NIST Special Publication 260-171

Charpy Machine Verification: Limits and Uncertainty

J. D. Splett
C. N. McCowan
C.-M. Wang

National Institute of
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J. D. Splett
C.-M. Wang
Statistical Engineering Division
Information Technology Laboratory

C. N. McCowan
Materials Reliability Division
Materials Science and Engineering Laboratory

National Institute of Standards and Technology
Boulder, Colorado 80305

September 2008

U.S. Department of Commerce
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National Institute of Standards and Technology Special Publication 960-171
Natl. Inst. Stand. Technol. Spec. Publ. 960-171, 10 pages (September 2008)
CODEN: NSPUE2

U. S. GOVERNMENT PRINTING OFFICE
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J. D. Splett,[†] C. N. McCowan,[‡] and C.-M. Wang[†]

National Institute of Standards and Technology
325 Broadway
Boulder, CO 80305

We clarify some issues pertaining to uncertainty statements and the ASTM E 23 limits used in the Charpy machine verification program. We explain some of the distributional subtleties associated with uncertainty and ultimately relate these to the ASTM limits.

Key words: absorbed energy; Charpy V-notch; impact test; pendulum impact test; uncertainty; verification testing

1. Introduction

To indirectly verify a Charpy machine, a set of five Charpy verification specimens are tested on the machine of interest and the broken specimens are returned to NIST along with the test results. Next, the customer receives a verification letter from NIST indicating whether or not the machine passed the indirect verification test. In addition, the verification letter reports the average absorbed energy for the verification specimens (the certified reference value), and the uncertainty of the certified reference value. In this document, we clarify some issues pertaining to the uncertainty reported in the verification letter and the ASTM verification limits for E 23 [1]. Specifically, we address the following questions from a customer's perspective:

1. What is the meaning of the uncertainty provided with Charpy indirect verification specimens (standard reference materials (SRMs) 2092, 2096, and 2098)?
2. How should the uncertainty be used by a customer?
3. How is the stated uncertainty related to the outcome of a verification test?

[†] Statistical Engineering Division, Information Technology Laboratory
[‡] Materials Reliability Division, Materials Science and Engineering Laboratory

2. Background: Distributions and Uncertainty

There are various distributions used in the indirect verification of Charpy impact test machines, including the distributions associated with the machines used to certify the SRMs and the distributions associated with the customer's verification test. It is important to understand the role played by each of these distributions in the development of statistical uncertainty statements and verification limits in the Charpy machine verification program.

All individual specimens from a batch of SRMs are assumed to follow the same distribution of absorbed energies. Thus, data from verification specimens tested on machines being verified by customers should follow the same basic distribution as data from the same batch of verification specimens tested on the three reference machines at NIST. This is a fundamental assumption that is supported by the data shown in Figure 1. Here, the distribution of individual data points from three NIST reference machines tested for the certification of a batch of SRMs is compared to the distribution of individual data points from customer machines testing the SRMs in verification tests. The distributions in Figure 1 demonstrate that the customer and NIST distributions are quite similar; although the customer distribution has slightly larger spread than the NIST distribution. The larger spread in the customer data is probably due to the fact that there are more machines included in the histogram of customer data. However, the comparison indicates that specimens sent to customers for verification tests are representative of the batch, and that customer measurements are similar to NIST measurements.

We also need to consider the differences between the distributions of individual values and the distributions of average values. This detail is often overlooked and can cause confusion, resulting in a comparison between "apples and oranges." To simplify the discussion, the histogram in Figure 2(a) displays the distribution for 1000 simulated normal data points that have the same mean ($\mu = 93.76\ \mathrm{J}$) and standard deviation ($\sigma = 2.33\ \mathrm{J}$) as the NIST data in Figure 1. For further simplification, suppose that all the tests were all done on the same machine, and the quantities μ and σ represent "true" values rather than sample values.

With similar assumptions we can simulate several relevant distributions of averages, as shown in Figure 2(b) and 2(c), for comparison with Figure 2(a). For example, a laboratory typically tests five verification specimens for a verification test. In our simulated normal example, the standard deviation of a distribution based on the average of five specimens would be $\frac{\sigma}{\sqrt{5}} = \frac{2.33\ \mathrm{J}}{\sqrt{5}} = 1.04\ \mathrm{J}$, and the distribution of 1000 averages based on five observations would be similar to the distribution shown in Figure 2(b). As one would expect, the distribution of averages has a smaller range of values than the individual test data. In Figure 2(c), the effect of increasing the number of samples used for the average is shown. For this example, we generated 1000 averages of samples of size of 75 based on the normal distribution of Figure 2(a).

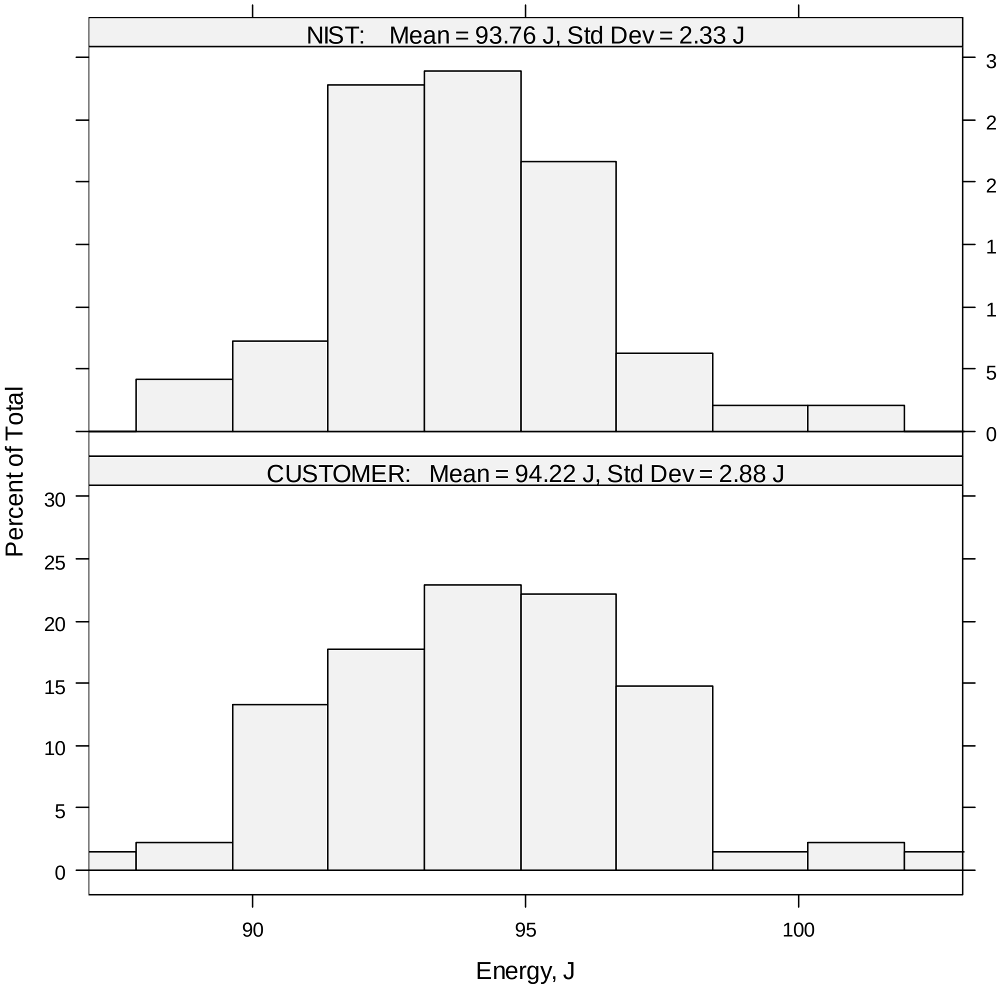

Figure 1. The upper distribution is based on 97 individual measurements from three NIST machines used to certify a high energy value for an SRM. The lower distribution represents customer data (135 individual measurements) for the same SRM batch. Only results for customer machines that pass the ASTM indirect verification requirements are included in the histogram. The number of customer machines that tested verification specimens from this batch is 27.

Notice that the range of values for the distribution of averages of 75 specimens is much smaller than the range of the original normal distribution of single observations, and it is significantly smaller than the range of the distribution based on averages of five specimens. In general, the standard deviation of the distribution of averages is $\frac{\sigma}{\sqrt{n}}$, where σ denotes the actual standard deviation of single observations and *n* is the number of observations in each average. In our example, the standard deviation of the distribution of the average of 75 specimens is $\frac{\sigma}{\sqrt{75}} = \frac{2.33\text{ J}}{\sqrt{75}} = 0.27\text{ J}$.

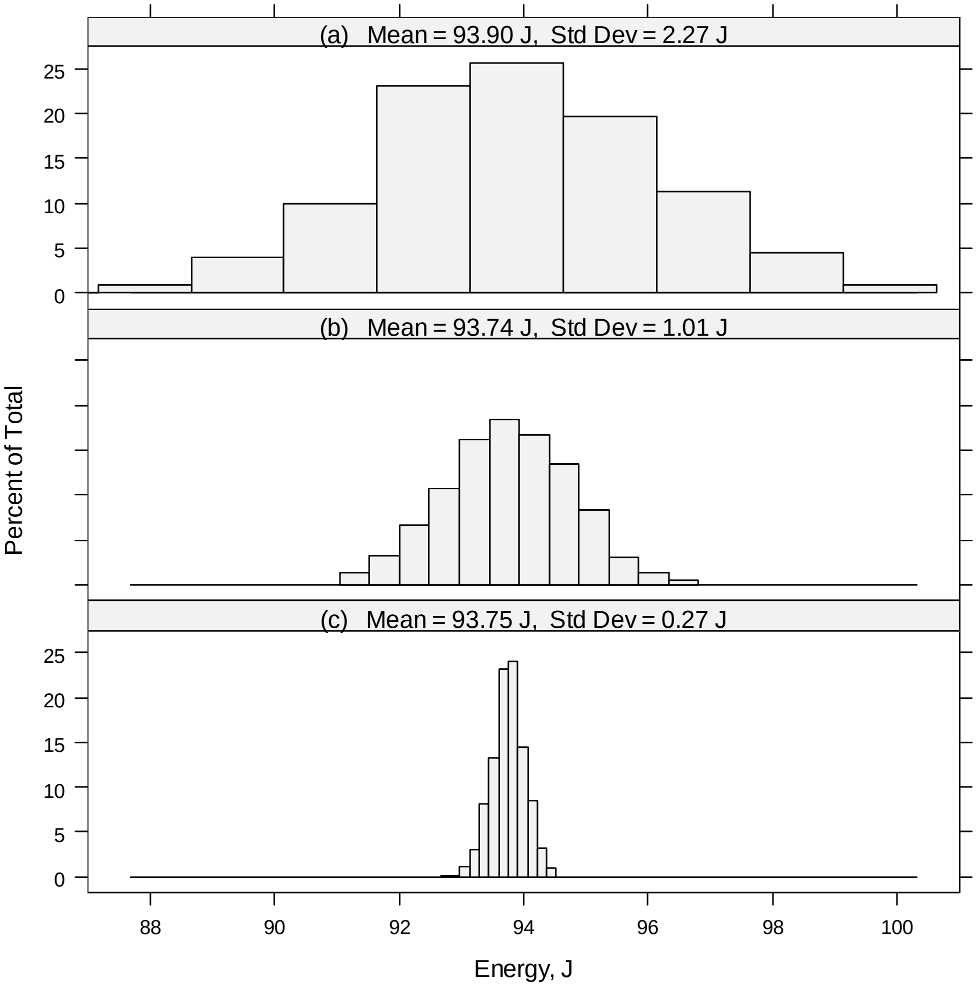

Figure 2. (a) Distribution of 1000 simulated normal observations. (b) Distribution of 1000 averages from samples of size 5. (c) Distribution of 1000 averages from samples of size 75.

The point is that the distributions are not the same, and since uncertainty is directly related to the standard deviation associated with these distributions, it follows that the uncertainties would also differ for these cases.

3. Discussion

3.1 Explanation and Use of Uncertainty

The verification letter associated with five test results for verification specimens includes the NIST certified reference value (R) and its associated uncertainty ($u(R)$). *The value of* $u(R)$ *quantifies the uncertainty we have about the closeness of the reference value to the true average* *absorbed energy of the batch.* It includes many sources of variation, such as between-machine variation, within-machine variation, material homogeneity, and operator error, to name a few. (To complicate matters, we cannot even estimate each individual component of uncertainty separately because Charpy tests are destructive.) Thus, the value of $u(R)$ not only represents the variation in a batch of specimens, it contains many more sources of error as well.

The verification set mean ($\bar{V}$) and its associated standard deviation ($S_V/\sqrt{5}$, where S_V is the standard deviation of the five measurements) are calculated once verification testing is complete. The values of $S_V/\sqrt{5}$ and $u(R)$ are different because the distributions of $\bar{V}$ and R are different, as demonstrated in Section 2. In addition to the differences between the number of samples associated with the respective averages, there are differences between machines and operators, and the standard deviation of the verification set mean does not include between-machine variation (like the NIST certified reference value) because all samples were broken on the same machine.

We do not define the uncertainty of the verification set mean as $S_V/\sqrt{5}$ because, according to the “Guide to the Expression of Uncertainty in Measurement” [2], the word “uncertainty” implies that *all* sources of error have been quantified and accounted for in the uncertainty estimate. Only the customer can conduct a thorough uncertainty analysis and determine the appropriate uncertainty for their particular machine.

Once a customer’s machine has been verified, the indirect verification test results, along with the reference value and its uncertainty, can be used by the customer in the estimation of the uncertainty of the mean for a new material that the customer wants to evaluate [3]. Basically, the verification test results define the bias (and its uncertainty) between the customer’s Charpy machine and the NIST reference value. The uncertainty of the bias is then combined with other uncertainties to obtain the final combined standard uncertainty of a test result for a new material.

3.2 ASTM Verification Limits

Customers testing NIST SRMs to meet the verification limits set in ASTM E23 want to know whether the uncertainty associated with the reference value influences their chance of passing the verification test. It turns out that this is a difficult question to answer directly, because the ASTM limits were not established based on modern uncertainty analyses. The ASTM limits were originally developed in the 1950’s using the distribution of the average of five measurements for “good” machines, and were designed to include a large proportion of the good machines tested [4].

Intuitively we understand that as the uncertainty associated with the certified absorbed energy for a particular SRM increases, the mean of the customer's verification set also has increased uncertainty, but exactly how this relates to the ASTM verification limits is not clear. However, we know from experience that the ASTM limits are reasonable for current variation levels associated with the verification specimens, and the verification results shown in Figure 3 support this conclusion.

Figure 3 displays distributions of customer averages (box-and-whisker plots) along with the pilot-lot averages for the three NIST reference machines (X's) and the calculated ASTM limits (solid dots) for various batches of material. The vertical lines extending from the top and bottom of each box terminate at the distribution's most extreme points within 1.5 times the interquartile range. (The interquartile range is the difference between the 75th and 25th percentiles of the sample.) Values larger than 1.5 times the interquartile range are displayed as open circles and are sometimes considered extreme values. The box itself contains the middle 50 % of the data and the horizontal line in the middle of the box represents the median. Both passing and failing machines were included in the calculation of percentiles shown in the figure. Machines falling outside the solid dots would not pass the verification test.

To more directly understand the relationship between the uncertainties associated with verification specimen mean and limits that might reasonably bracket a "good" machine, it is easiest to derive a new form of limits that considers uncertainty contributions directly. One such approach is currently being developed at NIST. In short, new limits are being developed for both the mean and standard deviation of the verification test result based on actual data for the particular SRM tested.

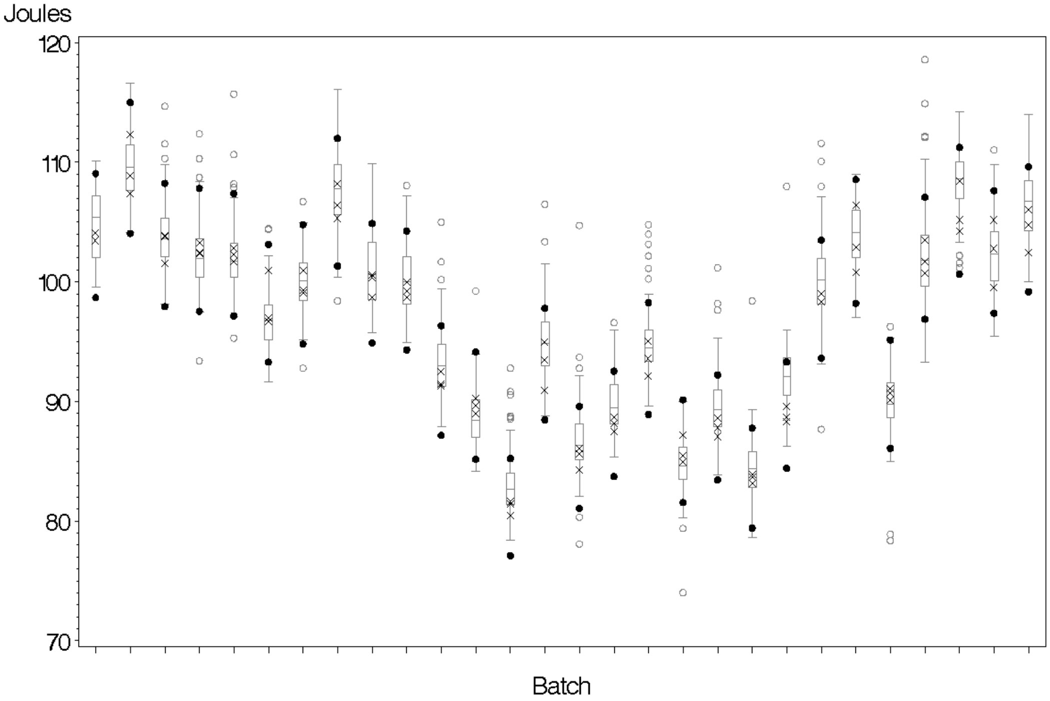

Figure 3. Distribution of all available customer means (box-and-whisker plot), reference machine averages (X's), and ASTM limits (solid dots) for various high-energy lots. Each box contains the middle 50 % of the data. The lower and upper horizontal lines represent the minimum and maximum values within 1.5 times the interquartile range. Values beyond 1.5 times the interquartile range are represented by open circles.

Initial work has shown that limits based on uncertainty are similar to ASTM E23 limits, indicating that the ASTM limits are reasonable for the level of variability currently associated with impact verification specimens. The "uncertainty" limits will not be proposed as replacements to the existing "fixed" ASTM limits, but they can serve as a useful tool for predicting the influence of variability in verification specimens on test results. This approach will also be used to predict how proposed changes in verification limits (ASTM and ISO) might affect the users of NIST verification specimens, and be used as the basis of arguments supporting "good" rules for international impact standards.

4. Summary

We have discussed issues pertaining to uncertainty and verification limits for the Charpy machine verification program from a customer's perspective. We have shown how distributions are related to uncertainty and have explained how to interpret the various uncertainties in the verification program.

The authors thank Dr. Dominic Vecchia and Dr. Hari Iyer for their very helpful comments and suggestions during the preparation of this document.

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