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Analysis of Charpy Impact Verification Data: 1993–2003

ABSTRACT: Indirect verification tests used to verify the performance of Charpy impact machines according to ASTM Standard E23 were evaluated by the National Institute of Standards and Technology (NIST), and the data from these tests are collected in a database. The data include the capacity and the pendulum design of the impact machine, the energy obtained for each specimen tested, the reference energy for the specimen lot tested, and the test date. The principal use of this data is to track the performance of individual impact machines. However, the data also provide an opportunity to evaluate existing and proposed requirements for the indirect verification of Charpy impact machines. The results of more than 16 000 verification tests are used to compare the current verification requirements of ASTM Standard E23 with those of ISO Standard 148-2. Discussions focus on the identification of reasonable, practical, and meaningful verification requirements that might be proposed for use in both documents.

KEYWORDS: Charpy V-notch, impact certification program, impact testing, notched-bar testing, pendulum impact machines, reference specimens

Introduction

The Charpy impact machine verification program has been administered by the National Institute of Standards and Technology (NIST) since 1989 [1]. NIST's role in the program is to procure and characterize batches of verification specimens, and to distribute verification specimens to customers who wish to verify their Charpy machines. After the customer tests the five verification specimens, the resulting data and broken specimens are returned to NIST to determine whether or not the customer's machine is consistent with requirements of ASTM Standard E-23 [2]. A database containing the results of verification tests and associated machine information is maintained by NIST to track individual Charpy machines and to monitor the verification program.

The main purpose of this study is to examine the properties of ASTM Standard E23 and ISO Standard 148-2 [3] for Charpy machine verification rules. We investigate existing rules and some proposed extensions to the ASTM rules, such as the adoption of a rule limiting the variation in verification tests. Historical data from the Charpy V-notch machine verification program administered by NIST are used to compare the rules of interest. We also compare two different pendulum types and investigate the effect of machine capacity on the performance of ASTM verification rules. Finally, we compare ASTM passing rates based on country affiliation.

It is necessary to define some quantities before describing the verification limits under study.

- Reference energy value: k_R
- Pooled standard deviation of the pilot lot: S_P
- Customer average: k_C
- Difference: $d = |k_C - k_R|$
- Normalized difference: $d_n = |k_C - k_R| / k_R$
- Customer range: R
- Normalized range: $R_n = R / k_R$
- Customer standard deviation: S_C

The reference energy value for a single batch of impact specimens is determined by testing 25 specimens on each of three NIST reference machines. The reference value is the average absorbed energy

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TABLE 1—*Verification limits to define "passing" Charpy machines.*

Verification rule	Low energy	High and super-high energy
ASTM	$d \leqslant 1.4$ J	$d_n \leqslant 5$ %
ASTM A	$d \leqslant 1.4$ J and $R \leqslant 5$ J	$d_n \leqslant 5$ % and $R \leqslant 15$ J
ASTM B	$d \leqslant 1.4$ J and $R_n \leqslant 25$ %	$d_n \leqslant 5$ % and $R_n \leqslant 25$ %
ISO—Reference machines	$d \leqslant 2$ J and $R \leqslant 3$ J	$d_n \leqslant 5$ % and $R_n \leqslant 7.5$ %
ISO—Industrial machines	$d \leqslant 4$ J and $R \leqslant 6$ J	$d_n \leqslant 10$ % and $R_n \leqslant 15$ %

for the 75 tests. The pooled standard deviation of the pilot lot is needed for an alternative verification limit which we call Wang's rule [4]. See Appendix A for information regarding the calculation of S_P. The customer average is the average absorbed energy for five verification specimens.

A customer's results based on five verification tests must meet certain requirements before the customer's machine can be verified. Table 1 lists current ASTM and ISO verification limits as well as two proposed additions to the ASTM limits, which we will refer to as ASTM A and ASTM B [5]. ASTM A and ASTM B attempt to control customer variation by imposing limits to the range and normalized range, respectively.

The reason for limiting customer variation is to ensure a certain degree of precision so that test results are fairly repeatable. For all analyses presented in this document, we assume the data were independent even though some machines were tested multiple times at each energy level.

Stability over Time

Before examining verification limits, we need to determine the stability of the verification program over time. Figure 1 displays differences or normalized differences between customer averages and reference values over time for each energy level. ASTM, ISO reference machine, and ISO industrial machine limits are displayed on each plot (the ASTM and ISO reference machine limits are the same for high and super-high energy). The differences represent customer data observed from January 1993 to November 2003 for each energy level. The plots indicate that the differences are stable over time for all energies.

Passing Rates

We compared the various verification limits defined in Table 1 by applying them to historical customer data retrospectively and computing pass/fail rates. The results are listed in Table 2. Also shown in Table 2 are results for ISO industrial and ISO reference machine rules when the range and normalized range rules are ignored so that only the energy limits are used to determine pass/fail rates. (For high and super-high energies, the ISO reference machine limits are the same as the ASTM limits when the normalized range rules are ignored.)

The results in Table 2 indicate the following:

- Passing rates for ISO industrial machine rules at all energy levels are extremely high.
- Virtually all machines pass ISO industrial machine rules if we ignore the range rules and consider only the energy limits.
- ISO reference machine range rules are very stringent for high and super-high energies.
- Low energy passing rates are similar (about 88 %) for the various ASTM rules considered and the ISO reference machine rule, but the passing rate for the ISO industrial machine rule is substantially higher.
- At low energy, adding the proposed range or normalized range rule does not substantially change passing rates, although the ASTM A rule fails a few additional machines with high variation.
- At high energy, passing rates are nearly identical for ASTM and ASTM B. ASTM A fails a few machines with high variation.
- For super-high energy, the ASTM A limits are too strict, while the ASTM B limits produce nearly the same results as the ASTM rule.

Yearly passing rates at each energy level were computed based on the historical customer data (Fig. 2) for the five verification rules. Passing rates for the existing ASTM rules (represented by stars in the figures) appear to be fairly stable with the exception of 1999 at the Low energy level.

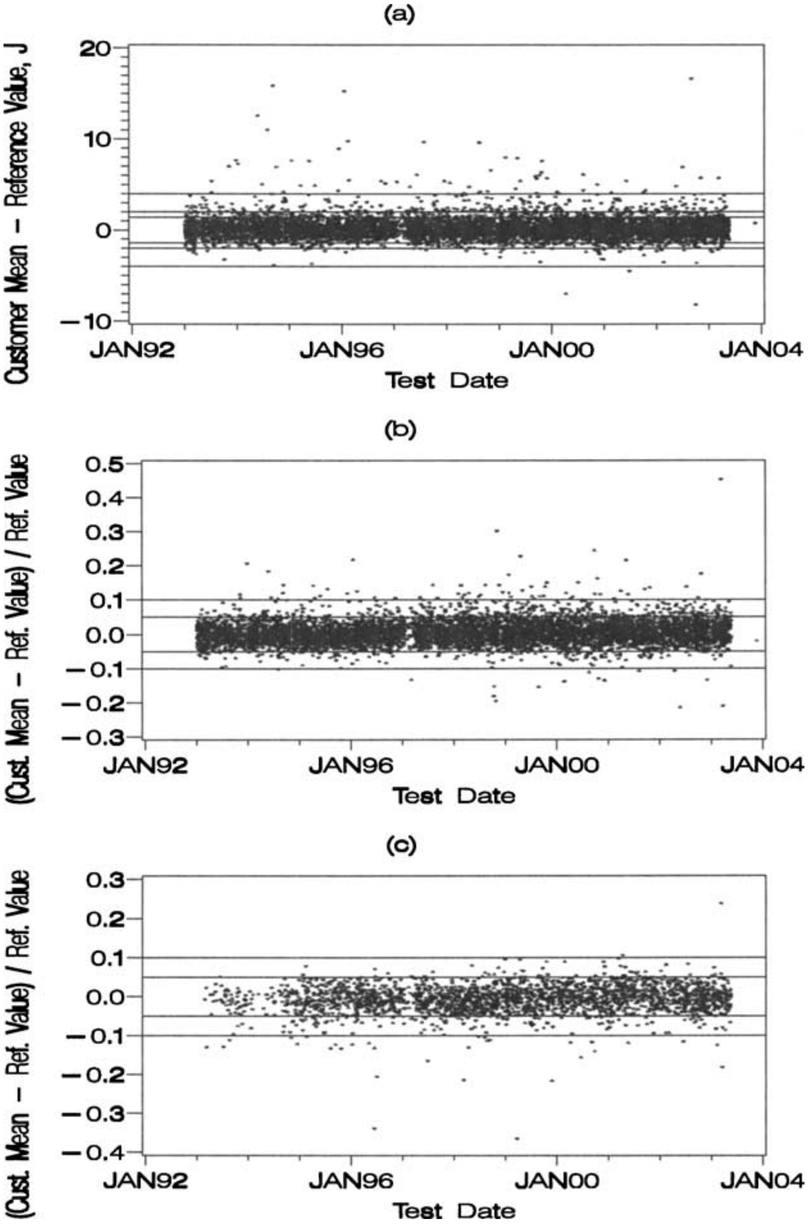

FIG. 1—*(a) Plot of differences over time for Low energy. ASTM, ISO reference machine, and ISO industrial machine energy limits are displayed (1.4, 2, and 4 J, respectively). (b) High energy and (c) Super-high energy normalized differences over time. ASTM, ISO reference machine, and ISO industrial machine energy limits are displayed (5, 5, and 10 %, respectively).*

Plots of all customer deviations versus their ranges (R) or normalized ranges (R_n) are shown in Fig. 3. The various acceptance limits from Table 1 are displayed on each plot. The plots indicate that many machines with large variation are certified using the ASTM criteria for all energy levels. Also, the arbitrary range and normalized range limits for ASTM A and ASTM B, respectively, should be adjusted so that they are more realistic with respect to the data. For example, a reasonable limit might be the 95th percentile of the historical customer ranges so that machines with the largest 5 % of variation would be failed. Histograms of customer ranges for each energy level are shown in Fig. 4. The 95th percentiles are indicated with a vertical dashed line.

The new verification rules, based on current ASTM limits in conjunction with range restrictions defined by the 95th percentiles of customer ranges, will be called ASTM C and ASTM D for the absolute range rule and relative range rule, respectively. Using the 95th percentiles as limits to the range and normalized range produces the pass/fail rates shown in Table 3.

Failing machines with the largest 5 % of ranges produces pass/fail rates that are similar across energy

TABLE 2—*Passing and failing rates for verification limits.*

	Pass	Fail	Total
Low energy			6955 (100 %)
ASTM	6146 (88.4 %)	809 (11.6 %)	
ASTM A	6101 (87.7 %)	854 (12.3 %)	
ASTM B	6023 (86.6 %)	932 (13.4 %)	
ISO—Reference machines	6120 (88.0 %)	835 (12 %)	
ISO—Industrial machines	6862 (98.7 %)	93 (1.3 %)	
ISO—Reference machines Energy Limit only	6567 (94.4 %)	388 (5.6 %)	
ISO—Industrial machines Energy Limit only	6893 (99.1 %)	62 (0.9 %)	
High energy			6938 (100 %)
ASTM	6302 (90.8 %)	636 (9.2 %)	
ASTM A	6196 (89.3 %)	742 (10.7 %)	
ASTM B	6301 (90.8 %)	637 (9.2 %)	
ISO—Reference machines	4042 (58.3 %)	2896 (41.7 %)	
ISO—Industrial machines	6706 (96.7 %)	232 (3.3 %)	
ISO-Reference machines Energy Limit only	6302 (90.8 %)	636 (9.2 %)	
ISO—Industrial machines Energy Limit only	6856 (98.8 %)	82 (1.2 %)	
Super-High energy			2426 (100 %)
ASTM	2191 (90.3 %)	235 (9.7 %)	
ASTM A	1015 (41.8 %)	1411 (58.2 %)	
ASTM B	2185 (90.1 %)	241 (9.9 %)	
ISO—Reference machines	1186 (48.9 %)	1240 (51.1 %)	
ISO—Industrial machines	2274 (93.7 %)	152 (6.3 %)	
ISO-Reference machines Energy Limit only	2191 (90.3 %)	235 (9.7 %)	
ISO—Industrial machines Energy Limit only	2392 (98.6 %)	34 (1.4 %)	

levels and decreases passing rates by at most 4.2 %. Annual passing rates for each energy level for the existing ISO and ASTM limits, as well as ASTM limits with proposed range rules based on 95th percentiles of the range, are shown in Fig. 5.

We computed correlations between energy levels based on relative ranges for machines in which specimens for two or more energy levels were tested on the same day. The analyses did not indicate that machines with high variation at one energy level would also have high variation at other energy levels. The correlation between low energy relative ranges and high energy relative ranges is 0.12, between high energy and super-high energy relative ranges is 0.11, and between low energy and super-high energy relative ranges is 0.06.

Wang's Verification Rule

One disadvantage to using a fixed range or normalized range rule is that it does not take into account variation in the pilot lot. Acceptance limits have been proposed by Wang that minimize the probability of failing a good machine and that account for pilot lot variation. First, we perform a test to determine whether the variance of the candidate machine data is the same as the variation in the pilot lot (Appendix B), and second, we compare the candidate machine mean to limits that account for variation. The candidate machine must pass both rules to be certified. The difference d between the candidate machine mean and the reference value must fall within

$$\mathrm{U} = -\mathrm{L} = (\mathrm{D} + 0.4619 \cdot \mathrm{S} \cdot t_{1-\alpha:76})\ \mathrm{J}, \tag{1}$$

where $\mathrm{S}^2 = (72\ \mathrm{S}_\mathrm{P}^2 + 4\ \mathrm{S}_\mathrm{C}^2)/76$, $t_{1-\alpha:76}$ is the $100(1-\alpha)$th percentile of Student's t distribution with 76 degrees of freedom, and D is the amount of allowable deviation between the customer's mean and the reference value. The value of D is arbitrary and depends on engineering judgment. For illustrative purposes, we will choose $\mathrm{D}=1.4$ J for low energy, $\mathrm{D}=6.0$ J for high energy, and $\mathrm{D}=12.0$ J for super-high

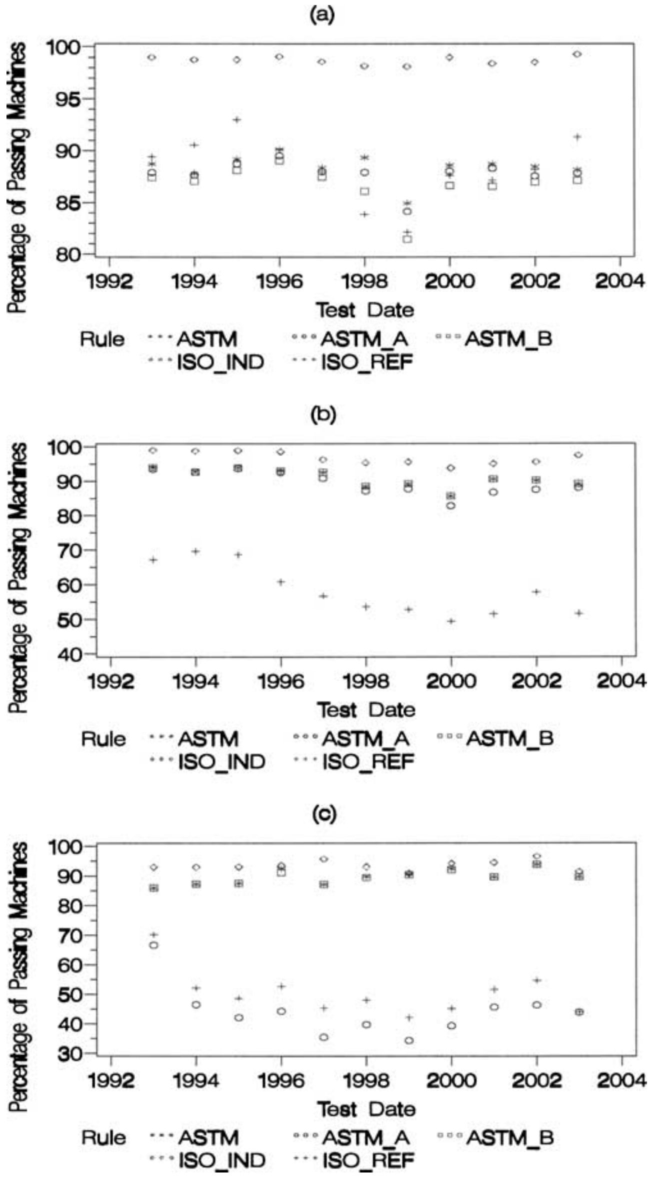

FIG. 2—*Annual passing rates for various verification rules at (a) low energy, (b) high energy, and (c) super-high energy.*

energy. The high and super-high energy values of D approximate 5 % limits based on the largest observed reference values, respectively. Table 4 displays pass/fail rates for each energy level based on Wang's rule. Not all pilot lot data were available to match with customer data, so the total number of observations is less than in previous analyses. Also, pilot lot sample sizes for individual reference machines were not available, so they are assumed to be equal.

The low energy passing rate in Table 4 is slightly higher than those listed in Table 3. However, the high and super-high passing rates are extremely low mainly because the variability in pilot lots is much smaller than customer variability. A histogram of customer standard deviations for super-high energy is shown in Fig. 6. The average observed standard deviation for super-high pilot lots is about 2.6 J, while customer variability averages 7.0 J. The discrepancy is less for high energy, where pilot lot standard deviations average 1.7 J and customer standard deviations average 2.8 J. Large customer variability is disturbing because it indicates that customer's measurements are not repeatable.

Simulation Study

To compare the performance of different verification rules, we simulated pilot lot and customer data and computed passing rates for low, medium, and high variation for each energy level. The simulated data had

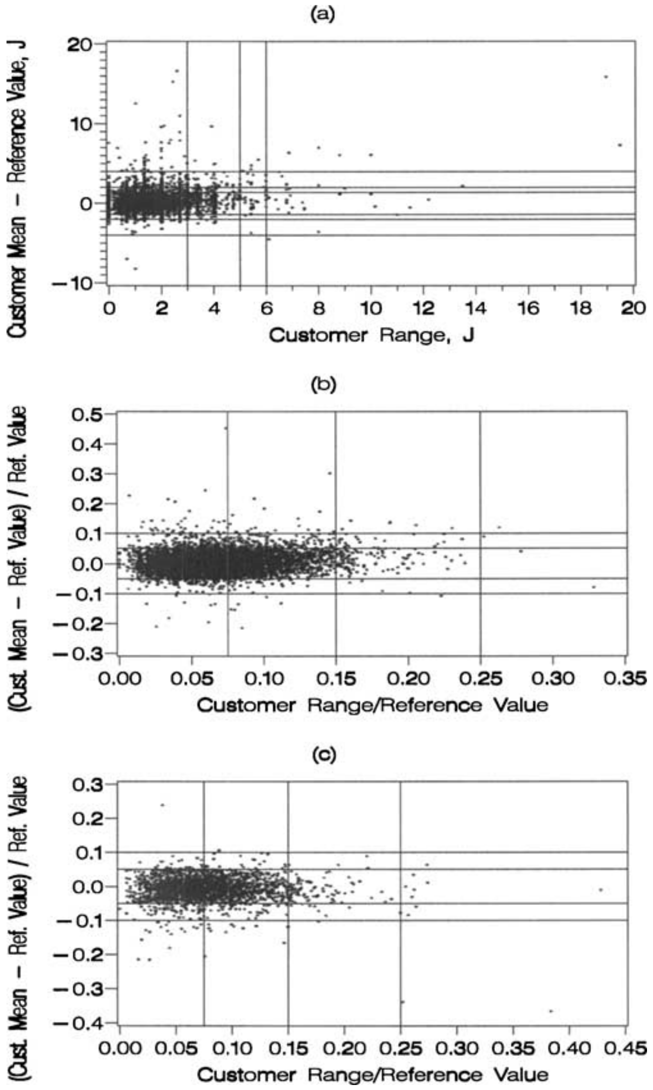

FIG. 3—*(a) Differences versus customer ranges for low energy specimens. Verification limits from Table 1 are represented by vertical and horizontal lines. The range limit for ASTM B is not shown in (a). Normalized differences versus normalized ranges for customers testing (b) high energy and (c) super-high energy specimens. Verification limits from Table 1 are represented by vertical and horizontal lines. The normalized range limits for ASTM A are not shown in (b) and (c).*

equal variance for customers and pilot lots. For each energy level, the verification rules were applied to the same simulated data. The results for all energy levels are displayed in Figs. 7–9. The verification rules of interest are the existing ASTM rule, the ISO reference machine rule, the ASTM rule with range/relative range restrictions based on the 95th percentile of customer ranges, and Wang's rule.

The simulation results indicate that passing rates for all verification rules are sensitive to variation inherent in the measurement system and specimens. When the customer mean is close to the reference value, the lines corresponding to the highest variations in Figs. 7–9 have the lowest passing rates. The high and super-high energy ISO rules for reference machines have very low passing rates with only moderate variation and small differences between the customer's mean and the reference value; however, passing rates for the low energy case are all above 75 % regardless of variation. Adding reasonable range and normalized range rules to the existing ASTM rules improves passing rates, but does not eliminate the influence of specimen and system variation. In contrast, Wang's rule yields nearly identical passing rates for machines falling within the allowable difference D regardless of variation.

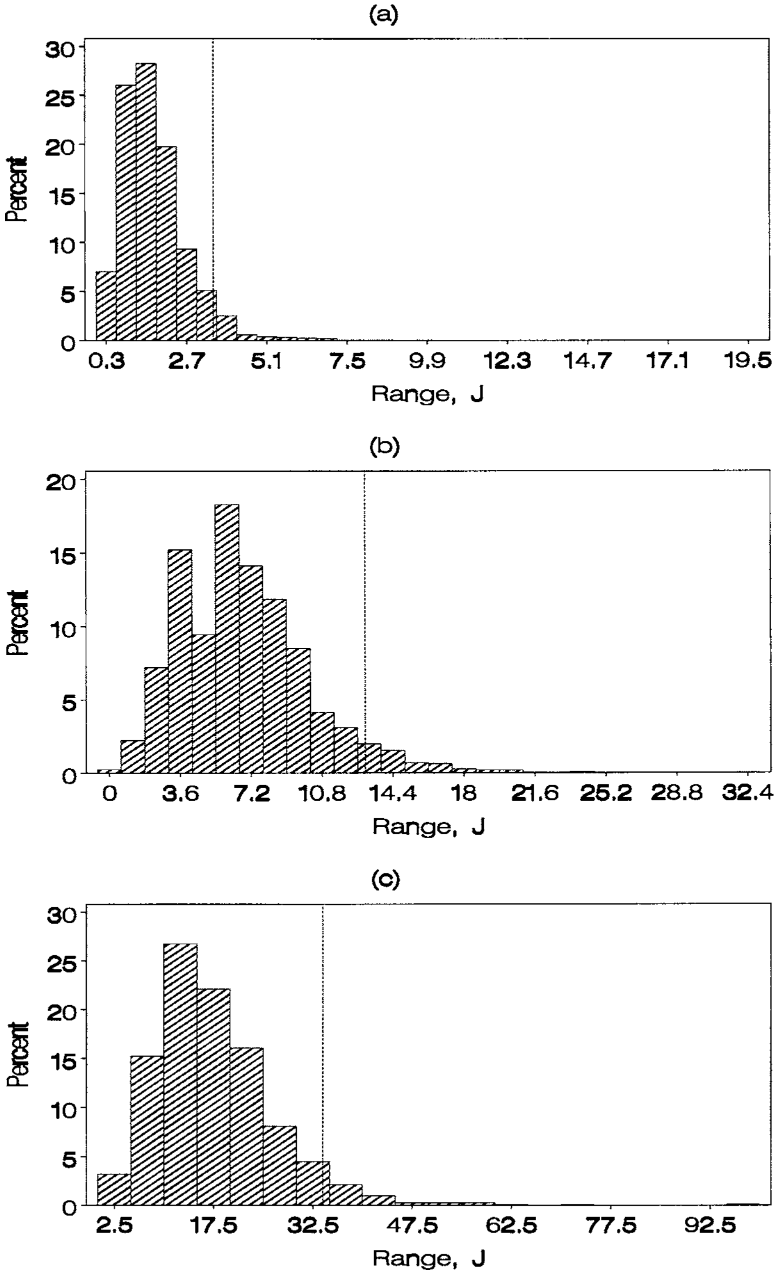

FIG. 4—*(a) Distribution of low energy customer ranges. The 95th percentile is indicated by a dashed vertical line at 3.5 J. (b) Distribution of high energy customer ranges. The 95th percentile is indicated by a dashed vertical line at 13.0 J. (c) Distribution of super-high energy customer ranges. The 95th percentile is indicated by a dashed vertical line at 34.0 J.*

Pendulum Type Comparison

We compared two pendulum types C and U by examining passing rates for the existing ASTM program. Table 5 lists passing rates for each pendulum type and energy level as well as the *P*-value computed for a test comparing the passing rates.

While the observed passing rates for pendulum types are similar at each energy level, the *P*-values indicate that the rates are significantly different. It is common for tests of proportions to produce significant results when sample sizes are large; however, the differences might not be of practical significance.

Other analyses of pendulum type involve comparing mean energy values of machines that pass the existing ASTM verification rules. Calculated average impact energies for each energy level, machine, and lot were categorized according to pendulum type. Two types of analyses were performed using the mean energies and pendulum types: (1) two-sample *t* tests for each energy level and lot separately, and (2) an

TABLE 3—*Passing rates for current ASTM rules and ASTM verification limits using 95th percentile range and normalized range limits.*

	Pass	Fail	Total
Low energy			6955 (100 %)
ASTM	6146 (88.4 %)	809 (11.6 %)	
ASTM C—$R \leqslant 3.5$ J	5914 (85.0 %)	1041 (15.0 %)	
ASTM D—$R_n \leqslant 23$ %	5970 (85.8 %)	985 (14.2 %)	
High energy			6938 (100 %)
ASTM	6302 (90.8 %)	636 (9.2 %)	
ASTM C—$R \leqslant 13$ J	6033 (87.0 %)	905 (13.0 %)	
ASTM D—$R_n \leqslant 13$ %	6022 (86.8 %)	916 (13.2 %)	
Super-high energy			2426 (100 %)
ASTM	2191 (90.3 %)	235 (9.7 %)	
ASTM C—$R \leqslant 34$ J	2102 (86.6 %)	324 (13.4 %)	
ASTM D—$R_n \leqslant 15$ %	2088 (86.1 %)	338 (13.9 %)	

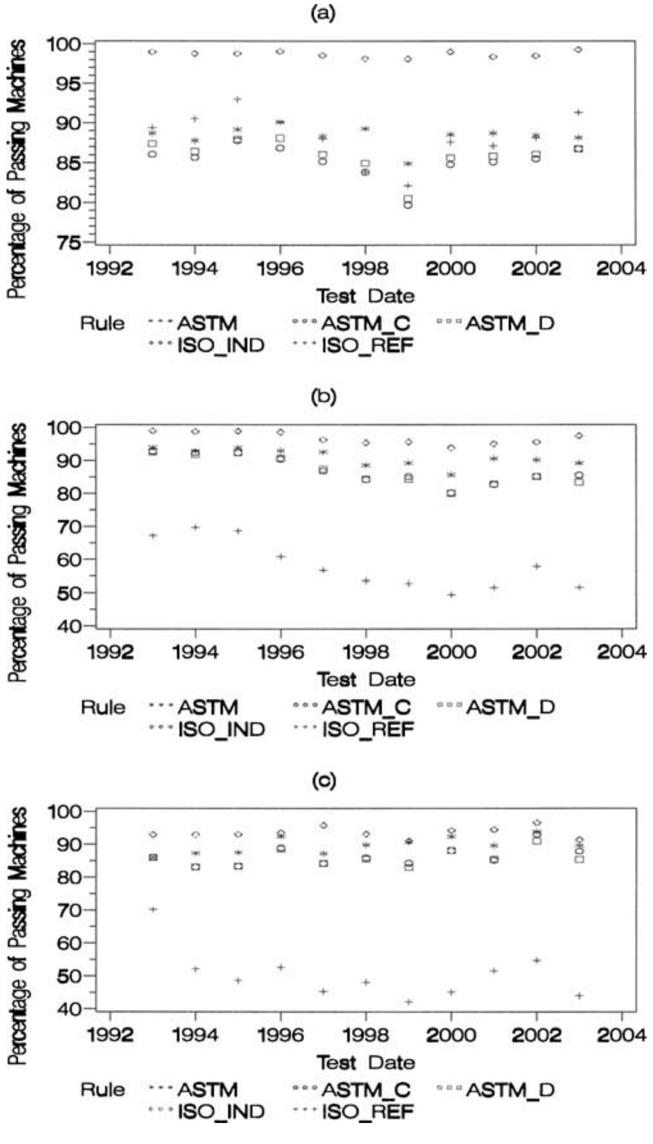

FIG. 5—*Annual passing rates for (a) low energy, (b) high energy, and (c) super-high energy. ASTM C and ASTM D limits are the 95th percentile of low energy customer ranges.*

analysis of variance at each energy level in which we accounted for differences among lots.

Overall, the results of the two-sample *t* tests were inconclusive. Some of the differences between the means of the two pendulum types were significant and some were not, indicating that there is a relationship between pendulum type and lot. In other words, conclusions about differences between the two pendulum types depended on the lot used in the test.

An analysis of variance was performed to determine whether differences between average impact

TABLE 4—*Passing rates for Wang's verification limits. The allowable difference D and the average value of the upper limit U are shown for each energy level.*

Energy level	Pass	Fail	Total
Low (D = 1.4 J, U = 2.1 J)	5217 (89 %)	665 (11 %)	5882 (100 %)
High (D = 6.0 J, U = 7.6 J)	2197 (52 %)	2034 (48 %)	4231 (100 %)
Super-high (D = 12.0 J, U = 14.4 J)	312 (19 %)	1370 (81 %)	1682 (100 %)

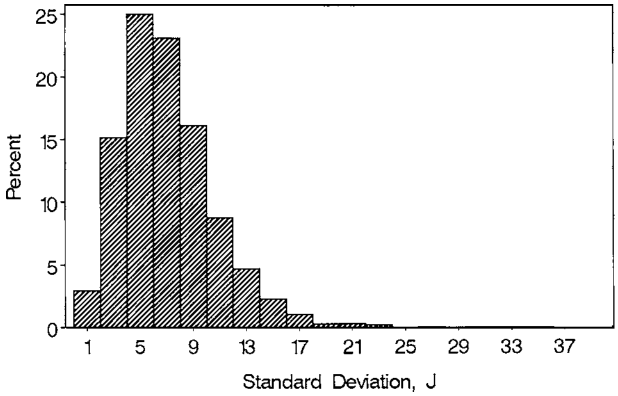

FIG. 6—*Distribution of super-high energy customer standard deviations.*

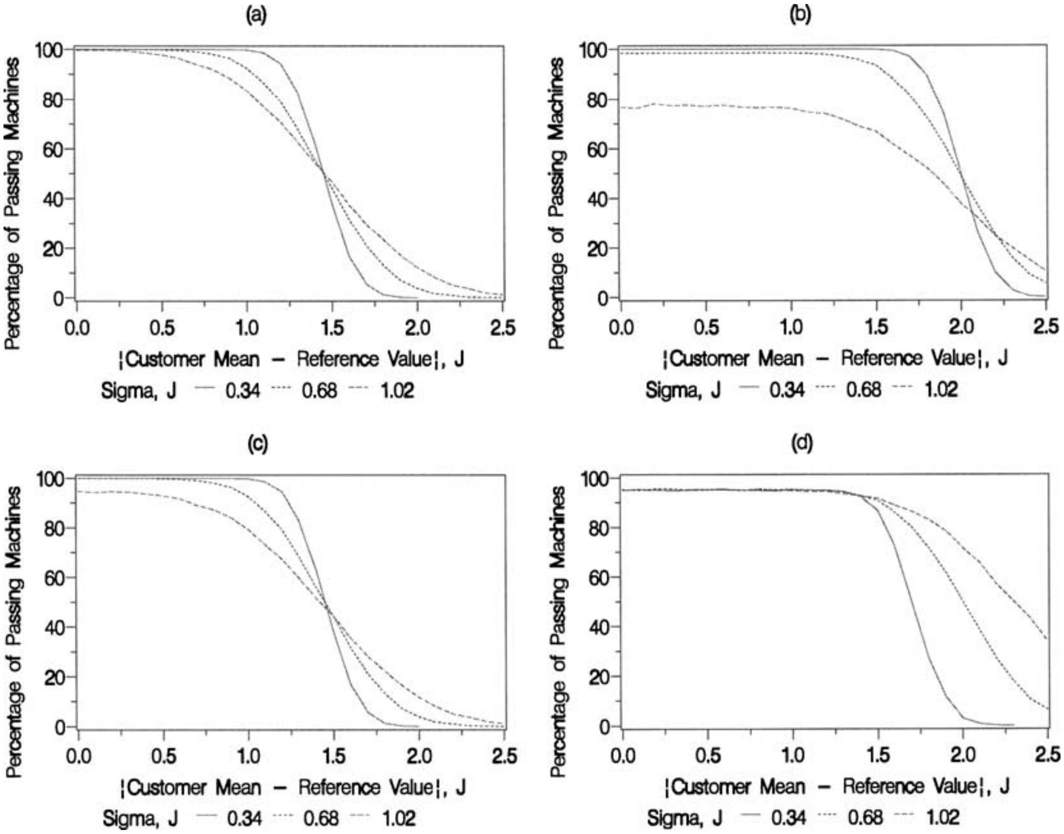

FIG. 7—*(a) Simulation results for the existing low energy ASTM verification rule. (b) Simulation results for the low energy ISO reference machine verification rule. (c) Simulation results for the low energy ASTM rule with range ≤3.5 J. (d) Simulation results for Wang's proposed low energy rule with D = 1.4 J.*

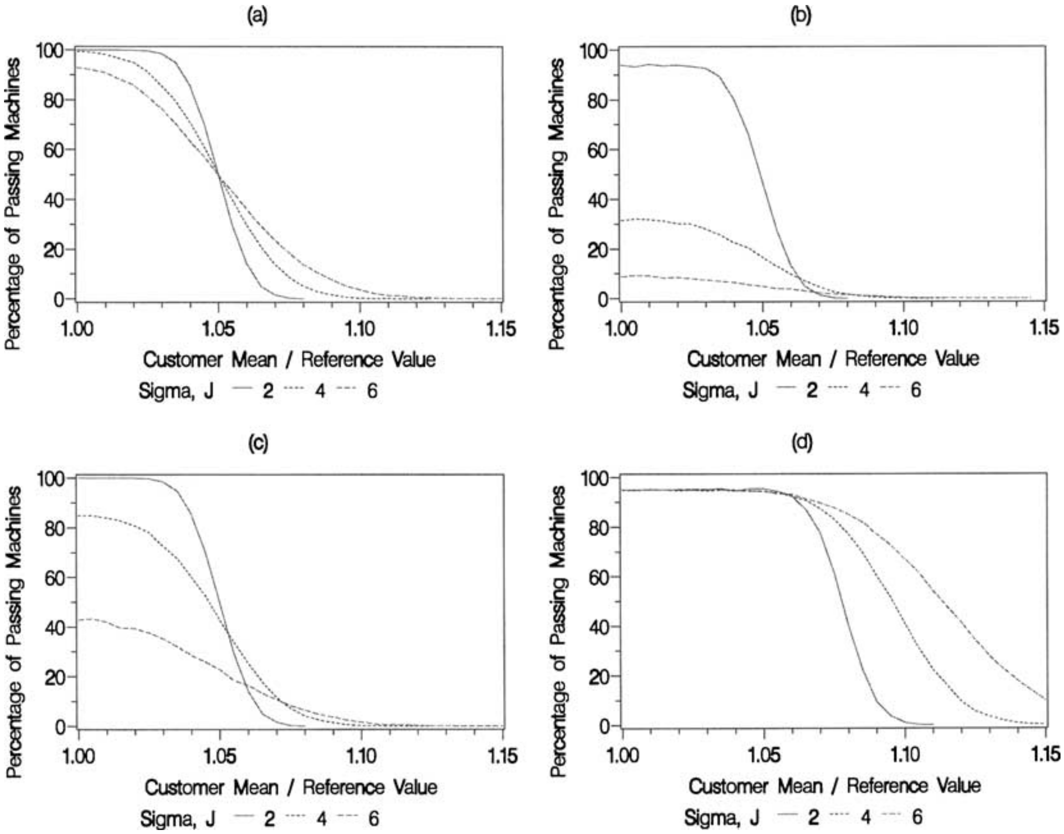

FIG. 8—*(a) Simulation results for the existing high energy ASTM verification rule. (b) Simulation results for the high energy ISO reference machine verification rule. (c) Simulation results for the high energy ASTM rule with relative range ≤13 %. (d) Simulation results for Wang's proposed high energy rule with $D=6$ J.*

energies for the two pendulum types were significant after accounting for differences among lots. The analysis of variance results are shown in Table 6.

The *P*-values indicate that means for the two pendulum types are significantly different at the low and high energies, but are not significantly different for super-high energy at the 0.05 level. The analysis of variance also indicated that there is some relationship between pendulum type and lot. Additional work is needed in this area to fully understand the effect of pendulum type and its dependence on lot.

Machine Capacity Analysis

We examined average impact energy and ASTM passing rates associated with the machine capacities reported by customers. We fit a straight line to customer average versus machine capacity for each energy level. Only data associated with machines passing the existing ASTM verification rules were used in the analysis since data from failing machines are unreliable. The graphical results are shown in Fig. 10, and Table 7 displays slopes, *P*-values, and correlation coefficients for each energy level.

The slopes for high and super-high energies were not significantly different from zero, indicating that machine capacity is not a good predictor of the average breaking strength. For low and high energies, higher machine capacities were associated with slightly larger customer averages (positive slope), while higher machine capacities were associated with slightly lower customer averages for super-high energy machines (negative slope).

Although the low energy slope is significantly different from zero, the result may not be of practical significance. The average impact energy for a machine with a 50 J capacity is only 0.63 J less than the average impact energy for a machine with a capacity of 750 J. Also, it is common to achieve a statistically significant result when the sample size is large. Thus, it is left to engineering judgment as to whether average impact energy is increasing as machine capacity increases at the low energy level.

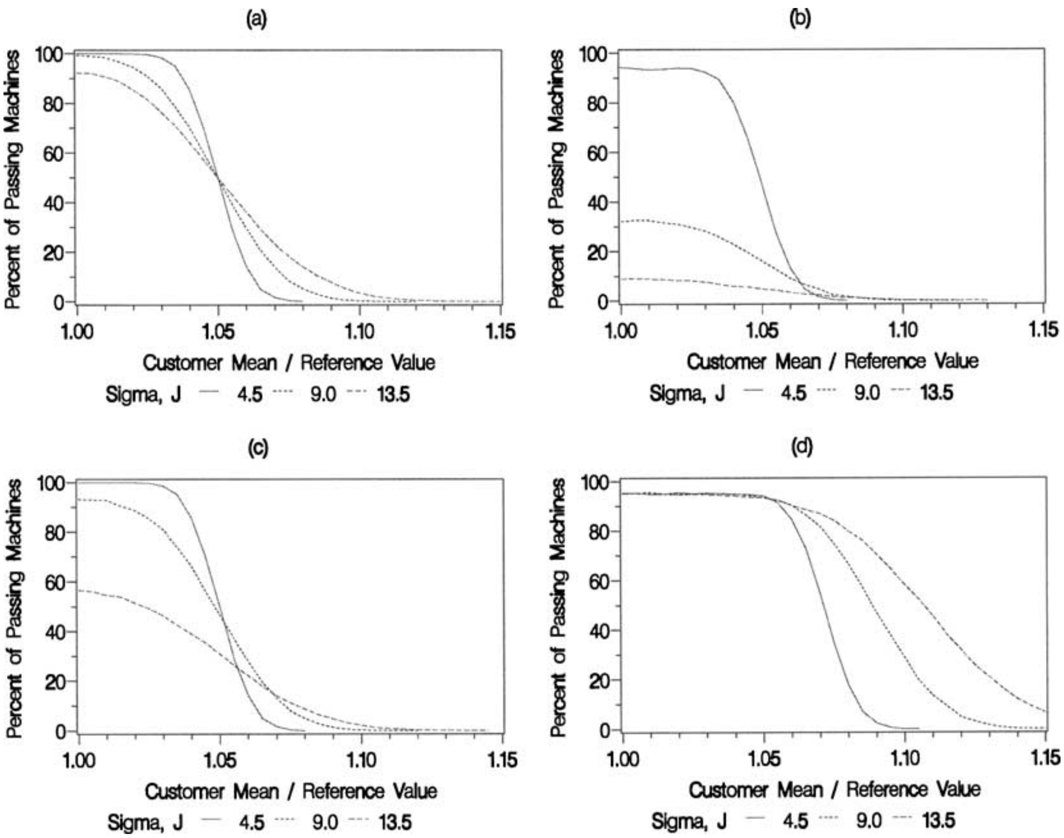

FIG. 9—*(a) Simulation results for the existing super-high energy ASTM rule. (b) Simulation results for the super-high energy ISO reference machine rule. (c) Simulation results for the super-high energy ASTM rule with relative range ≤15 %. (d) Simulation results for Wang's proposed super-high energy rule with D = 12 J.*

To examine passing rates for existing ASTM verification limits, machine capacities were discretized by rounding them to the nearest 50 J. Plots of passing rates versus rounded machine capacities are shown in Fig. 11. Machine capacities with less than ten passing machines were excluded from the plots. While there appears to be a slight upward trend in the data for each energy level, a linear fit of passing rate versus machine capacity did not produce any slopes that are significantly different from zero.

Country Analysis

We examined passing rates based on country affiliation. Because of the sensitive nature of revealing passing rates for each country, we divided countries into two groups, the United States and all others. Table

TABLE 5—*Passing rates for two pendulum types based on ASTM verification limits.*

Energy level	C type	U type	*P*-value
Low	2221 (89.4 %)	3889 (87.8 %)	0.02
High	2209 (89.0 %)	4056 (91.8 %)	<0.0001
Super-High	961 (91.7 %)	1219 (89.2 %)	0.02

TABLE 6—*P-values corresponding to hypothesis tests comparing means for two pendulum types based on an analysis of variance using machines passing the ASTM verification rules.*

Energy level	*P*-value
Low	0.005
High	0.001
Super-high	0.3

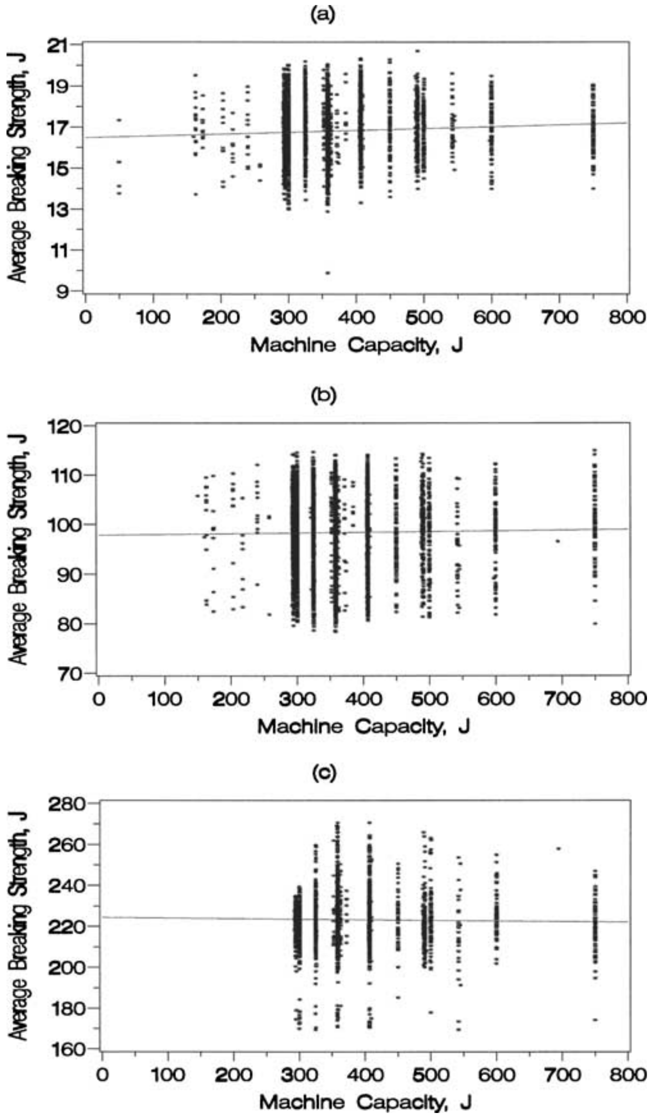

FIG. 10—*Customer averages versus machine capacity for (a) low energy, (b) high energy, and (c) super-high energy. The straight line fit to the data is represented by the line.*

8 displays passing rates for the two groups based on the existing ASTM verification rules at each energy level. A *P*-value associated with a test of equal proportions is also shown in Table 8.

Passing rates are about three percentage points higher for the United States than for all other countries for low and high energy levels. The super-high passing rate is slightly smaller for the United States than it is for all other countries, although there is no significant difference between the two rates.

Figure 12 displays passing rates based on existing ASTM verification rules for individual countries having more than ten passing machines. Country names have been removed from the plots. The data

TABLE 7—*Slopes, P-values (in parentheses), and correlation coefficients associated with lines fit to customer averages versus machine capacity for machines passing the existing ASTM verification rules.*

Energy level	Slope (*P*-value)	Correlation coefficient, r
Low	0.00090 ($<$0.0001)	0.06
High	0.0015 (0.2)	0.02
Super-high	−0.0028 (0.4)	0.02

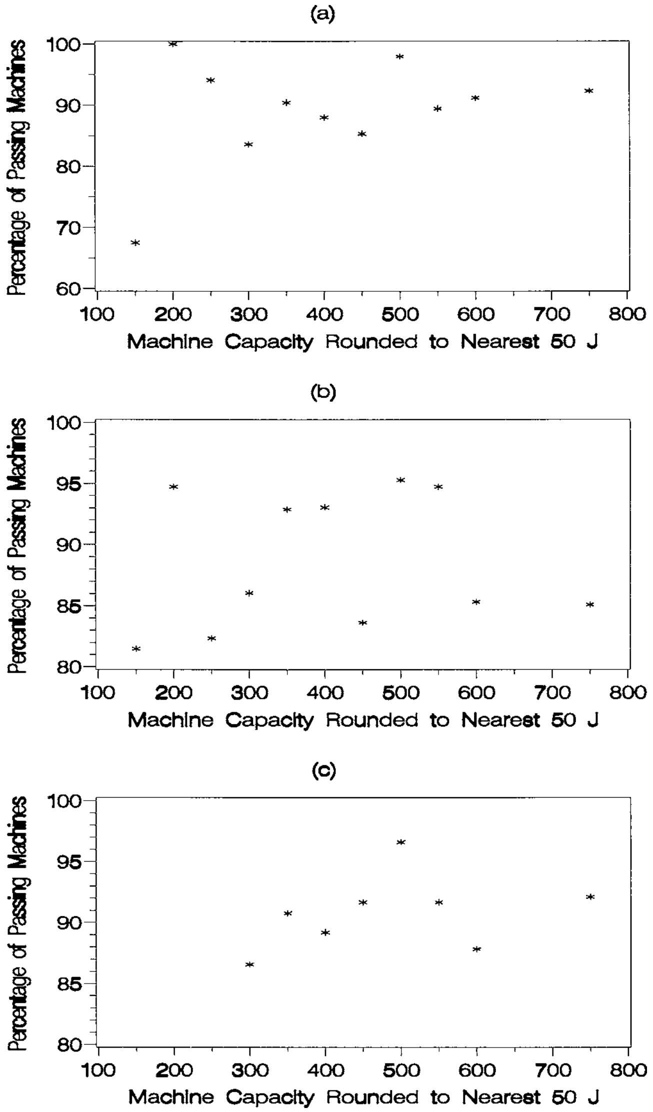

FIG. 11—*Percentage of machines passing the (a) low energy, (b) high energy, and (c) super-high energy ASTM verification limits versus machine capacity. Machine capacities with less than ten passing machines are not shown.*

indicate that ASTM passing rates for the United States are comparable to those of other countries at every energy level.

Discussion

The acceptable deviation of a customer mean from a reference value is not a quantity that can be determined through statistical means. It depends on the amount deemed appropriate based on engineering judgment. Through statistics, we can examine the properties of existing and proposed rules and provide information that can be used to make informed decisions.

The ASTM verification limits currently in use do not account for inherent specimen and system variation. Wang's rule accounts for this variation, but does not provide fixed limits for every lot of

TABLE 8—*ASTM passing rates for the United States and all other countries combined.*

Energy Level	United States	All other countries	*P*-value
Low	2649 (90.7 %)	3482 (86.7 %)	<0.0001
High	2686 (92.8 %)	3604 (89.5 %)	<0.0001
Super-high	758 (89.8 %)	1432 (90.6 %)	0.3

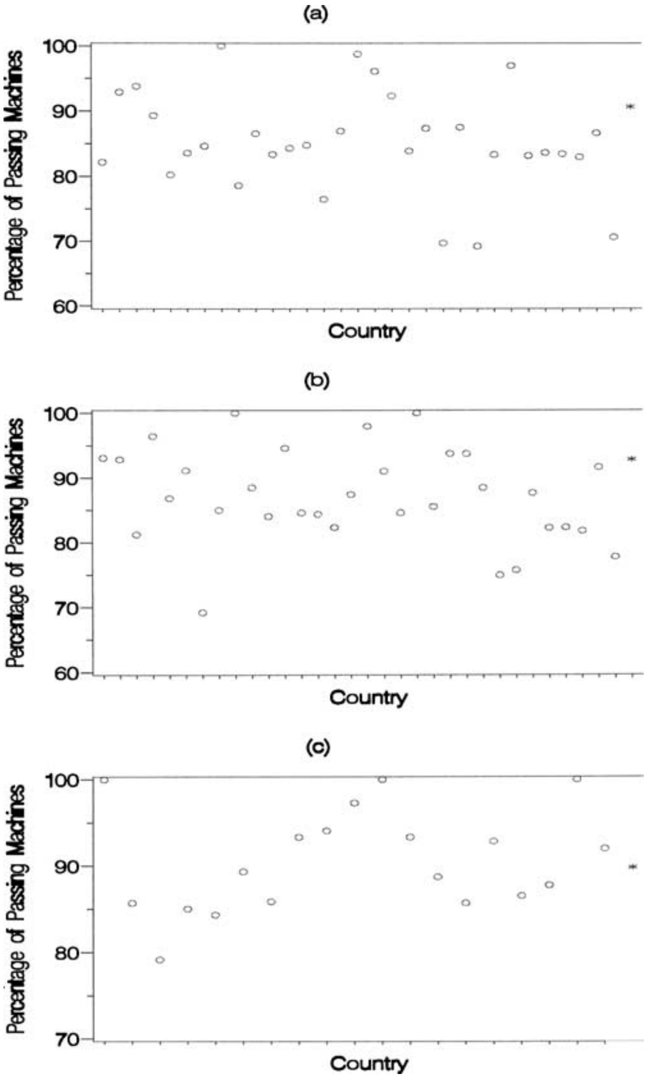

FIG. 12—*(a) low energy, (b) high energy, and (c) super-high energy ASTM passing rates by country. The United States appears as a star.*

specimens. Some participants in the Charpy program might be uncomfortable with limits that change depending on pilot lot variation since these limits could be wider than the current ASTM limits. Wang's rule is statistically justifiable, can be tailored to meet the needs of the program, and has a low probability of failing a "good" machine. Although Wang's rule is appealing from a statistical standpoint, it might not be the best solution in practice, especially for the super-high energy case. Typical customer variability at the super-high energy level is so large relative to pilot lot variability that most customers would fail the equality of variance test using Wang's rule. The large customer variability also brings into question the repeatability of customer measurements. Additional work is needed to understand and decrease customer variability.

We do not recommend increasing the current ASTM limits, unless this is done in combination with the addition of a range rule. Widening any existing limits without accounting for variation would only serve to increase the potential for large differences between the customer's average and the true unknown breaking strength of the material. In particular, increasing the existing Low energy ASTM limit to 4 J, without implementing a range rule as well, would completely undermine the program objectives since virtually all machines would pass.

Determining appropriate rules to limit variation via range and relative range rules is a good way to improve the ASTM program, and limiting customer ranges based on the 95th percentile of the range distribution appears to be a reasonable approach. Since ASTM A and ASTM B rules can be adjusted so that they produce nearly identical passing rates, we really only need to determine a single rule that can be expressed in absolute units or on a percentage basis. If, for example, a range rule based on the 95th percentile were proposed to accompany a 2 J or 5 % energy rule, we might achieve a reasonable compromise between ASTM and ISO rules that could satisfy both organizations. Based on low energy historical data, a 2 J energy limit with a 95th percentile range rule (3.5 J) would have a 90.7 % passing rate.

We examined the passing rates and distributions of means for C and U type pendulums. Although we found statistically significant differences between passing rates for the two groups, it is unclear whether the differences are of practical significance. Also, we discovered dependence between pendulum type and lot which merits further study.

Analyses of machine capacity did not reveal any significant relationships between passing rates and machine capacity. We also determined that there is no convincing evidence that average impact energy is increasing or decreasing as machine capacity increases. While there are slight trends in average impact energies for the low energy level, more work is needed to verify that the trend is significant.

Passing rates based on existing ASTM verification rules indicate that machines in the United States are comparable to machines in other countries for all energy levels. Low and high energy passing rates are about 3 % higher for the United States than for all other countries.

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Appendix A

In the ASTM verification program, the pooled standard deviation of the pilot lot ($\mathrm{S_P}$) is computed as

$$\mathrm{S_P} = \sqrt{\frac{(n_1-1)s_1^2+(n_2-1)s_2^2+(n_3-1)s_3^2}{n_1+n_2+n_3-3}}, \qquad (A1)$$

where n_1, n_2, n_3 are the number of verification specimens tested on each of the three master machines, and s_1, s_2, s_3 are the associated standard deviations. Typically, 25 verification specimens are tested on each machine.

Appendix B

The F test is used to determine the equality of two sample variances. For our problem, we are only concerned if the customer's sample variance ($\mathrm{S_C^2}$) is large compared to the pooled pilot lot variance ($\mathrm{S_P^2}$). If the ratio

$$F = \frac{\mathrm{S_C^2}}{\mathrm{S_P^2}} \qquad (A2)$$

is greater than the 100(1-α)th percentile of the F distribution, denoted by $F_{1-\alpha;4,72}$, then we would conclude that $\mathrm{S_C^2}$ is significantly larger than $\mathrm{S_P^2}$. The quantities 4 and 72 correspond to the degrees of freedom for the customer and pooled pilot lot variances, respectively, and α is the significance level of the test (usually 0.05). See [6] for more information regarding equality of variance tests.

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