_{CVN} - DBTT_{SCVN/MCVN}) \) for each non-standard specimen type investigated, considering \( KV, LE, \) and \( SFA \). The data in Fig. 5 confirm that the magnitude of the shift decreases with decreasing specimen cross section, as previously reported by many authors [8-16].

Several investigators have proposed empirical correlations between transition temperature shifts and various dimensional parameters for sub-size or miniaturized Charpy specimens, such as thickness, cross sectional area or normalized fracture volume.

Both Towers [13] and Wallin [15] have correlated temperature shifts \( \Delta T \) with specimen thickness \( B \), respectively suggesting the following correlations:

\[
\Delta T = 0.7(10 - B)^2 \tag{2}
\]

\[
\Delta T = -51.4 \cdot \ln \left[ 2 \left( \frac{B}{10} \right)^{0.25} - 1 \right] \tag{3}
\]

In eq. (2), transition temperature is defined as the temperature corresponding to an energy density of 0.25 J/mm\(^2\) (20 J for CVN specimens). Eq. (3), on the other hand, was obtained by fitting temperature shifts based on transition temperatures calculated
for energy densities in the range 0.25 J/mm$^2$ to 0.5 J/mm$^2$ (20 J to 40 J for CVN specimens).

Various transition temperature shifts ($\Delta DBTT_{KV}$, $\Delta DBTT_{LE}$, $\Delta FATT_{KV}$, $\Delta T_{0.25J/mm^2}$, $\Delta T_{0.5J/mm^2}$) are plotted in Fig. 6 as a function of specimen thickness for all tests performed. The figure compares experimental data points with eqs. (2) and (3). Despite a significant amount of scatter, our test results generally appear to follow the trends of eqs. (2) and (3). It is interesting to note that, although for KLST and RHS specimens thickness is just one of the reduced dimensions, their results seem to follow the same trend as SCVN specimens.

The scatter is considerably reduced if only transition temperatures based on energy density ($T_{0.25J/mm^2}$, $T_{0.5J/mm^2}$) are considered, see Fig. 7. The one data point which appears to be a clear outlier corresponds to $\Delta T_{0.25J/mm^2}$ for RHS specimens of LL141. Note also that in several instances $T_{0.25J/mm^2}$ is undefined because the lower shelf of the transition curve corresponds to an energy density higher than 0.25 J/mm$^2$ (HH-143 – 3/4-size, 1/2-size, 1/4-size; SH38 – all specimen types). Similarly, in a few cases $T_{0.5J/mm^2}$ is undefined because the upper shelf of the transition curves corresponds to an energy density lower than 0.5 J/mm$^2$ (LL141 – all specimen types; SH-38 – 1/4-size; X52 – KLST specimens).

In order to screen potential outliers, we decided to remove from the database any material/specimen combination for which $\Delta DBTT_{KV}$ differed by more than $\pm$ 25 °C from $\Delta DBTT_{LE}$ or $\Delta FATT_{50}$, see Fig. 8. The same screening criterion was applied to the comparison between $\Delta T_{0.25J/mm^2}$ and $\Delta T_{0.5J/mm^2}$, see Fig. 9. Note that the single outlier in Fig. 9 corresponds to the same outlier data point already outlined in Fig. 7.
The remaining database of temperature shifts was fitted by means of a logarithmic relationship, following Wallin’s example [15], and the results are illustrated in Fig. 10. The regression function obtained in Fig. 10:

$$\Delta T = 30 \cdot \ln(B) - 66.2$$

is extremely close to both eqs. (2) and (3), but particularly to Towers’ empirical model [13]. Eq. (4) yields a Mean Square Error MSE = 237 °C² and a Mean Residual MR = 0.07 °C.

We also correlated our “filtered” database with the SCVN/MCVN ligament cross section $s$ (in mm²), in consideration of the fact that MCVN specimens have both cross section dimensions (thickness and width) reduced, and not just the thickness. A reasonably linear relationship is apparent in Fig. 11:

$$\Delta T = 0.409 \cdot s - 32.71$$

with the imposed constraint that $\Delta T = 0$ for $s = 80$ mm² (CVN specimen). Eq. (5) yields a Mean Square Error MSE = 253 °C² and a Mean Residual MR = 0.47 °C. These statistics are marginally worse than those previously obtained for eq. (4).

**Absorbed energies for fully ductile specimens**

First and foremost, it is necessary to emphasize that any correlation between absorbed energies for different Charpy specimen types is only valid provided both specimens are in the fully ductile behavior regime (upper shelf).

The first author to propose an analytical correlation between energies absorbed by full-size and sub-size Charpy specimens was Curll in 1959 [11]:
where:

\[ E = \frac{KV}{S}, \text{ or energy density (J/mm}^2\text{)}, \]

\[ K = \text{energy of rupture (29.3 J for ductile steels)}, \]

\[ d, D = \text{ligament size for SCVN and CVN respectively, and} \]

\[ s, S = \text{cross sectional area for SCVN and CVN respectively.} \]

Note that \( d = D \) for SCVN specimens and therefore eq. (6) reduces to:

\[ E_{SCVN} = E_{CVN} \frac{s}{S} \quad (7) \]

i.e., energy densities are proportional to cross sectional areas.

For each investigated material, we calculated the energy density at three or four temperatures where all tested specimen types exhibited fully ductile behavior. The results obtained are plotted in Fig. 12, where data for each SCVN/MCVN specimen type are fitted with straight lines passing through the origin (i.e., \( E_{SCVN/MCVN} = 0 \) when \( E_{CVN} = 0 \)). It is apparent that the tougher the material, the higher is the energy density for SCVN/MCVN specimens with respect to CVN specimens. Moreover, smaller specimens tend to provide higher energy densities.

The energy density ratio \( (E_{CVN}/E_{SCVN/MCVN}) \) for the investigated specimen types, taken as the slope of the linear regressions shown in Fig. 12, is plotted and fitted in Fig. 13 as a function of cross sectional area. In the figure, data are compared to eq. (7) from Curll, which in principle only applies to SCVN specimens. The relationship obtained is:
If only SCVN are fitted, the equation of the linear regression is:

\[
\frac{E_{SCVN}}{E_{CVN}} = 0.0063s + 0.431
\]  

In both cases, energy densities for non-standard specimens are significantly higher than given by Curll in [11].

**Upper Shelf Energy (USE) Values**

The most commonly used approach for correlating USE values between Charpy specimens of different geometries involves the use of a normalization factor, \(NF\), which can be empirically derived from experimental data or calculated as the ratio between specific geometric parameters:

\[
USE_{CVN} = NF \cdot USE_{SCVN/MCVN}
\]

Published values of \(NF\) include:

- \(NF_1\) = ratio of fracture areas, expressed as \(Bd\), where \(d\) is the ligament size [17,18];
- \(NF_2\) = ratio of nominal fracture volumes, expressed as \((Bd)^{3/2}\) [17,18];
- \(NF_3\) = ratio of nominal fracture volumes, expressed as \(Bd^2\) [19,20];
- \(NF_4\) = ratio of \(Bd^2/AK\) (with \(A\) = span, or distance between the anvils, and \(K\) = elastic stress concentration factor, which depends on ligament size and notch root radius) [21];
• \( NF_5 \) = ratio of \((Bd)^{3/2}/QK_t\) (with \( Q \) = plastic stress concentration factor, given by \( Q = 1 + (\pi - \theta)/2 \), where \( \theta \) is the notch angle in radians) [22].

Additionally, empirical normalization factors were published by Sokolov and Alexander for 4 types of miniaturized Charpy specimens [23] (\( NF_6 \)) and by Lucon et al. for KLST specimens [24] (\( NF_7 \)).

The empirical normalization factors \( NF_8 \) calculated in this study by fitting the experimental USE values given in Table 3 are provided in Table 4, which compares them to the geometrical and empirical factors listed above.

Geometrical and empirical factors are plotted in Fig. 14 as a function of cross sectional area. Our results are in good agreement with both \( NF_2 \) (ratio of nominal fracture volumes \((Bd)^{3/2}\)) and \( NF_3 \) (ratio of nominal fracture volumes \( Bd^2 \)). Exponentially fitting our test results yields:

\[
\frac{USE_{CVN}}{USE_{SCVN}/MCVN} = 899.14 \cdot s^{-1.599}
\]

with coefficient of determination \( R^2 = 0.98 \).

In Fig. 14 the largest discrepancies are observed for KLST specimens. For this MCVN geometry, the results we obtained on line pipe steels were also compared in Fig. 15 to the following exponential fit, which was obtained in [24] from a number of reactor pressure vessel (RPV) ferritic steels:

\[
USE_{CVN} = 29.454 \cdot e^{0.2378 \cdot USE_{KLST}}
\]
The agreement between our results and eq. (12) is reasonable, although $USE_{CVN}$ is underestimated for X65 and X70, which have significantly higher toughness and strength than typical RPV steels.

**NIST VERIFICATION SPECIMENS FOR SMALL-SCALE PENDULUM MACHINES**

Reference full-size Charpy specimens used for the indirect verification of impact machines, produced by National Metrology Institutes such as NIST in the US and IRMM (Institute for Reference Materials and Measurements) in the European Union, cannot be used to verify small-scale impact machines, having capacity between 15 J and 50 J.

NIST in Boulder Colorado has recently qualified miniaturized KLST specimens, which can be used to verify small-scale machines at three energy levels: low energy (1.59 J), high energy (5.65 J), and super-high energy (10.03 J). The same reference specimens can also be used to verify the force scale if the striker is instrumented: certified maximum force values are 2.43 kN, 1.78 kN, and 1.79 kN at the three energy levels respectively. KLST verification specimens are tested at room temperature (21 °C ± 3 °C), and are available in sets of three samples.

Certified reference values for both maximum force and absorbed energy were established by means of an interlaboratory exercise (Round-Robin), which was coordinated by NIST and involved nine qualified international laboratories, mostly European. The Round-Robin results were analyzed by NIST in accordance with both ISO 5725-2 [25] and ASTM E691 [26], as well as standard procedures of the Charpy Verification Program at NIST [27].
CONCLUSIONS

The study presented here was aimed at correlating impact test results from Charpy specimens of different configurations (full-size, sub-size, and miniaturized). The materials investigated included four line pipe steels of varying toughness and strength, as well as three steels used by NIST for the fabrication of Charpy verification specimens. Four sub-size specimen types (3/4-size, 2/3-size, 1/2-size, and 1/4-size) and two miniaturized specimen types were considered (RHS and KLST). The main conclusions which emerged from the study are summarized below.

1. As generally reported in the literature, ductile-to-brittle transition temperatures (expressed in relation to different variables) were found to decrease with specimen size, mainly as a result of diminishing stress triaxiality and loss of constraint.

2. The transition temperature shift caused by size reduction can be correlated to specimen thickness for both sub-size and miniaturized specimens, even though for the latter both thickness and width are reduced with respect to full-size specimens. The empirical correlation we established is in good agreement with those proposed by Towers and Wallin. A simpler linear correlation was also obtained as a function of ligament cross section.

3. A direct correlation between Charpy energies absorbed by CVN and SCVN/MCVN specimens is only possible if the behavior is fully ductile for both specimens. In this
case, we established a logarithmic empirical correlation between the ratio of absorbed energies and the area of the MCVN/SCVN cross section.

4. As far as the correlation of Upper Shelf Energies is concerned, our test results were compared with several normalization factors \( NF = USE_{CVN}/USE_{SCVN/MCVN} \) published in the literature. A strong exponential correlation with cross sectional area was found, in close agreement with the normalization factor based on the ratio of nominal fracture volumes \( B d^2 \).

5. In general, we found that the same relationships can be used to correlate the behavior of full-size specimens with that of both sub-size specimens (where only the thickness is reduced) and miniaturized specimens (where both thickness and width are reduced). Cross sectional area appears to be an effective independent variable for the correlations.

6. In all cases, a significant amount of data scatter was observed. As a consequence, any full-size specimen prediction based on the empirical correlations obtained is subject to considerable uncertainty. Material-specific correlations (e.g. for line pipe steels, for RPV steels, etc.) may provide more accurate predictions.

7. The correlations in this study were obtained after screening possible outliers by comparing various measures of transition temperatures \( DBTT_{KV}, DBTT_{LE}, FATT_{50}, T_{0.25J/mm^2}, T_{0.5J/mm^2} \). If any of the different measures differed by more than \( \pm 25 \) °C, the material/specimen combination was excluded by subsequent analyses. This could be adopted as a reasonable “quality check” for future investigations.
REFERENCES


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KV transition curve for LL141, CVN specimens

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SFA transition curve for SH38, CVN specimens

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Fig. 9  
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Table 2  Charpy specimens tested for each material
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Table 1 - Chemical composition of the steels (wt %)

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Table 2 – Charpy specimens tested for each material

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Table 3 - Transition temperatures and USE values obtained

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Table 4 - Geometrical and empirical normalization factors for SCVN and MCVN specimens

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Fig. 1 - KV transition curve for LL141, CVN specimens
Fig. 2 - SFA transition curve for SH38, CVN specimens
Fig. 3 – $DBTT_{Kv}$ values calculated for X52 and LL141
Fig. 4 – Comparison between ductile-to-brittle transition temperatures calculated for LL141, HH143, and SH38
Fig. 5 – Transition temperature shifts between CVN and SCVN/MCVN specimens, as a function of specimen cross section.
Fig. 6 – Calculated transition temperature shifts as a function of specimen thickness, and comparison with eq. (2) and eq. (3)
Fig. 7 – $\Delta T_{0.25\text{J/mm}^2}$ and $\Delta T_{0.5\text{J/mm}^2}$ vs. specimen thickness, and comparison with eq. (2) and eq. (3)
Fig. 8 – Comparison between $\Delta DBTT_{KV}$, $\Delta DBTT_{LE}$ and $\Delta FATT_{50}$. 

The diagram shows a scatter plot with two sets of data points. One set is represented by blue circles labeled $DBTT_{LE}$, and the other by orange triangles labeled $FATT_{50}$. The plot includes two dashed lines with slopes of ±45°, indicating the limits for the comparison. Points outside these limits are labeled as outliers. The x-axis represents $\Delta DBTT_{KV}$ (°C), and the y-axis represents $\Delta DBTT_{LE}$ or $\Delta FATT_{50}$ (°C).
Fig. 9 – Comparison between $\Delta T_{0.25\text{J/mm}^2}$ and $\Delta T_{0.5\text{J/mm}^2}$
Fig. 10 – “Filtered” NIST database of transition temperature shifts, and comparison with eqs. (2) and (3)

\[ y = 30.0 \ln(x) - 66.2 \]
Fig. 11 – “Filtered” NIST database of transition temperature shifts as a function of ligament cross section

\[ \Delta T = 0.409 \cdot S - 32.71 \]
Fig. 12 – Energy densities for CVN, SCVN, and MCVN specimens
Fig. 13 – Energy density ratio as a function of SCVN/MCVN cross sectional area
Fig. 14 - Geometrical and empirical normalization factors for SCVN and MCVN specimens
Fig. 15 - Comparison between eq. (12) and NIST results from CVN and KLST tests of line pipe steels