***Manual of Codes of Practice for the Determination of Uncertainties in Mechanical Tests on Metallic Materials***

***Code of Practice No. 06***

# The Determination of Uncertainties in Charpy Impact Testing

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## 1. SCOPE

This procedure covers the evaluation of uncertainty in the determination of Charpy impact test energy and related quantities according to the European standard EN 10045: Metallic materials - Charpy impact test.

Part 1: Test method. (1990).
Part 2: Verification of the testing machine (pendulum impact). (1993).

This European standard specifies the impact test according to Charpy (U- and V-notch) for determining the impact strength of metallic materials. For certain special metals and applications the Charpy impact test may be subjected to specific standards or special regulations.

## 2. SYMBOLS AND DEFINITIONS

For a complete list of symbols and definitions of terms on uncertainties, see Section 2 of the main Manual[1]. It should be noted that not all the symbols and definitions of terms on uncertainties used in this Code of Practice are consistent with the GUM[2]. In a few cases there are conflicts between the symbols used in the above mentioned test standards and the GUM. In such cases the test Standards are given preference.

The following list gives the symbols and definitions used in this procedure.

| | |
|---|---|
| $A_S$ | indicated energy on the impact machine |
| $c_i$ | sensitivity coefficient |
| $c_T$ | sensitivity coefficient of temperature |
| COD | coefficient of determination |
| CoP | Code of Practice |
| CRM | Certified Reference Material |
| $d_v$ | divisor used to calculate the standard uncertainty |
| $e_{As}$ | error on the indicated energy of impact machine from calibration certificate |
| $e_{A1}$ | error of impact machine determined from testing CRM specimen |
| $e_{ABCR}$ | uncertainty of testing a batch of five CRM specimens |
| $e_{BCR}$ | uncertainty of the Certified value of CRM |
| E | value of absorbed energy from a batch of reference Charpy-V specimens |
| $E_{mean}$ | mean value of E from five CRM specimens |
| $E_{BCR}$ | Certified value for the energy of a batch of reference Charpy-V specimens |
| h | height of test piece |
| k | coverage factor used to calculate the expanded uncertainty (corresponding to a 95% confidence level) where a normal probability distribution can be assumed |

| | |
|---|---|
| $k_p$ | coverage factor used to calculate an expanded uncertainty (normally corresponding to 95% confidence level) ) where a normal probability distribution cannot be assumed (see Ref. [1], Section 2) |
| KU | energy absorbed, U-type notched test piece |
| KV | energy absorbed, V-type notched test piece |
| l | length of test piece |
| n | number of repeat measurements |
| p | confidence level |
| s | experimental standard deviation (of a random variable) determined from a limited number of measurements, n |
| T | nominal test temperature (in degrees Celsius or Kelvin, as indicated) |
| u | standard uncertainty |
| $u_c$ | combined standard uncertainty |
| $u_T$ | uncertainty in temperature |
| U | expanded uncertainty |
| V | value of the measurand |
| w | width of test piece |
| $x_2$ | mean value of measurements on $n_2$ test specimen |
| $\nu_{eff}$ | effective degrees of freedom used to obtain $k_p$ (see Ref. [1], Section 2) |
| $\nu_i$ | degrees of freedom of standard uncertainty u (see Ref. [1], Section 2) |

## 3. INTRODUCTION

It is good practice in any measurement to evaluate and report the uncertainty associated with the test results. A statement of uncertainty may be required by a customer who wishes to know the limits within which the reported result may be assumed to lie, or the test laboratory itself may wish to develop a better understanding of which particular aspects of the test procedure have the greatest effect on results so that this may be controlled more closely. This Code of Practice (CoP) has been prepared within UNCERT, a project funded by the European Commission's Standards, Measurement and Testing programme under reference SMT4-CT97-2165 to simplify the way in which uncertainties are evaluated. The aim is to produce a series of documents in a common format which is easily understood and accessible to customers, test laboratories and accreditation authorities.

This CoP is one of seventeen produced by the UNCERT consortium for the estimation of uncertainties associated with mechanical tests on metallic materials. The Codes of Practice have been collated in a single manual [1] that has the following sections:

1. Introduction to the evaluation of uncertainty
2. Glossary of definitions and symbols
3. Typical sources of uncertainty in materials testing
4. Guidelines for the estimation of uncertainty for a test series
5. Guidelines for reporting uncertainty

6. Individual Codes of Practice (of which this is one) for the estimation of uncertainties in mechanical tests on metallic materials

This CoP can be used as a stand-alone document. For further background information on measurement uncertainty and values of standard uncertainties of the equipment and instrumentation used commonly in material testing, the user may need to refer to Section 3 of the Manual [1]. The individual CoPs are kept as simple as possible by following the same structure; viz:

- The main procedure
- Details of the uncertainty calculations for the particular test type (Appendix A)
- A worked example. (Appendix B)

This CoP guides the user through the various steps to be carried out in order to estimate the uncertainty in Charpy Impact Energy.

## 4. A PROCEDURE FOR THE ESTIMATION OF UNCERTAINTY IN CHARPY IMPACT TEST ENERGY

### Step 1. Identifying the Parameters for Which Uncertainty is to be Estimated

The first step is to list the quantities (measurands) for which the uncertainties must be calculated. Table 1 shows the parameters that are usually reported as results from the test procedure. Often intermediate measurands are recorded by the laboratory, but are not necessarily reported to the customer. Both types of measurand are listed in Table 1.

**Table 1** Measurand, their units and symbols within EN 10045 – 1

| **Reported Measurand** | **Unit** | **Symbol** |
|---|---|---|
| Energy absorbed | J | KV or KU |
| **Other Measurements** | | |
| Height of test piece | mm | h |
| Width of test piece | mm | w |
| Length of test piece | mm | l |
| Notch geometry:<br>- Height below notch<br>- Radius of curvature<br>- Angle of notch | <br>mm<br>mm<br>° | <br>-<br>-<br>- |
| Test temperature | °C | T |

The energy absorbed is measured directly by the impact testing machine (pendulum type). The testing machine should be calibrated according to EN 10045 - 2.
The specimen dimensions should be within the specification according to EN 10045 - 1.

**Step 2. Identifying all Sources of Uncertainty in the Test**

In Step 2, the user must identify all possible sources of uncertainty which may have an effect (either directly or indirectly) on the test. The list cannot be identified comprehensively beforehand as it is associated uniquely with the individual test procedure and apparatus used. This means that a new list should be prepared each time a particular test parameter changes (e.g. when a plotter is replaced by a computer). To help the user list all sources, four categories have been defined. Table 2 lists the four categories and gives some examples of sources of uncertainty in each category.
It is important to note that Table 2 is NOT exhaustive and is for GUIDANCE only - relative contributions may vary according to the material tested and the test conditions. Individual laboratories are encouraged to prepare their own list to correspond to their own test facility and assess the associated significance of the contributions.

In the case of measuring the absorbed energy from impact testing it is very difficult to calculate the influence of each source of uncertainty. The approach of calibration by using a Certified Reference Material (CRM), and considering errors in the accuracy, CRM repeatability and test sample repeatability is probably the best approach. For the indirect verification of a Charpy impact machine 10 tests (5 x 2 sets of specimens) must be carried out periodically using a single CRM. However, for a laboratory making impact tests on a range of alloys, more classes of material toughness have to be considered. Five CRMs are available from BCR to cover this range (similar CRMs are available from USA). From this indirect verification the error of the test system is determined.

The other measurements from Table 1 are taken to check if the specimen dimensions and the temperature is within the limits of tolerance. If they are not, these measurements are not used for correcting the energy values, but it is reported that:

- the measured impact energy is measured on a specimen with different dimensions, or
- the measured impact energy is measured at a different temperature.

**Table 2** Typical sources of uncertainty and their likely contribution to the uncertainties on the measurand and measurements for a Charpy impact energy
(1 = major contribution, 2 = minor contribution, blank = insignificant (or no) contribution, * - affected indirectly)

| Source of uncertainty | Type† | KV or KU | h | w | l | T |
|---|---|---|---|---|---|---|
| **1.Test Piece** | | | | | | |
| Micrometer / operator errors in measuring specimen dimensions | A or B | 2* | 2 | 2 | 2 | |
| Shape tolerance, edge effects | B | 2* | 2 | 2 | 2 | |
| Shape tolerance of notch, notch depth | B | 1* | | | | |
| **2. Test system** | | | | | | |
| Stiffness of the machine, fastening on foundation | B | 1* | | | | |
| Accuracy of calibration energy measurement | A | 2* | | | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| Error of the test system | A | 1 | | | | |
| Adjustment of specimen anvils and supports, horizontal position of specimen with respect to the centre of strike | B | 1* | | | | |
| Temperature measurement, calibration | B | | | | | 1 - 2 |
| **3. Environment** | | | | | | |
| Poor control of ambient temperature | B | 2* | | | | |
| Takes too long time, specimen temperature change | B | 1* - 2 | | | | 1 - 2 |
| Poor control of specimen temperature | B | 1* - 2 | | | | 1 - 2 |
| **4. Test Procedure** | | | | | | |
| Incorrect adjustment of machine or specimen position | B | 1* | | | | |
| Incorrect read out of energy | B | 2* | | | | |

† see Step 3

To simplify the calculations it is advisable to group the significant sources of uncertainty in Table 2, in the following categories:

1 Uncertainty in Charpy input energy due to test piece and notch geometry.
2 Uncertainty in the test system.
3 Uncertainty in the environment.
4 Uncertainty in the test procedure.

**Step 3. Classifying the Uncertainty According to Type A or B**

In this third step, which is in accordance with Reference 2, *'Guide to the Expression of Uncertainties in Measurement'*, the sources of uncertainty are dassified as *Type A* or *B*, depending on the way their influence is quantified. If the uncertainty is evaluated by statistical means (from a number of repeated observations), it is classified *Type A*, if it is evaluated by any other means it should be classified as *Type B*.

The values associated with *Type B* uncertainties can be obtained from a number of sources including a calibration certificate, manufacturer's information, or an expert's estimation. For *Type B* uncertainties, it is necessary for the user to estimate the most appropriate probability distribution for each source (further details are given in Section 2 of Ref. [1]).

**Step 4. Estimating the Standard Uncertainty for each Source of Uncertainty**

In this step the standard uncertainty, u, for each input source identified in Table 2 is estimated (see Appendix A). The standard uncertainty is defined as one standard deviation and is derived from the uncertainty of the input quantity divided by the parameter, $d_v$, associated with the assumed probability distribution. The divisors for the typical distributions most likely to be encountered are given in Section 2 of Ref. [1].

The individual influences of each source of uncertainty on the energy absorbed is very complex and not practical. The simplest way is to use a CRM to calibrate the whole system, and consider the errors, CRM repeatability and test sample repeatability. The remaining sources of uncertainty and their influences on the evaluated quantities are summarised in Table 3, with a more complete explanation of their derivation appearing in Appendix A. Appendix B gives a worked example.

**Table 3** Typical worksheet for uncertainty calculations in Charpy-V absorbed energy measurement

| Symbol | Source of Uncertainty | Value [J] or [%] | Probability distribution | Divisor $d_v$ | $c_i$ | $u_i(KV)$ [J] | $v_i$ or $v_{eff}$ |
|---|---|---|---|---|---|---|---|
| $E_{BCR}$ | **Certified value of CRM** | | | | | | |
| $e_{BCR}$ | uncertainty of the Certified value of CRM[1)] | | normal | 2 | 1 | | ∞ |
| $e_{As}$ | error of impact machine from calibration certificate: | | | | | | |
| $E_{mean}$ | **Mean of 5 measurements on CRM** | | | | | | |
| $e_{ABCR}$ | uncertainty of CRM testing[2)] | | normal | 1 | 1 | | 4 |
| $e_{A1}$ | error of impact machine determined from testing 5 CRM specimen[3)] | | | | | | |
| | **Measure on a material with $n_2$ = 3** | | | | | | |
| $x_2$ | mean value | | | | | | |
| $e_{x2}$ | error of the impact machine for the mean value $x_2$ | | | | | | |
| $u_3$ | standard deviation from $n_2$ specimen[4)] | | normal | 1 | 1 | | 2 |
| $u_4$ | effect of error of reading[5)] | | rectangular | √3 | 1 | | ∞ |
| $u_5$ | effect of specimen dimensions[6)] | | rectangular | √3 | 1 | | ∞ |
| $u_c$ | combined standard uncertainty[7)] | | normal | | | | |
| U | **expanded uncertainty[8)] $k_p$ =** | | normal | | | | |

1) see Section A1
2) includes all variation of the machine and adjustments at that time
3) the error is a percentage of the absorbed energy, determined from a higher energy level
4) includes all contributions of the material
5) divisor is √3 for analogue and √12 for digital readouts
6) includes specimen dimensions within specification
7) see Step 5
8) see Step 6

**Step 5. Computing the Combined Uncertainty $u_c$**

Assuming that individual uncertainty sources are uncorrelated, the measurand's combined uncertainty of the measurand, $u_c(y)$, can be computed using the root sum squares:

$$u_c(y)=\sqrt{\sum_{i=1}^{N} [c_i.u(x_i)]^2} \qquad (1)$$

where $c_i$ is the sensitivity coefficient associated with $x_i$. This uncertainty corresponds to plus or minus one standard deviation on the normal distribution law representing the studied quantity. The combined uncertainty has an associated confidence level of 68.27%.

**Step 6. Computing the Expanded Uncertainty U**

The expanded uncertainty, U, is defined in Reference 2 as "the interval about the result of a measurement that may be expected to encompass a large fraction of the distribution of values that could **reasonably** be attributed to the measurand". It is obtained by multiplying the combined uncertainty, $u_c$, by a coverage factor, k, which is selected on the basis of the level of confidence required. For a normal probability distribution, the most generally used coverage factor is 2, which corresponds to a confidence interval of 95.4% (effectively 95% for most practical purposes). The expanded uncertainty, U, is therefore, broader than the combined uncertainty, $u_c$. Where a higher confidence level is demanded by the customer (such as for aerospace, electronics, ...), a coverage factor of 3 is often used so that the corresponding confidence level increases to 99.73%.

In cases where the probability distribution of $u_c$ is not normal or where the number of data points used in *Type A* analysis is small, the value of k should be calculated from the degrees of freedom given by the Welsh-Satterthwaite method (see Reference 1, Section 4 for more details).

**Step 7. Reporting of Results**

Once the expanded uncertainty has been estimated, the results should be reported in the following way:

$$V= y \pm U \qquad (2)$$

where V is the estimated value of the measurand, y is the test (or measurement) mean result, U is the expanded uncertainty associated with y. An explanatory note, such as that given in the following example should be added (change when appropriate):

"The reported expanded uncertainty is based on a standard uncertainty multiplied by a coverage factor, k = 2, which for a normal distribution corresponds to a coverage probability, p, of approximately 95%. The uncertainty evaluation was carried out in accordance with UNCERT CoP 06:2000."

## 5. REFERENCES

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2. BIPM, IEC, IFCC, ISO, IUPAC, OIML, "*Guide to the Expression of Uncertainty in Measurement*". International Organisation for Standardisation, Geneva, Switzerland, ISBN 92-67-10188-9, First Edition, 1993. [This Guide is often referred to as the GUM or the ISO TAG4 document after the ISO Technical Advisory Group that drafted it.]

   BSI (identical), "*Vocabulary of metrology, Part 3. Guide to the expression of uncertainty in measurement*", PD 6461: Part 3 : 1995, British Standards Institution.

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5. ISO 5725: Accuracy (trueness and precision) of measurements methods and results
   Part 1: General principles and definitions (1994)
   Part 2: Basic method for the determination (1994)
   Part 3: Intermediate measures of the precision of a standard measurement method
   Part 4: Basic methods for the determination of the trueness of a standard measurement method (1994)
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# APPENDIX A

## FUNDAMENTAL ASPECTS AND MATHEMATICAL FORMULAE FOR CALCULATING UNCERTAINTIES IN CHARPY IMPACT TESTING

Assessment of the individual influence of each source on the energy absorbed is very complex and not practical. Therefore we use indirect verification with a Certified Reference Material as the only reasonable approach. Indirect verification accounts for the total energy absorbed at fracture of the specimen. The remaining sources of uncertainty and their influences on the evaluated quantities are summarised in Table 3 of the CoP.

The calibration certificate for the direct verification includes the error in the indicated energy of the impact machine.

EN 10045-2 specifies that impact toughness machines should be certified by using the BCR certified reference Charpy specimens or other specimens traceable to the latter, whereas ASTM E-23 requires the use of verification specimens with reference values determined by NIST. CRMs have been made available by BCR at the following five nominal energy levels: 30 J, 60 J, 80 J, 120 J, and 160 J. CRMs are available from NIST at three ranges of energy (12.2 – 20.3 J, 88.1 – 115 J, 210 - 230 J).

Because it is not common practice to correct for the systematic error of the machine, this error is taken into account linearly to the expanded uncertainty. According to NIST, calibration or correction curves should not be used because the source(s) and magnitude of the errors in the measured values at one energy level may not be the same at different energy levels.

### A1. Uncertainties In The Certified Value Of CRM

The certified values of the CRM, which are given in the certificate belonging to the specimen, are the mean value $E_{BCR}$ and the uncertainty of the certified value of the CRM $e_{BCR}$. The uncertainty mainly includes the effect of the variation between samples.

The ISO 5725 standard is additional to the GUM. The methods described in it have long been used in test environments. They are based on the principles of a standardised method, reference material, comparison and inter- or intra-laboratory variance. These methods, although seemingly very different from that of the GUM, can be considered as a determination of uncertainty by a *type A* method: experiments carried out by a wide range of laboratories with very similar specialisation and statistical processing of the results.

The values generally published are:
- r: repeatability limit: The value less than or equal to which the absolute difference between two test results obtained under repeatable conditions may be expected to be with a probability

of 95% (results are obtained with the same method on identical test items in the same laboratory by the same operator using the same equipment).
- R: reproducibility limit: The value less than or equal to which the absolute difference between two test results obtained under reproducible conditions may be expected to be with a probability of 95% (results are obtained with the same method on identical test items in different laboratories with different operators using different equipment).
If the R of a standardised method is published, then $s = \frac{R}{2\sqrt{2}}$ can be taken as the standard deviation of a measurement carried out scrupulously in accordance with the method, by approximating $2\sqrt{2} \approx 2.8$. In other cases we use $\sigma = e_{BCR} / 2$.

The following uncertainties have to be considered:

1) Uncertainty from standard deviation of a measurement on a CRM:

$$u_1 = e_{BCR} / 2\sqrt{2} \qquad (4)$$

2) The uncertainty due to testing the CRM specimens

The error of the impact machine $e_{A1}$ is calculated as $E_{mean} - E_{BCR}$, where:

$$E_{mean} = (E_1 + E_1 + E_1 + E_1 + E_1) / 5 \qquad (5)$$

$E_{BCR}$ = the certified value of the absorbed energy from a single batch of reference Charpy- V specimens.

BCR did not follow the GUM in the uncertainty calculation until end of 1999, in the example in Appendix B the value $d_v = 2$ is used. For new samples from BCR the value $d_v = 2.8$ should be used.

It is not common practice to correct for the systematic error of the machine, therefore this error is taken into account linearly with the expended uncertainty. Calibration or correction curves should not be used according to NIST, because the source(s) and magnitude of error for energy values at one energy level may not be the same at different energy levels.

## A2. Uncertainty In Energy Values Obtained From Test Specimens

The following uncertainties have to be considered:

1) Uncertainty due to testing n specimens

2) Uncertainty due to the error of reading of the energy value, associated with the grade mark on the energy scale:

$$u = \frac{\text{tolerance limit}}{d_v} \tag{6}$$

The divisor $d_v$ is $\sqrt{3}$ for analogue readouts and $\sqrt{12}$ for digital readouts.

## A3. Uncertainty Due To Specimen Dimensions

As the measured impact energy is not corrected for the specimen cross-section, the dimensions of the cross-sectional area below the notch directly influences the energy absorbed. The calculated uncertainty due to the uncertainty in cross-sectional area caused by variations in the specimen dimensions, including the depth of the notch, is assumed to vary linearly with the cross-sectional area. Probably this is not a conservative approach. Table X1.1 of ASTM E23 [3] shows the effect of varying the notch dimensions on standard specimens. From this table it can be calculated that changing the notch depth by 1.5% can give energy changes up to about 5 to 8%, depending on the mean energy value. This is based on a few measurements only and the reproducibility of the mean value is about the same order of magnitude. As long as more data are not available, the proposed influence is the most practical approach. Uncertainty due to specimen dimensions, assuming a linear relationship according (6). The tolerance limit is about 1%, with a rectangular probability distribution.

## A4. Uncertainty Due To Test Temperature

The measured energy depends directly on the specific test temperature at which the test was performed. The stated temperature should be corrected for uncertainty and in that case no uncertainty for temperature should be added. If the impact energy is required for a specified temperature, at which the test is done, then the uncertainty due to temperature should be included. Special attention should be paid to select the right value for the sensitivity coefficient $c_i$, especially if the temperature is in the transition range of the material being tested. The uncertainty is:

$$u = c_T \,.\, u_T \,/\, d_v \tag{7}$$

where $c_T$ is the sensitivity coefficient, $u_T$ is the uncertainty in temperature and $d_v$ depends on the distribution of the temperature uncertainty.

## A5. Uncertainty Due To Specimen Notch Geometry

The influence of the specimen notch geometry is strong, especially outside the allowable tolerances of the standards. This influence is not covered by the use of a CRM as they are always supplied in machined form and therefore any comparison does not include these effects. It can be predicted that a sharper notch will give a lower energy level, and a more blunt notch will give a higher one. The effect of the notch geometry is dependent on material, mean level of energy (temperature), the sharpness of the fabrication tool and probably the roughness of its cutting edge. Using a blunt tool can induce a degree of work hardening at the notch which can conceivably influence the impact energy, particularly when this energy level is on the lower shelf for steel specimens.

# Appendix B

## Worked example for calculating uncertainties in Charpy Impact Test Energy

A customer asked a laboratory to obtain the Charpy Impact Energy of a material at a specific temperature, tested according to EN 10045-1. The laboratory has a certified impact testing machine, which was verified both with the direct and indirect verification according to EN 10045-2. The sources of the uncertainty measured on the CRM specimens are known, and given in Table B1.1.

Suppose three steel Charpy-V specimens were tested at T = –10 °C. The impact energy values are given in Table B1.2. and the mean value and standard deviation from the three specimens can be calculated. Now the uncertainty can be calculated according the outline and formulae given in Table 3 of the CoP. In the example worksheet Table B2, the data from Table B1 were used to calculate the individual uncertainties which contribute to the total uncertainty.

**1. Uncertainty from BCR reference specimens (CRM)**

Certified value of reference specimen $E_{BCR}$ 123.8 J

Uncertainty 4.5 J

Testing five CRM specimen on the impact machine.

| | energy absorbed E [J] | residual | residual$^2$ |
|---|---|---|---|
| specimen 1 | 126.2 | 4.72 | 22.28 |
| specimen 2 | 127.1 | 3.82 | 14.59 |
| specimen 3 | 129.5 | 1.42 | 2.02 |
| specimen 4 | 134.8 | -3.88 | 15.05 |
| specimen 5 | 137.0 | -6.08 | 36.97 |
| sum | 654.6 | sum | 90.91 |
| $E_{mean}$ | 130.92 | $s_1$ | 4.77 |

| | | |
|---|---|---|
| repeatability = $E_{max}$ - $E_{min}$ | 10.8 J | 8.7% (< 15%) |
| error $e_{A1}$ = $E_{mean}$ - $E_{BCR}$ | 7.12 J | 5.8% (< 10%) |

**2. Uncertainty from three test specimens**

Material: steel Test temperature T = -10°C

| | energy absorbed E [J] | residual | residual$^2$ |
|---|---|---|---|
| specimen 1 | 90.5 | -6.7 | 44.89 |
| specimen 2 | 75.6 | 8.2 | 67.24 |
| specimen 3 | 85.3 | -1.5 | 2.25 |
| sum | 251.4 | sum | 114.38 |
| Mean $x_2$ | 83.80 | $s_2$ | 7.56 |

**Table B1** Input data for the example worksheet for uncertainty calculation.

**Table B2** Example worksheet for uncertainty calculations in Charpy-V absorbed energy measurements.

| Symbol | Source of Uncertainty | Value [J] or [%] | Probability distribution | Divisor $d_v$ | $c_i$ | $u_i$(KV) [J] | $v_i$ or $v_{eff}$ |
|---|---|---|---|---|---|---|---|
| $E_{BCR}$ | **Certified value of CRM** | 123.8 | | | | | |
| $e_{BCR}$ | uncertainty of the Certified value of CRM[1)] | 4.5 | normal | 2 | 1 | 2.25 | ∞ |
| $e_{As}$ | error of impact machine from calibration certificate: | 1 | | | | | |
| $E_{mean}$ | **Mean of 5 measurements on CRM** | 130.9 | | | | | |
| $e_{ABCR}$ | uncertainty of CRM testing[2)] | 4.77 | normal | 1 | 1 | 2.13 | 4 |
| $e_{A1}$ | error of impact machine determined from testing 5 CRM specimen[3)] | **5.8%** | | | | | |
| | **Measure on a material with $n_2$ = 3** | | | | | | |
| $x_2$ | mean value | **83.8** | | | | | |
| $e_{x2}$ | error of the impact machine for the mean value $x_2$ | **4.8** | | | | | |
| $u_3$ | standard deviation from $n_2$ specimen[4)] | 7.56 | normal | 1 | 1 | 4.37 | 2 |
| $u_4$ | effect of error of reading[5)] | 2.00 | rectangular | √3 | 1 | 1.15 | ∞ |
| $u_5$ | effect of specimen dimensions[6)] | 1% | rectangular | √3 | 1 | 0.48 | ∞ |
| $u_c$ | combined standard uncertainty[7)] | | normal | | | 5.50 | 4.9 |
| U | **expanded uncertainty[8)] $k_p$ = 2.66** | | normal | | | **19.5** | |

8) A coverage factor of 2.66 was obtained from the student's t-distribution table by interpolation for $\nu_{eff}$ = 4.9. The expended uncertainty: 4.8 + 2.66 *5.5 = 19.5 J.
9) $u_{CRM}$ = 4.5 / 2 = 2.25
10) $u_{ABCR}$ = 4.77 /  5 = 2.13
11) $e_{A1}$ = (130.9 – 123.8)/123.8 = 5.8%
12) $u_3$ = 7.56 /  3 = 4.37
13) $u_4$ = 2 /  3 = 1.15
14) $u_5$ = 83.8 / 100 / √3 = 0.44
15) $u_c = \sqrt{(2.25^2 + 2.13^2 + 4.37^2 + 1.15^2 + 0.48^2)} = 5.50$. The effective degrees of freedom, $\nu_{eff}$, was calculated according to Eqn.7 in Ref. [1], Section 2, viz.:
16)

$$n_{eff} = \frac{5.50^4}{\frac{2.13^4}{4} + \frac{4.37^4}{2}}$$

**Reported result**

The mean Charpy Impact Energy from three specimens is 84 ± 20 J.

*"The above reported expanded uncertainty is based on a standard uncertainty multiplied by a coverage factor k = 2.66, which for a normal distribution and $n_{eff}$ = 4.9 corresponds to a coverage probability, p, of 95%. The uncertainty evaluation was carried out in accordance with UNCERT COP 06:2000."*