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Standard Reference Materials® Certification Report for SRM 2237, 2238, 2239: RHS (Miniaturized) Charpy V-Notch Impact Specimens

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Abstract

This Certification Report documents the procedures used to develop certified values of absorbed energy (*KV*) for the following RHS (*Reduced Half-Size*)-type miniaturized verification Charpy V-notch impact specimens:

- SRM 2237 (low-energy level, *KV* = 3.87 J)
- SRM 2238 (high-energy level, *KV* = 14.01 J)
- SRM 2239 (super-high energy level, *KV* = 35.26 J).

Certified values were obtained from the statistical analysis of a large number of impact tests performed on RHS specimens by means of a tabletop small-scale Charpy machine at NIST in Boulder, Colorado. The RHS specimens tested were machined from previously tested (broken) full-size Charpy V-notch verification specimens with energy levels corresponding to low energy (SRM 2092), high energy (SRM 2096), and super-high energy (SRM 2098). This report is intended to provide outside observers with accurate and detailed information on how the materials were certified and how the certification program was conducted. All certified values were established at room temperature (21 °C ± 1 °C).

Key words

Charpy testing; indirect verification; MCVN; miniaturized Charpy specimens; RHS; small specimens; small-scale impact testers.

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1. Introduction

This Certification Report documents the procedures used to develop certified values of absorbed energy (*KV*) for miniaturized Charpy V-notch impact specimens at three absorbed energy levels (low, high and super-high).

Miniaturization of mechanical test samples, including impact specimens, is becoming increasingly important as material consumption and material availability often represent limiting factors for mechanical testing. Historically, miniaturized Charpy V-notch (MCVN) specimens have been used since the 1980s in many countries, mainly as a means of re-using already tested Charpy samples. The most commonly used miniaturized Charpy specimen is designated KLST (from the German *Kleinstprobe*, or "small specimen") [1,2]. However, international test standards such as ISO 14556 [3] and ASTM E2248 [4] cover additional miniaturized Charpy specimen geometries, including the RHS (*Reduced Half-Size*) specimen. The dimensions of the RHS specimen are proportional to those of a standard ASTM E23 [5] Charpy V-notch specimen, with a scaling ratio of 48.3 % (slightly below 50 %, in order to allow the extraction of four RHS specimens from half of a full-size Charpy specimen). RHS specimens have the nominal dimensions illustrated in Fig. 1.

The RHS specimen is the recommended proportional specimen configuration for ASTM E2248, which advocates the use of scaled specimens as well as scaled striker radius, anvil radii, and anvil span, in order to maintain scalability of the stress fields. On the other hand, the reference geometry for ISO 14556 is the KLST specimen, whereas RHS is only listed as an alternative configuration.

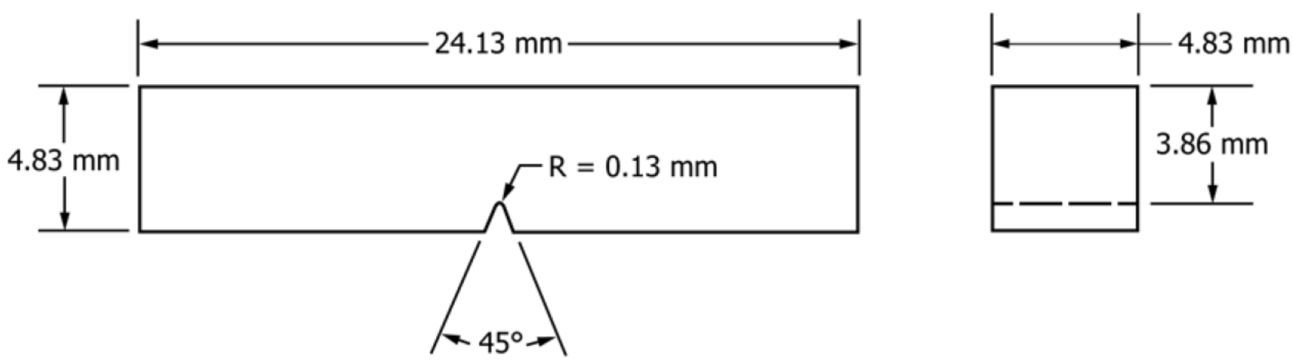

Fig. 1 - RHS-type MCVN specimen.

RHS specimens can be tested on a conventional, full-size impact tester, provided the anvils and supports are adequately modified to account for specimen dimensions and reduced anvil span. However, the recommended procedure is to use a small-scale pendulum with a significantly lower potential energy (typically 50 J instead of 300 J or more) and slightly lower impact speed (approximately 3.5 m/s instead of 5 m/s or more). Small-scale impact testers cannot be indirectly verified by means of full-size Charpy reference specimens, for both dimensional and energy reasons.

Currently, the only available MCVN specimens with certified values of absorbed energy are NIST SRM[1] 2216, SRM 2218, and SRM 2219 (KLST verification specimens of

[1] SRM = Standard Reference Material.

low, high, and super-high energy respectively) [2]. To date, no certified RHS specimens are available for users of small-scale impact testers.

2. Materials and Specimens

The RHS-type MCVN specimens used for SRMs 2237, 2238, and 2239 were extracted from previously tested (broken) full-size impact verification specimens from the following lots:

- LL-137 (low energy, SRM 2092);
- HH-164 (high energy, SRM 2096);
- SH-54 (super-high energy, SRM 2098).

The certified values of absorbed energy for the three full-size specimen lots are shown in Table 1, with expanded uncertainties corresponding to 95 % uncertainty intervals.

Table 1 - Certified values of absorbed energy for the full-size impact specimens from which RHS specimens were extracted. (k = coverage factor; N/A = not available.)

		KV at -40 °C ± 1 °C			*KV* at 21 °C ± 1 °C		
SRM	Lot	Reference Value (J)	k	Expanded Uncertainty (J)	Reference Value (J)	k	Expanded Uncertainty (J)
2092	LL-137	13.2	1.9799	0.2	17.6	1.9845	0.1
2096	HH-164	86.5	1.9939	0.3	N/A	N/A	N/A
2098	SH-54	N/A	N/A	N/A	199.5	2.0025	1.5

Specimens from lots LL-137 and HH-164 were manufactured from AISI 4340 steel bars from a single heat-treated batch in order to minimize compositional and microstructural variations. The chemical composition of the steel is given in Table 2. Additional information on the material and the heat treatment and machining processes can be found in [6].

Table 2 – Chemical composition (average between top and bottom of ingot) of AISI 4340 steel, used for lots LL-137 and HH-164 (weight %).

C	Si	Mn	Ni	Cr	Mo	S	P	Fe
0.395	0.29	0.755	1.915	0.825	0.25	0.001	0.003	Bal.

Specimens from lot SH-54 were manufactured from AISI 9310 (AMS 6265) steel bars from a single heat-treated batch in order to minimize compositional and microstructural variations. The chemical composition of the steel is shown in Table 3.

Table 3 – Chemical composition (average between top and bottom of ingot) of AISI 9310 steel, used for lot SH-54 (weight %).

C	Si	Mn	Ni	Cr	Mo	S	P	Ti	V	Fe
0.11	0.001	0.525	3.325	1.295	0.125	0.001	0.006	0.002	0.003	Bal.

RHS specimens were extracted from unbroken full-size Charpy samples through the use of EDM (Electro-Discharge Machining), ensuring the orientations of the specimen and the notch were preserved (Fig. 2). An EDM wire with 0.254 mm (0.010 in) diameter was used to cut the notches.

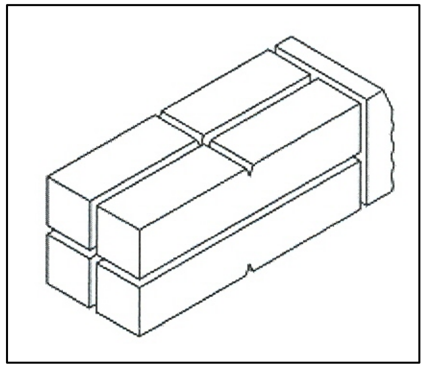

Fig. 2 – Extraction of four RHS miniaturized specimens from a full-size Charpy sample half.

3. Description of the Certification Process

The certified values of absorbed energy for the RHS verification specimens were established on the basis of 60 tests per energy level performed at NIST in Boulder, Colorado. All tests were carried out on a tabletop small-scale impact machine that had already been used for certifying KLST-type miniaturized verification specimens in 2013 [1,2].

All tests were performed at room temperature (21 °C ± 1 °C). The NIST small-scale impact tester was equipped with a striker having an edge radius of 3.86 mm (nominal 4 mm striker, Fig. 3), in accordance with ASTM E2248 [4]. The anvil span for RHS specimens is 19.3 mm. More details on the experimental setup, the machine characteristic, and the test procedures can be found in [1].

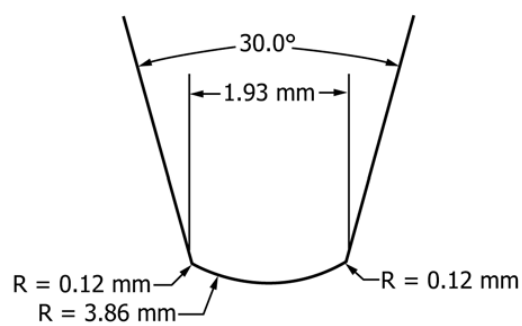

Fig. 3 – Nominal 4 mm striker used for performing impact tests on RHS specimens.

For each test performed, the energy absorbed by the impact process, *KV* (corrected for the contribution of windage and friction in accordance with ASTM E2248-18, Section 11.4), as provided by the machine encoder, was recorded.

4. Certification Test Results

4.1. Low Energy

Sixty (60) RHS specimens were tested at 21 °C ±1 °C to establish the certified absorbed energy, KV_{ref}, at the low-energy level. A basic statistical analysis of the test results yielded the following information:

- Mean absorbed energy, $\overline{KV}$ = 3.873 J .
- Standard deviation, s_{KV} = 0.099 J .
- Variance, s_{KV}^2 = 0.010 J^2 .
- Degrees of freedom = 59 .
- Standard error of the mean, SEM = 0.013 J .
- Range of absorbed energies, ΔKV = 0.46 J .
- Coefficient of variation[2], CV = 2.6 % .

The values of absorbed energy obtained from the tests performed are listed in Table 4. All the specimens broke completely as a result of impact testing.

Table 4 - Results of the impact tests performed on low-energy RHS specimens.

Specimen #	*KV* (J)	Specimen #	*KV* (J)	Specimen #	*KV* (J)
LL-101	3.60	LL-121	3.94	LL-141	3.95
LL-102	3.67	LL-122	3.88	LL-142	3.88
LL-103	3.80	LL-123	3.73	LL-143	3.79
LL-104	3.77	LL-124	3.95	LL-144	3.91
LL-105	3.88	LL-125	4.02	LL-145	3.73
LL-106	3.87	LL-126	3.87	LL-146	3.93
LL-107	4.06	LL-127	3.77	LL-147	3.97
LL-108	3.99	LL-128	3.93	LL-148	3.86
LL-109	3.76	LL-129	3.92	LL-149	3.71
LL-110	3.91	LL-130	3.82	LL-150	3.79
LL-111	3.87	LL-131	3.92	LL-151	3.83
LL-112	4.01	LL-132	4.02	LL-152	3.81
LL-113	4.00	LL-133	3.83	LL-153	3.73
LL-114	4.04	LL-134	3.85	LL-154	3.84
LL-115	3.89	LL-135	3.98	LL-155	3.98
LL-116	3.88	LL-136	3.79	LL-156	3.78
LL-117	3.91	LL-137	4.00	LL-157	3.89
LL-118	3.94	LL-138	3.89	LL-158	3.89
LL-119	3.90	LL-139	4.04	LL-159	3.75
LL-120	3.84	LL-140	3.79	LL-160	3.85

In accordance with the Internal Procedures of the NIST Charpy Machine Verification Program [6], the results were examined for the presence of outliers by means of the box-and-whiskers method. Outliers are defined as values that are lower than the first quartile or higher than the third quartile by more than 1.5 times the absolute difference between the first and

[2] The coefficient of variation is the ratio of the standard deviation to the mean, expressed in %.

third quartiles. If a Charpy specimen lot has more than 10 % outliers, it may be rejected.

As shown in **Fig. 4**, no outliers were identified by the box-and-whiskers method for the tests performed on the low-energy RHS miniaturized Charpy specimens.

The distribution of absorbed energy values obtained from the tests performed is illustrated in the histogram of **Fig. 5**.

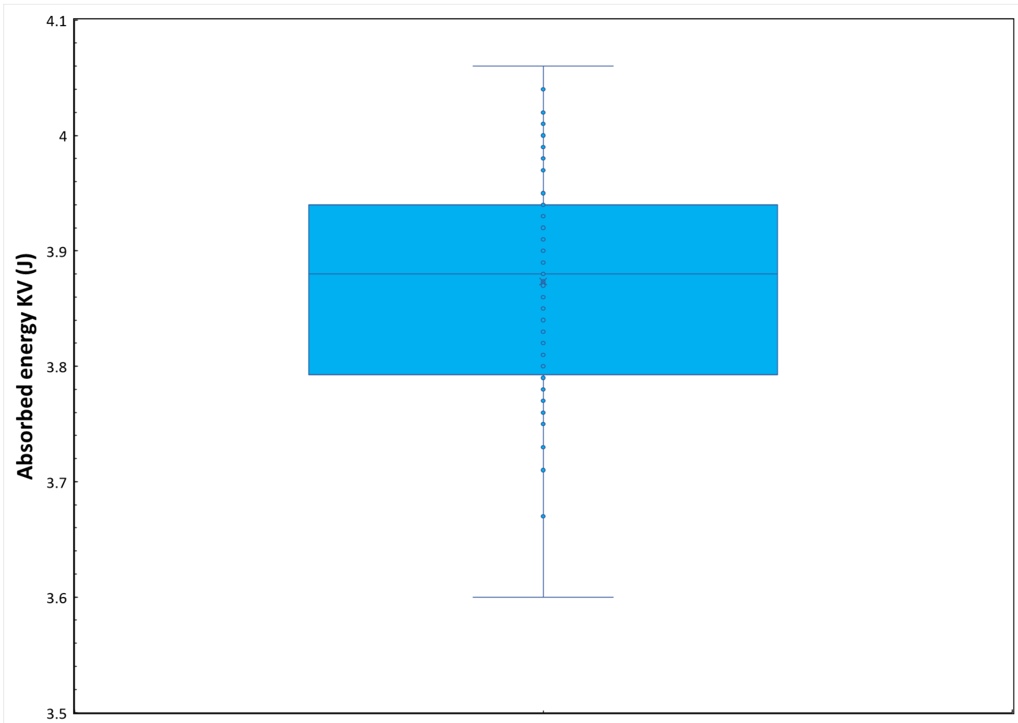

Fig. 4 – Box-and-whiskers plot for the impact tests on low-energy RHS specimens.

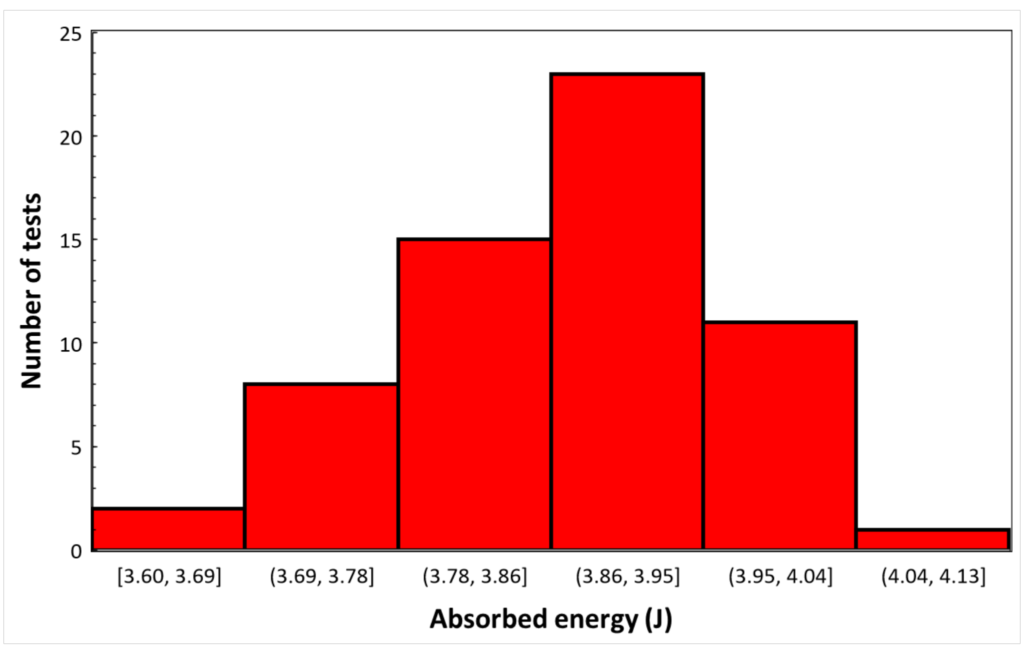

Fig. 5 – Histogram for the impact tests performed on low-energy RHS specimens.

4.2. High Energy

Sixty (60) RHS specimens were tested at 21 °C ±1 °C to establish the certified absorbed energy, KV_{ref}, at the high-energy level. A basic statistical analysis of the test results yielded the following information:

- Mean absorbed energy, $\overline{KV}$ = 14.005 J .
- Standard deviation, s_{KV} = 0.390 J .
- Variance, s_{KV}^2 = 0.152 J^2 .
- Degrees of freedom = 59 .
- Standard error of the mean, SEM = 0.050 J .
- Range of absorbed energies, ΔKV = 1.84 J .
- Coefficient of variation, CV = 2.8 % .

The values of absorbed energy obtained from the tests performed are listed in Table 5. The majority of the specimens did not completely break as a result of impact testing.

Table 5 - Results of the impact tests performed on high-energy RHS specimens.

Specimen #	*KV* (J)	Specimen #	*KV* (J)	Specimen #	*KV* (J)
HH-1	14.43	HH-21	14.43	HH-41	13.43
HH-2	14.40	HH-22	14.15	HH-42	13.93
HH-3	13.49	HH-23	14.02	HH-43	13.24
HH-4	14.56	HH-24	13.93	HH-44	13.99
HH-5	13.86	HH-25	13.99	HH-45	13.61
HH-6	14.65	HH-26	14.16	HH-46	13.95
HH-7	14.52	HH-27	13.83	HH-47	13.51
HH-8	14.17	HH-28	14.62	HH-48	13.75
HH-9	14.00	HH-29	14.09	HH-49	13.79
HH-10	14.47	HH-30	14.25	HH-50	14.27
HH-11	14.28	HH-31	14.13	HH-51	13.44
HH-12	13.34	HH-32	14.02	HH-52	13.84
HH-13	14.59	HH-33	13.85	HH-53	13.34
HH-14	14.37	HH-34	13.72	HH-54	13.73
HH-15	13.57	HH-35	13.84	HH-55	15.08
HH-16	13.95	HH-36	13.87	HH-56	13.65
HH-17	13.98	HH-37	13.88	HH-57	14.62
HH-18	14.65	HH-38	13.91	HH-58	14.11
HH-19	13.79	HH-39	13.82	HH-59	13.81
HH-20	13.35	HH-40	14.12	HH-60	14.14

In accordance with the Internal Procedures of the NIST Charpy Machine Verification Program [6], the results were examined for the presence of outliers by means of the box-and-whiskers method.

As shown in Fig. 6, only one outlier (1.7 % of the tests performed) was identified by the box-and-whiskers method for the high-energy RHS miniaturized Charpy specimens. This is well below the threshold value (10 %) for possible rejection of the lot.

The distribution of absorbed energy values obtained from the tests performed is illustrated in the histogram of Fig. 7.

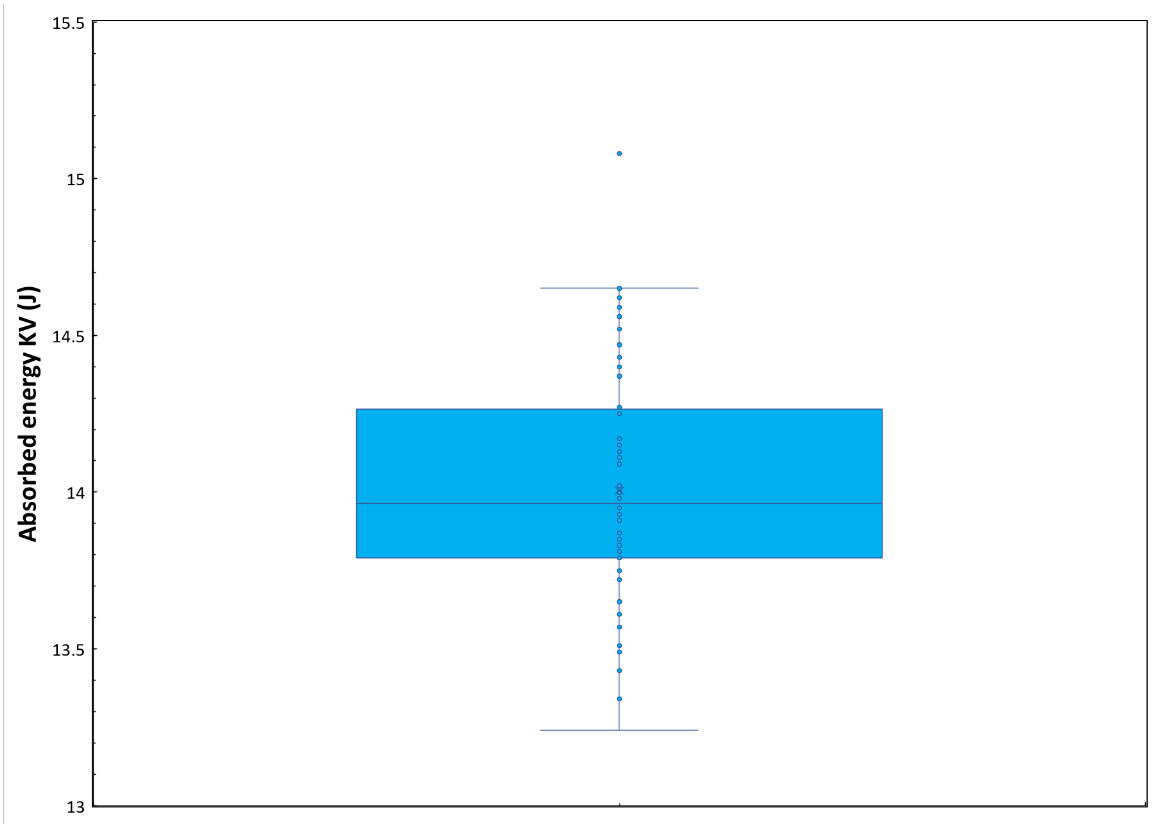

Fig. 6 – Box-and-whiskers plot for the impact tests performed on high-energy RHS specimens.

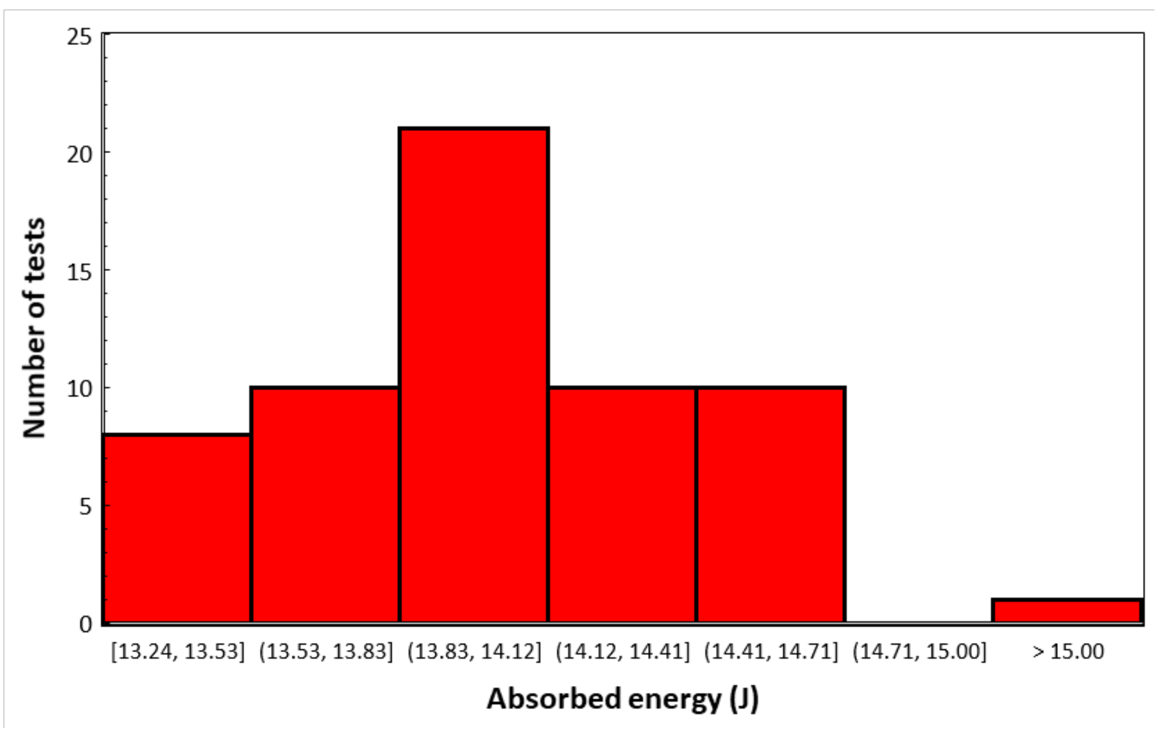

Fig. 7 – Histogram for the impact tests performed on high-energy RHS specimens.

4.3. Super-High Energy

Sixty (60) RHS specimens were tested at 21 °C ± 1 °C to establish the certified absorbed energy, KV_{ref}, at the super-high-energy level. A basic statistical analysis of the test results yielded the following information:

- Mean absorbed energy, $\overline{KV}$ = 35.258 J .
- Standard deviation, s_{KV} = 1.285 J .
- Variance, s^2_{KV} = 1.652 J^2 .
- Degrees of freedom = 59 .
- Standard error of the mean, SEM = 0.166 J .
- Range of absorbed energies, ΔKV = 6.02 J .
- Coefficient of variation, CV = 3.6 % .

The values of absorbed energy obtained from the tests performed are listed in Table 6. None of the specimens fully broke as a result of impact testing.

Table 6 - Results of the impact tests performed on super-high-energy RHS specimens.

Specimen #	*KV* (J)	Specimen #	*KV* (J)	Specimen #	*KV* (J)
SH-1	38.93	SH-21	36.06	SH-41	37.23
SH-2	35.82	SH-22	33.84	SH-42	36.49
SH-3	34.85	SH-23	36.01	SH-43	33.14
SH-4	33.79	SH-24	35.32	SH-44	35.33
SH-5	35.29	SH-25	33.41	SH-45	34.63
SH-6	34.85	SH-26	34.70	SH-46	35.00
SH-7	35.39	SH-27	35.66	SH-47	36.95
SH-8	34.42	SH-28	34.89	SH-48	34.26
SH-9	34.30	SH-29	38.19	SH-49	37.37
SH-10	37.79	SH-30	37.54	SH-50	35.35
SH-11	36.99	SH-31	34.21	SH-51	35.91
SH-12	33.94	SH-32	35.17	SH-52	35.75
SH-13	35.06	SH-33	33.90	SH-53	34.09
SH-14	36.46	SH-34	35.50	SH-54	35.25
SH-15	35.55	SH-35	34.86	SH-55	34.82
SH-16	34.40	SH-36	35.63	SH-56	34.89
SH-17	33.47	SH-37	35.08	SH-57	34.65
SH-18	37.09	SH-38	35.73	SH-58	32.91
SH-19	35.31	SH-39	35.50	SH-59	34.09
SH-20	33.00	SH-40	34.06	SH-60	35.41

In accordance with the Internal Procedures of the NIST Charpy Machine Verification Program [6], the results were examined for the presence of outliers by means of the box-and-whiskers method.

As shown in Fig. 8, only two outliers (3.3 % of the tests performed) were identified by the box-and-whiskers method for the super-high-energy RHS miniaturized Charpy specimens. This is well below the threshold value (10 %) for possible rejection of the lot.

The distribution of absorbed energy values obtained from the tests performed is illustrated in the histogram of Fig. 9.

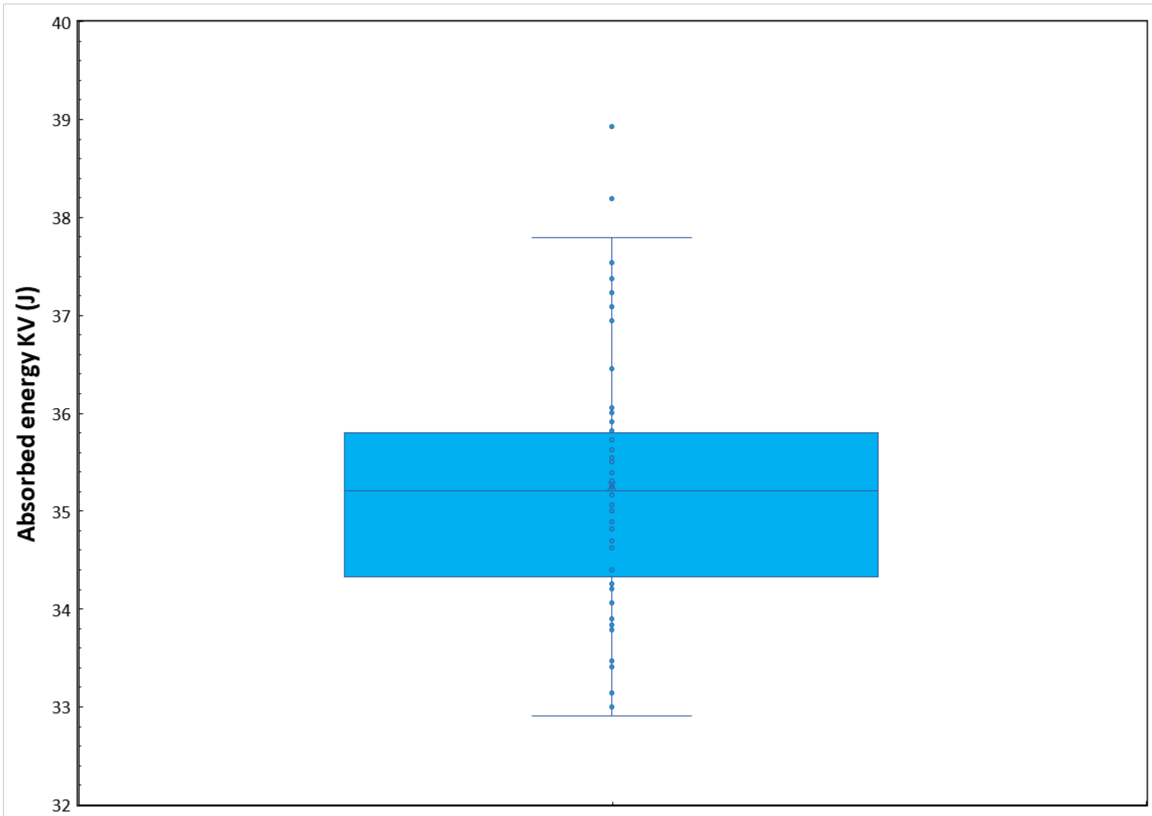

Fig. 8 – Box-and-whiskers plot for the impact tests performed on super-high-energy RHS specimens.

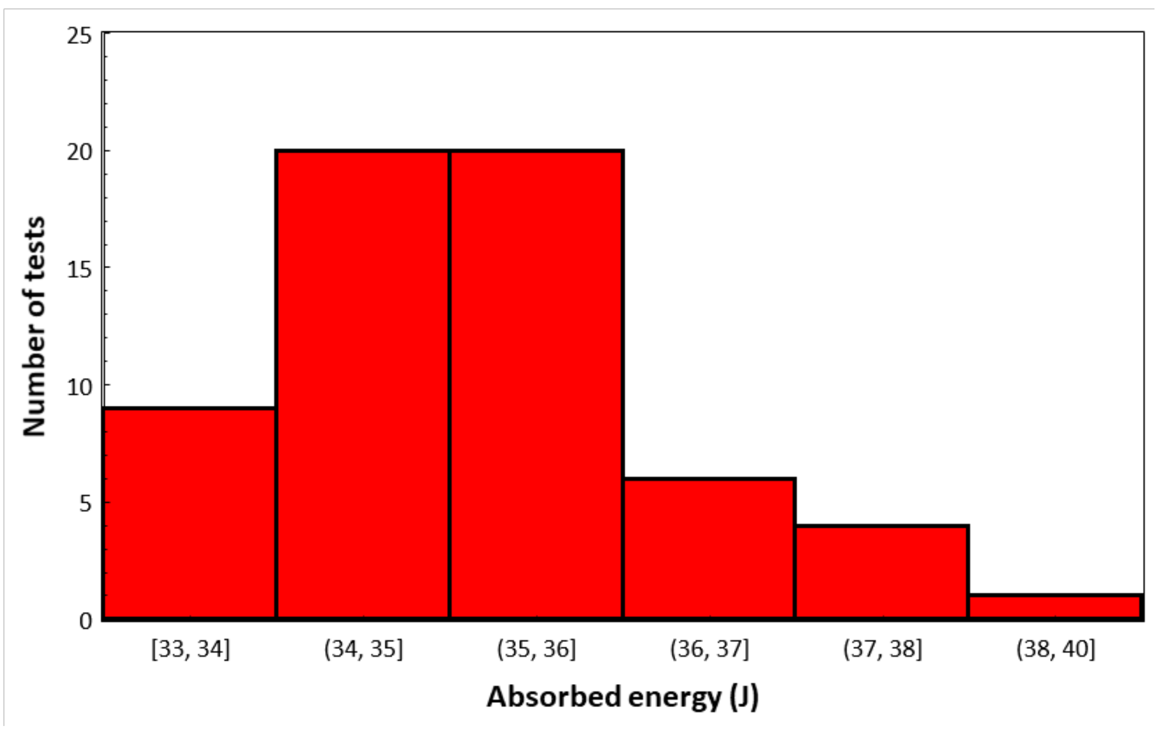

Fig. 9 – Histogram for the impact tests performed on super-high-energy RHS specimens.

5. Establishment of Reference Absorbed Energy Values

5.1. Analytical Procedure

The reference (certified) absorbed energy value, KV_{ref}, for a specific energy level (low, high, or super-high) is defined as the grand average of the 60 specimens tested at that energy level. The grand average energy is defined as:

$$\overline{KV} = \frac{\sum_{i=1}^{N} KV_i}{N} \quad , \tag{1}$$

where $N = 60$ for each energy level tested. In this case, the grand average energy corresponds to the reference absorbed energy value, KV_{ref}, for the specific energy level. The standard deviation is defined as:

$$s_{KV} = \sqrt{\frac{\sum_{i=1}^{N}(KV_i - \overline{KV})}{N-1}} \quad . \tag{2}$$

The sample size, which represents the minimum number of specimens from a given specimen lot that have to be tested for the verification of an impact machine, is defined as:

$$n_{ss} = \left(\frac{3s}{E}\right)^2 \quad , \tag{3}$$

where E is 5 % of the mean energy $\overline{KV}$.

According to the procedures of the Charpy Machine Verification Program at NIST [6], if the sample size of a Charpy specimen lot exceeds 5.0, the lot is rejected. In other words, a sample size larger than 5 indicates that the material in question is not adequate for producing reference specimens.

The results of the calculations performed at the three energy levels, summarized in Table 7, support the acceptance of all three RHS specimen lots.

Table 7 – Sample size calculations for RHS specimens at three energy levels.

Energy Level	N	$\overline{KV}$ (J)	s_{KV} (J)	CV	E	n_{SS}
Low	60	3.873	0.099	2.6 %	0.194	2.347
High	60	14.005	0.390	2.8 %	0.700	2.793
Super-High	60	35.258	1.285	3.6 %	1.763	4.783

Although three (3) RHS specimens would be sufficient for the verification of a small-scale impact tester at the low- and high-energy level, NIST verification sets of certified RHS specimens will comprise five (5) specimens. This is consistent with the general NIST policy for full-size Charpy verification specimens.

The standard uncertainty of $\overline{KV}$ for given lot can be determined by combining two components of uncertainty: within-machine uncertainty ($u(P)$) and uncertainty due to machine bias ($u(B)$). The combined standard uncertainty is given by:

$$u_T = \sqrt{u^2(P) + u^2(B)} \quad . \tag{4}$$

The within-machine uncertainty, $u(P)$, is estimated by the standard error of the mean, $s_{KV}/\sqrt{n}$. The degrees of freedom associated with $u(P)$ are 59 (*i.e.*, 60 – 1). Since Charpy testing is destructive, within-machine uncertainty includes both measurement variability and specimen homogeneity.

The uncertainty due to machine bias accounts for possible bias in the observed average. Information regarding possible machine bias is not available since the use of RHS specimens is not very common. Thus, the value of $u(B)$ is obtained from a Type B uncertainty evaluation where engineering judgement is used to provide a reasonable uncertainty estimate. Assuming the distribution of machine bias is uniform on the interval defined by $[-0.05 \cdot \overline{KV}, 0.05 \cdot \overline{KV}]$, then $u(B)$ is $0.05 \cdot \overline{KV}/\sqrt{3}$ (section 4.3.7 of [7]). Degrees of freedom for $u(B)$ are specified as 30.

The expanded uncertainty, U, is obtained by multiplying the standard uncertainty u_T by a coverage factor k. The value of k is obtained from a t table corresponding to a 95 % uncertainty interval on the reference value based on the effective degrees of freedom. Effective degrees of freedom are computed using the Welsh-Satterthwaite approximation (G.4 of [7]).

5.2. Reference Values and Expanded Uncertainties for Certified RHS Specimens

Based on the analytical procedure described in Section 5.1, the statistical values shown in Table 8 were established for the three energy levels of certified RHS specimens.

Table 8 – Statistical calculations for RHS specimens of low, high, and super-high energy.

Energy Level	KV_{ref} (J)	$u(P)$ (J)	$u(B)$ (J)	u_T (J)	Degrees of Freedom	k	U (J)	n_{SS}
Low	3.873	0.013	0.112	0.113	31	2.0395	0.230	2.347
High	14.005	0.050	0.404	0.407	31	2.0395	0.831	2.793
Super-High	35.258	0.166	1.018	1.031	32	2.0369	2.100	4.783

6. Technical Discussion: Correlation Between Full-Size and RHS Absorbed Energies

The correlation between values of KV yielded by different Charpy specimen configurations have been extensively investigated. An overview of various correlations between full-size and sub-size upper shelf energy[3] (*USE*) data was provided by Sokolov and Alexander [8].

A method commonly used in Europe consists of establishing an empirical ratio between full-size Upper Shelf Energy, *USE* (USE_{fs}), and sub-size *USE* (USE_{ss}) based on a large number of tests. A different approach, often used by US and Japanese researchers, correlates *USE* values with the ratio of various geometrical parameters, GP_x (with $x = fs$ or ss, full-size or sub-size respectively) for different specimen geometries, in the form:

$$\frac{USE_{fs}}{USE_{ss}} = \frac{GP_{fs}}{GP_{ss}} \quad . \tag{5}$$

[3] The upper shelf energy (*USE*) is defined as the energy absorbed in Charpy tests by a material under fully ductile conditions.

Eq. (5) can also be expressed in terms of a normalization factor, *NF*, which corresponds to the ratio of geometrical parameters mentioned above:

$$USE_{fs} = NF \times USE_{ss} \quad . \tag{6}$$

The most common expressions for NF that can be found in the literature are the following:

$$NF_1 = \frac{(Bb)_{fs}}{(Bb)_{ss}} \tag{7}$$

based on the ratio of fracture areas, with *B* = specimen thickness and *b* = ligament size [10,11];

$$NF_2 = \frac{[(Bb)^{3/2}]_{fs}}{[(Bb)^{3/2}]_{ss}} \tag{8}$$

based on the ratio of nominal fracture volumes [9,10];

$$NF_3 = \frac{(Bb^2)_{fs}}{(Bb^2)_{ss}} \tag{9}$$

based on a different expression for the ratio of nominal fracture volumes [11,12], and

$$NF_4 = \frac{\left(\frac{Bb^2}{LK_t}\right)_{fs}}{\left(\frac{Bb^2}{LK_t}\right)_{ss}} \tag{10}$$

where L = span and K_t = elastic stress concentration factor [13].

Furthermore, Sokolov and Alexander [8] established empirical normalization factors, NF_5, for 4 types of sub-size specimens considered in their study (one of which corresponds to HS specimens[4], slightly bigger than but proportional to RHS) by averaging the values of USE_{fs}/USE_{ss} obtained on ten different materials (mostly pressure vessel steels with different heat treatments).

A summary of the different normalization factors that can be used for RHS miniaturized specimens, according to the methods listed above, is provided in Table 9. Note that, since super-high-energy full-size specimens from lot SH-54 were side-grooved for a total thickness reduction of 1.4 mm (net thickness B_N = 8.6 mm), their geometric normalization factors are different than for low- or high-energy specimens, which were not side-grooved.

Table 9 - Summary of normalization factors for estimating full-size *USE* based on RHS *USE*, see Eq. (6). N/A = not available.

Energy Level	NF_1 Eq.(7)	NF_2 Eq.(8)	NF_3 Eq.(9)	NF_4 Eq.(10)	NF_5 [8]
Low	4.3	8.9	8.9	5.6	5.1
High					
Super-High	3.7	7.1	7.6	N/A	N/A

[4] HS (Half-Size) miniaturized specimens have cross section dimensions (thickness and width) equal to 5 mm.

Considering the RHS tests performed at three energy levels in the framework of this certification exercise, experimental normalization factors NF_{exp} were calculated by dividing the certified/average values of KV_{fs} at room temperature by the average RHS absorbed energies, KV_{RHS}, for each energy level. Note that for the high-energy full-size specimens, reference absorbed energy is only available at -40 °C, but not at room temperature (Table 1). However, assuming that the absorbed energy at the high-energy level increases by 25 % as in the case of low-energy specimens (from 13.2 J at -40 °C to 17.6 J at 21 °C), we can estimate the reference absorbed energy at room temperature for high-energy full-size specimens to be 86.5 J × 1.25 ≈ 108.1 J. Using this estimated value, the obtained experimental normalization factors are shown in Table 10 and can be compared with the normalized factors listed in Table 9.

Table 10 - Experimental normalization factors obtained from the RHS tests performed.

Energy level	Specimen type	$\overline{KV}$ (J)	NF_{exp}
Low	Full-size RHS	17.6 3.9	4.5
High	Full-size RHS	108.1 14.0	7.7
Super-high	Full-size RHS	199.5 35.3	5.7

The different normalization factors are evaluated in Fig. 10, which compares reference values of KV_{fs} to predicted values obtained from KV_{RHS} by the use of the five normalization factors presented in Table 10.

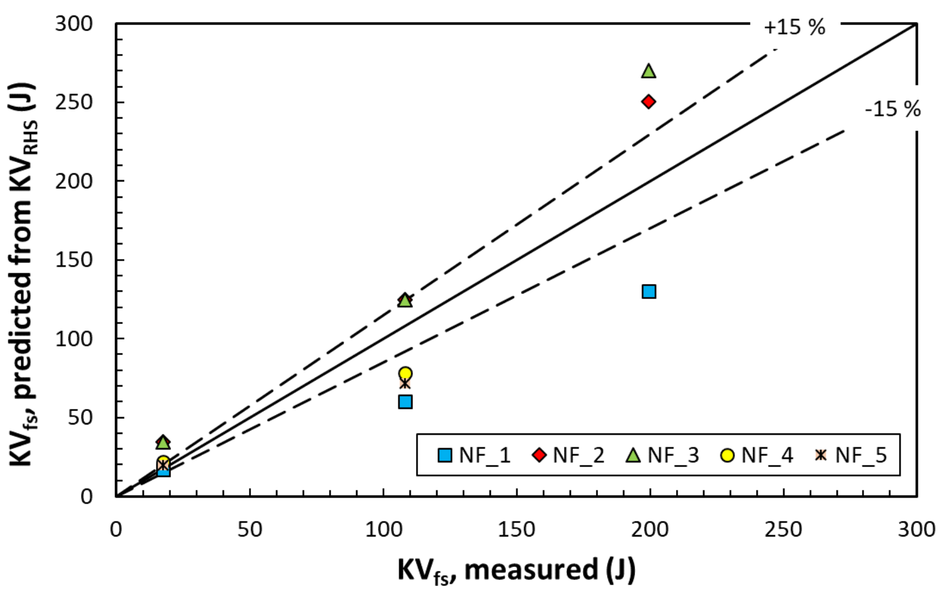

Fig. 10 - Prediction of full-size absorbed energy from RHS specimens. The solid line corresponds to KV_{fs} predicted = KV_{fs} measured.

When examining Table 10 and Fig. 10, one must remember that all the methods previously described address USE values, rather than generic values of absorbed energy. At the high- and super-high energy levels, fully ductile behavior can be expected; therefore, it is appropriate to assume $KV = USE$. For low-energy specimens, however, the material's behavior is typical of the ductile-to-brittle transition regime, hence it is not appropriate to assume $KV = USE$.

The most immediate conclusion is that normalization factors depend on absorbed energy and fracture regime (brittle, transitional, ductile). In particular, NF_1, NF_4, and NF_5 work reasonably well at the low-energy level, while at higher energies they significantly underpredict KV_{fs}. Conversely, non-conservative estimates were generally obtained through the use of NF_2 and NF_3. In short, none of the approaches considered appears convincing for all energy levels.

7. Conclusions

We have successfully certified miniaturized Charpy specimens of the RHS (*Reduced Half-Size*) type for the indirect verification of small-scale impact testers at three energy levels (low, high, and super-high). The RHS specimens were extracted from existing full-size Charpy specimens of the same energy levels, previously certified for the verification of full-scale Charpy machines in accordance with ASTM E23.

The reference values of absorbed energy at the three energy levels are approximately 4 J, 14 J, and 35 J, evenly covering 70 % of the typical range of machines used for testing RHS specimens (0 J – 50 J). At each energy level, a statistically reliable indirect verification of the machine is obtained by testing 5 (five) RHS specimens at room temperature (21 °C ± 1 °C).

We also investigated the relationship between mean absorbed energy values for RHS and full-size specimens, using geometrical normalization factors based on the ratio of various geometrical parameters, and found that correlations are strongly dependent on energy values and mechanical behavior (brittle, transitional, ductile).

References

[1] Lucon E (2012) Miniaturized Charpy Specimens for the Indirect Verification of Small-Scale Charpy Machines: Initial Qualification Phase. (National Institute of Standards and Technology, Boulder, CO), NIST Technical Note (TN) 1562. http://dx.doi.org/10.6028/NIST.TN.1562-1

[2] Lucon E, McCowan CN, Santoyo RL, and Splett J (2013) Certification Report for SRM 2216, 2218,2219: KLST (Miniaturized) Charpy V-Notch Impact Specimens. (National Institute of Standards and Technology, Boulder, CO), NIST Special Publication (SP) 260-180. http://dx.doi.org/10.6028/NIST.SP.260-180

[3] ISO (2015) *ISO 14556:2015 – Metallic materials — Charpy V-notch pendulum impact test — Instrumented test method* (International Standards Organization, Vernier, Geneva, Switzerland).

[4] ASTM International (2018) *ASTM E2248-18 – Standard Test Method for Impact Testing of Miniaturized Charpy V-Notch Specimens* (ASTM International, West Conshohocken, PA).

[5] ASTM International (2018) *ASTM E23-18 – Standard Test Methods for Notched Bar Impact Testing of Metallic Materials* (ASTM International, West Conshohocken, PA).
[6] McCowan CN, Siewert TA, and Vigliotti DP (2003) The NIST Charpy V-notch Verification Program: Overview and Operating Procedures. In: NIST Technical Note (TN) 1500-9, "Charpy Verification Program: Reports Covering 1989-2002," pp 3-42. http://dx.doi.org/10.6028/NIST.TN.1500-9
[7] BIPM I, I IFCC, I IUPAC, and OIML (2008) Guide to the expression of uncertainty in measurement, Geneva: International Organization for Standardization; JCGM 100:2008, GUM 1995 with minor corrections. https://www.bipm.org/en/publications/guides/gum.html
[8] Sokolov MA and Alexander DJ (1997) An Improved Correlation Procedure for Subsize and Full-Size Charpy Impact Specimen Data. (Oak Ridge National Laboratory, Oak Ridge, TN) NUREG/CR-6379, ORNL-6888.
[9] Corwin WR, Klueh RL, and Vitek JM (1984) Effect of specimen size and nickel content on the impact properties of 12 Cr-1 MoVW ferritic steel. *Journal of Nuclear Materials* 122(1-3):343-348. http://dx.doi.org/10.1016/0022-3115(84)90622-6
[10] Corwin WR and Hougland AM (1986) Effect of Specimen Size and Material Condition on the Charpy Impact Properties of 9Cr-1Mo-V-Nb Steel. *The Use of Small-Scale Specimens for Testing Irradiated Material*, ASTM STP 888, eds W. R. Corwin and G. E. Lucas (ASTM, Philadelphia, PA), pp 325-338. http://dx.doi.org/10.1520/STP33014S
[11] Lucas GE, Odette GR, Sheckherd JW, McConnell P, and Perrin J (1986) Subsized Bend and Charpy V-Notch Specimens for Irradiated Testing. *The Use of Small-Scale Specimens for Testing Irradiated Material*, ASTM STP 888, eds W. R. Corwin and G. E. Lucas (ASTM, Philadelphia, PA), pp 304-324. http://dx.doi.org/10.1520/STP33012S
[12] Lucas GE, Odette GR, Sheckherd JW, and Krishnadev MR (1986) Recent Progress in Subsized Charpy Impact Specimen Testing for Fusion Reactor Materials Development. *Fusion Technology* 10:728-733. http://dx.doi.org/10.13182/FST86-A24827
[13] Louden BS, Kumar AS, Garner FA, Hamilton ML, and Hu WL (1988) The influence of specimen size on Charpy impact testing of unirradiated HT-9. *Journal of Nuclear Materials* 155-157:662-667. http://dx.doi.org/10.1016/0022-3115(88)90391-1