NIST Technical Note 1875

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## Abstract

As a contribution to the establishment of an international scale for instrumented Charpy testing, aimed at ensuring that impact forces are obtained more accurately, NIST and *Laboratoire National de métrologie et d'Essais* (LNE, France) have participated in an interlaboratory comparison of instrumented impact tests on reference specimens of different energy levels from seven certified verification batches. In both locations, tests have been performed using nominally identical Charpy machines and the same instrumentation (Charpy striker and acquisition system). The comparison between NIST and LNE test results has revealed statistically significant differences, particularly in terms of absorbed energies and instrumented forces. The reasons for such discrepancies are unclear, although a malfunction of the acquisition system during the tests at LNE and possible differences in the surface finish of the machine anvils and supports in the two labs are possible contributing factors.

## Keywords

Absorbed energy; instrumented Charpy testing; instrumented forces; interlaboratory comparison; lateral expansion; LNE; NIST; reference Charpy specimens; surface finish.

# Table of Contents

# 1. Introduction

Even though the Charpy impact test has already celebrated its $100^{th}$ anniversary [1,2], it is still widely used in laboratories and industries all over the world to obtain information on the impact toughness of materials.

The Charpy test method was first standardized by the American Society for Testing and Materials (ASTM) in 1933 [3], followed by an International Organization for Standardization (ISO) standard published in 1983 [4].

Even though instrumented impact testing is often considered to be a relatively recent technical development of Charpy testing, the earliest known paper on the topic actually predates the first pendulum test machine publication by one year [5]. This type of test started to gain popularity in the technical community in the early 1920's, when it was considered a sort of laboratory curiosity. The first review of instrumented impact methods was published in 1926 [6], but it was during the 1960's that the volume of work on instrumented impact testing started to increase drastically.

The first attempt to standardize instrumented impact testing dates back to the 1970's, when an ASTM Technical Subcommittee was formed with the objective of producing a test method for measuring the dynamic fracture toughness of fatigue precracked Charpy specimens. This work was later abandoned, and it was only in the late 1990's that ISO started work on a test standard for instrumented impact testing. This standard (ISO 14556) was finally published in 2000 [7], and was later followed by the first edition of ASTM E2298, published in 2009 [8].

Although instrumented Charpy tests are routinely performed in many laboratories around the world and international standards are now available for the execution of the tests and the analysis of the results, there remains a need to ensure that impact forces are obtained more accurately. To accomplish this, an international scale based on SI units needs to be established to reduce bias between National Metrology Institutes (NMIs).

To this regard, during the annual meeting of ISO/TC 164 SC4 (*Mechanical Testing of Metals*, *Toughness Testing -- Fracture, Pendulum, Tear*) held in Paris France in 2011, multiple intercomparisons of instrumented Charpy tests between NMIs were discussed and proposed as a means to reduce bias between National Institutes.

The first step of this activity was an interlaboratory comparison of instrumented Charpy test results between NIST and the Brazilian National Institute of Metrology, Quality and Technology (Inmetro). This exercise was conducted in 2012-2013, and consisted of testing NIST reference specimens of low and high energy on nominally identical[1] impact machines available at NIST and Inmetro, equipped with the same instrumented striker. Tests were performed in four stages, two at NIST and two at Inmetro, over a period spanning from August 2012 to February 2013. NIST acted as the Pilot Laboratory for this Supplementary Comparison among the SIM.MWG7 (Inter-American Metrology Institutes - Technical Committee of Mass and Related Quantity-Working Group of Force 7), in cooperation with Inmetro for the development and the planning of this interlaboratory comparison. The results of this activity have been published jointly by NIST and Inmetro in the form of a Technical Report [9].

[1] By "nominally identical", we mean here that the two machines are from the same manufacturer, correspond to the same model, and have the same potential energy (capacity) and impact velocity.

The following stage of the project consisted in a similar interlaboratory comparison of instrumented Charpy test results between NIST and the *Laboratoire National de métrologie et d'Essais* (LNE, France). The scope of the comparison was expanded to include tests on reference specimens produced by both institutes at different absorbed energy levels, as well as instrumented and non-instrumented impact tests. The experimental activity was conducted on two nominally identical pendulum impact machines, one operated by NIST Boulder, CO (USA) and the other by LNE Trappes (France), equipped with the same instrumented striker. Signal acquisition was accomplished by means of the same instrumentation. The complete results of this activity are provided in this document.

# 2. Description of the technical program

## 2.1 Materials and specimens

Both NIST and LNE produce and sell certified reference Charpy specimens for the indirect verification of impact pendulum machines, in accordance with ASTM E23 and ISO 148 respectively.

NIST certified reference specimens cover three absorbed energy (*KV*) levels at -40 °C: low energy (≈ 15 J), high energy (≈ 100 J), and super-high energy (≈ 200 J). LNE certified reference Charpy specimens cover five absorbed energy levels at 20 °C: low energy (≈ 25 J), medium energy (≈ 80 J), high energy (≈ 120 J and ≈ 160 J), and super high energy (≈ 200 J).

Within this intercomparison between NIST and LNE, full-size Charpy specimens from the following reference lots have been tested (expanded uncertainties are also provided):

- NIST LL-103 (low energy, certified *KV* = 15.3 J ± 0.1 J at -40 °C and 18.2 J ± 0.1 J at 21 °C)
- NIST HH-103 (high energy, *KV* = 97.5 J ± 0.6 J at -40 °C and 105.3 J ± 0.6 J at 21 °C)
- NIST LL-136 (low energy, certified *KV* = 17.1 J ± 0.1 J at -40 °C)
- NIST HH-140 (high energy, certified *KV* = 97.6 J ± 0.6 J at -40 °C)
- LNE 1AD (certified *KV* = 29.7 J ± 0.9 J at 20 °C)
- LNE 5AB (certified *KV* = 131.9 J ± 3.6 J at 20 °C)
- LNE 9E (certified *KV* = 199.1 J ± 4.0 J at 20 °C).

Note that lots LL-103 and HH-103 (force verification specimens) have also been certified at NIST for the dynamic verification of instrumented strikers by means of an international round-robin exercise [10]. Their certified values of maximum force, $F_m$, at 21 °C are (expanded uncertainties are also provided):

- LL-103 – $F_m$ = 33.00 kN ± 1.86 kN
- HH-103 – $F_m$ = 24.06 kN ± 0.07 kN.

A total of 140 Charpy tests (70 instrumented and 70 non-instrumented) have been performed. The complete test matrix, organized in chronological fashion, is provided in Table 1.

## 2.2 Test machines

Two nominally identical impact pendulum machines have been used for this exercise. Both machines had the following characteristics:

– potential energy (machine capacity) = 358.63 J
– impact velocity = 5.13 m/s.

The most notable difference is the angle of taper of the anvils. The NIST machine had an angle of 10 ° in accordance with ASTM E23-12c, whereas the machine at LNE had an angle of 11 °, which satisfies the requirements of ISO 148-2:2008 [10].

*Table 1 - Test matrix of the interlaboratory comparison between NIST and LNE.*

<table>
<tr><th>Test location</th><th>Test date</th><th>Specimen lot/batch</th><th>Number of tests</th><th>Type of test</th></tr>
<tr><td rowspan="4">NIST</td><td rowspan="4">May 13, 2014</td><td>LL-103</td><td>3</td><td rowspan="13">Instrumented</td></tr>
<tr><td>HH-103</td><td>3</td></tr>
<tr><td>LL-136</td><td>5</td></tr>
<tr><td>HH-140</td><td>5</td></tr>
<tr><td rowspan="14">LNE</td><td rowspan="7">May 20, 2014</td><td>LL-103</td><td>3</td></tr>
<tr><td>HH-103</td><td>3</td></tr>
<tr><td>LL-136</td><td>5</td></tr>
<tr><td>HH-140</td><td>5</td></tr>
<tr><td>1AD</td><td>5</td></tr>
<tr><td>5AB</td><td>5</td></tr>
<tr><td>9E</td><td>5</td></tr>
<tr><td rowspan="7">May 21, 2014</td><td>LL-103</td><td>2</td></tr>
<tr><td>HH-103</td><td>2</td></tr>
<tr><td>LL-136</td><td>10</td><td rowspan="5">Non-instrumented</td></tr>
<tr><td>HH-140</td><td>10</td></tr>
<tr><td>1AD</td><td>5</td></tr>
<tr><td>5AB</td><td>5</td></tr>
<tr><td>9E</td><td>5</td></tr>
<tr><td rowspan="10">NIST</td><td rowspan="5">June 3, 2014</td><td>LL-103</td><td>2</td><td rowspan="5">Instrumented</td></tr>
<tr><td>HH-103</td><td>2</td></tr>
<tr><td>1AD</td><td>5</td></tr>
<tr><td>5AB</td><td>5</td></tr>
<tr><td>9E</td><td>5</td></tr>
<tr><td rowspan="5">June 4, 2014</td><td>LL-136</td><td>10</td><td rowspan="5">Non-instrumented</td></tr>
<tr><td>HH-140</td><td>10</td></tr>
<tr><td>1AD</td><td>5</td></tr>
<tr><td>5AB</td><td>5</td></tr>
<tr><td>9E</td><td>5</td></tr>
</table>

## 2.3 Instrumented striker and acquisition system

The same instrumented striker and data acquisition system was used for all Charpy tests. This striker, designated JS-1, had a radius of the striking edge equal to 8 mm, in accordance with ASTM E23-12c. The striker was instrumented with strain-gages in a "left-right" configuration with respect to the direction of impact[2].

[2] The other common design for an instrumented striker is the so-called "top-bottom" configuration.

Before starting the intercomparison exercise, the striker had been statically calibrated at NIST using a universal testing machine. The results of the striker calibration (applied force vs. striker output) are shown in Figure 1.

The acquisition system used for the instrumented impact tests consisted of a dynamic signal conditioner and amplifier, coupled with an analog-to-digital converter. The sampling rate used ranged from 500 kHz to 1MHz.

The initial plan for the intercomparison exercise was to perform all tests as instrumented. However, during the testing phase at LNE the acquisition system started to malfunction, and consequently half of the tests conducted in this program were performed without instrumentation (see Table 1).

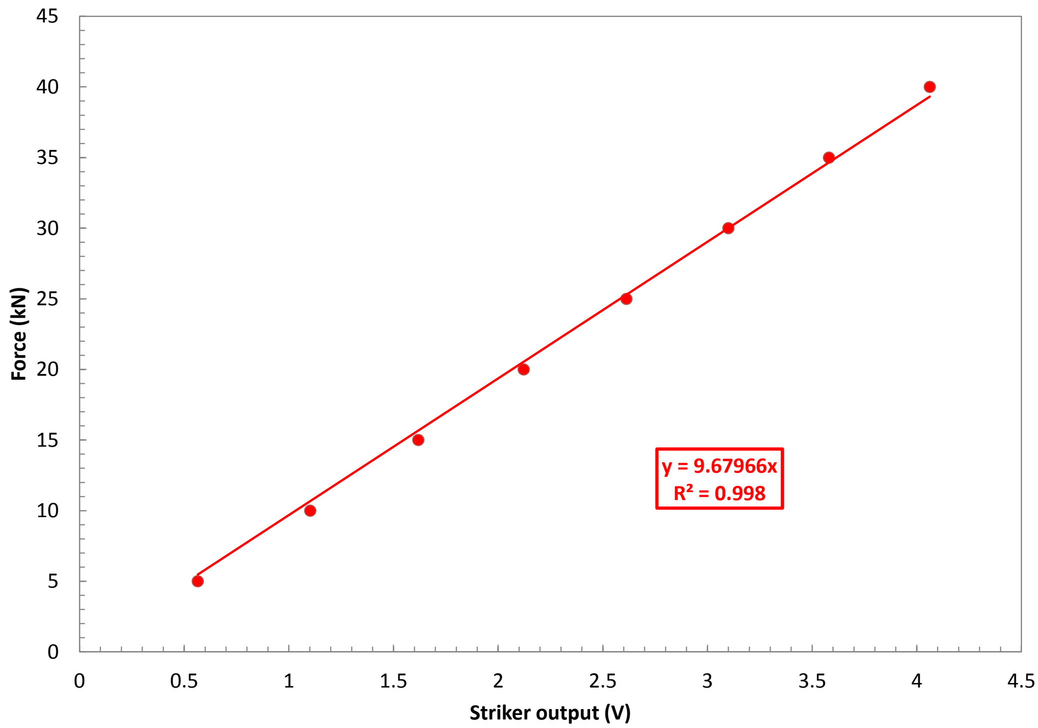


*Figure 1 - Static calibration of the 8-mm instrumented striker used for this intercomparison.*

# 3. Test results

## 3.1 NIST force verification specimens (LL-103 and HH-103)

The individual test results obtained at NIST and LNE on LL-103 and HH-103 are presented in Table 2 and Table 3, respectively. In the tables, the following parameters are reported:

- force at general yield, $F_{gy}$;
- elastic compliance[3], $C_{el}$;
- maximum force, $F_m$;
- absorbed energy calculated under the instrumented test record, $W_t$;
- absorbed energy provided by the machine encoder, $KV$;
- ratio $KV/W_t$;
- lateral expansion[4], $LE$.

For each parameter average values, standard deviations and coefficients of variation[5] ($CV$) are reported for each individual test day and considering all tests performed in one location.

*Table 2 - Results of the tests performed on LL-103.*

| Charpy lot | Lab | Specimen id | $F_{gy}$ (kN) | $C_{el}$ (mm/kN) | $F_m$ (kN) | $W_t$ (J) | $KV$ (J) | $KV/W_t$ | $LE$ (mm) |
|---|---|---|---|---|---|---|---|---|---|
| LL-103 | NIST (5/13/14) | 96 | 25.99 | 0.019 | 34.02 | 20.17 | 18.67 | 0.926 | 0.047 |
| | | 420 | 27.02 | 0.020 | 33.39 | 19.91 | 18.76 | 0.942 | 0.040 |
| | | 938 | 26.02 | 0.018 | 33.70 | 21.13 | 19.89 | 0.941 | 0.055 |
| | | Average | 26.34 | 0.019 | 33.70 | 20.40 | 19.33 | 0.942 | 0.048 |
| | | $\sigma$ | 0.586 | 7.00E-04 | 0.315 | 0.643 | 0.680 | 0.009 | 0.008 |
| | | CV, % | 2.23 | 3.65 | 0.93 | 3.15 | 3.52 | 0.99 | 15.80 |
| | LNE (5/20/14) | 186 | 31.71 | 0.021 | 36.01 | 22.86 | 20.61 | 0.902 | 0.066 |
| | | 153 | 28.57 | 0.023 | 36.83 | 21.90 | 20.17 | 0.921 | 0.062 |
| | | 747 | 29.49 | 0.021 | 39.89 | 24.12 | 20.85 | 0.864 | 0.106 |
| | | Average | 29.92 | 0.022 | 37.58 | 22.96 | 20.54 | 0.896 | 0.078 |
| | | $\sigma$ | 1.614 | 1.01E-03 | 2.045 | 1.113 | 0.345 | 0.029 | 0.024 |
| | | CV, % | 5.39 | 4.71 | 5.44 | 4.85 | 1.68 | 3.21 | 31.19 |
| | LNE (5/21/14) | 237 | 30.67 | 0.021 | 34.05 | 21.81 | 19.04 | 0.873 | 0.076 |
| | | 1162 | 29.82 | 0.021 | 36.53 | 23.83 | 20.93 | 0.878 | 0.105 |
| | | Average | 30.25 | 0.021 | 35.29 | 22.82 | 19.99 | 0.876 | 0.091 |
| | | $\sigma$ | 0.601 | 6.51E-04 | 1.754 | 1.428 | 1.336 | 0.004 | 0.021 |
| | | CV, % | 1.99 | 3.10 | 4.97 | 6.26 | 6.69 | 0.43 | 22.66 |
| | NIST (6/3/14) | 639 | 20.25 | 0.037 | 23.98 | 15.31 | 19.89 | 1.299 | 0.052 |
| | | 1144 | 20.31 | 0.032 | 21.36 | 18.91 | 18.67 | 0.987 | 0.044 |
| | | Average | 20.28 | 0.034 | 22.67 | 17.11 | 19.28 | 1.143 | 0.048 |
| | | $\sigma$ | 0.042 | 4.04E-03 | 1.853 | 2.546 | 0.863 | 0.221 | 0.006 |
| | | CV, % | 0.21 | 11.72 | 8.17 | 14.88 | 4.47 | 19.29 | 11.79 |
| | NIST (all) | Average | 23.92 | 0.025 | 29.29 | 19.09 | 19.18 | 1.019 | 0.048 |
| | | $\sigma$ | 3.347 | 8.63E-03 | 6.118 | 2.254 | 0.653 | 0.158 | 0.006 |
| | | CV, % | 13.99 | 34.16 | 20.89 | 11.81 | 3.40 | 15.52 | 12.66 |
| | LNE (all) | Average | 30.05 | 0.021 | 36.66 | 22.90 | 20.32 | 0.888 | 0.083 |
| | | $\sigma$ | 1.193 | 8.44E-04 | 2.104 | 1.066 | 0.774 | 0.023 | 0.021 |
| | | CV, % | 3.97 | 3.96 | 5.74 | 4.65 | 3.81 | 2.61 | 25.50 |

[3] The elastic compliance was obtained by visually selecting the force oscillations belonging to the initial linear portion of the force-displacement curve.
[4] Note that all lateral expansion measurements, on specimens tested both at NIST and LNE, were executed at NIST by the same operator.
[5] The coefficient of variation is obtained, in percent, by dividing the standard deviation by the average value.

*Table 3 - Results of the tests performed on HH-103.*

| Charpy lot | Lab | Specimen id | $F_{gy}$ (kN) | $C_{el}$ (mm/kN) | $F_m$ (kN) | $W_t$ (J) | $KV$ (J) | $KV/W_t$ | $LE$ (mm) |
|---|---|---|---|---|---|---|---|---|---|
| HH-103 | NIST (5/13/14) | 114 | 23.06 | 0.019 | 27.93 | 122.47 | 109.30 | 0.892 | 1.319 |
| | | 473 | 22.33 | 0.023 | 28.24 | 126.28 | 114.14 | 0.904 | 1.294 |
| | | 854 | 22.44 | 0.020 | 27.85 | 122.76 | 110.25 | 0.898 | 1.223 |
| | | Average | 22.61 | 0.021 | 28.01 | 123.84 | 111.23 | 0.901 | 1.259 |
| | | $\sigma$ | 0.394 | 1.87E-03 | 0.206 | 2.121 | 2.565 | 0.006 | 0.050 |
| | | CV, % | 1.74 | 8.94 | 0.74 | 1.71 | 2.31 | 0.63 | 3.96 |
| | LNE (5/20/14) | 453 | 21.25 | 0.023 | 29.48 | 121.75 | 106.43 | 0.874 | 1.329 |
| | | 988 | 21.66 | 0.023 | 28.96 | 119.46 | 105.44 | 0.883 | 1.293 |
| | | 1058 | 21.09 | 0.024 | 29.56 | 122.05 | 112.35 | 0.921 | 1.425 |
| | | Average | 21.33 | 0.023 | 29.33 | 121.09 | 108.07 | 0.892 | 1.349 |
| | | $\sigma$ | 0.294 | 3.09E-04 | 0.326 | 1.417 | 3.737 | 0.025 | 0.068 |
| | | CV, % | 1.38 | 1.32 | 1.11 | 1.17 | 3.46 | 2.77 | 5.06 |
| | LNE (5/21/14) | 525 | 23.85 | 0.019 | 28.69 | 124.90 | 105.26 | 0.843 | 1.286 |
| | | 244 | 23.85 | 0.022 | 28.90 | 128.73 | 109.30 | 0.849 | 1.375 |
| | | Average | 23.85 | 0.020 | 28.80 | 126.82 | 107.28 | 0.846 | 1.331 |
| | | $\sigma$ | 0.000 | 2.11E-03 | 0.148 | 2.708 | 2.857 | 0.004 | 0.063 |
| | | CV, % | 0.00 | 10.30 | 0.52 | 2.14 | 2.66 | 0.53 | 4.73 |
| | NIST (6/3/14) | 942 | 16.13 | 0.034 | 24.58 | 130.65 | 106.56 | 0.816 | 1.048 |
| | | 1078 | 15.70 | 0.044 | 23.42 | 121.16 | 115.08 | 0.950 | 1.374 |
| | | Average | 15.92 | 0.039 | 24.00 | 125.91 | 110.82 | 0.883 | 1.211 |
| | | $\sigma$ | 0.304 | 7.34E-03 | 0.820 | 6.710 | 6.025 | 0.095 | 0.231 |
| | | CV, % | 1.91 | 18.75 | 3.42 | 5.33 | 5.44 | 10.75 | 19.04 |
| | NIST (all) | Average | 19.93 | 0.028 | 26.40 | 124.66 | 111.07 | 0.892 | 1.252 |
| | | $\sigma$ | 3.681 | 1.07E-02 | 2.237 | 3.846 | 3.523 | 0.048 | 0.126 |
| | | CV, % | 18.47 | 38.06 | 8.47 | 3.08 | 3.17 | 5.42 | 10.07 |
| | LNE (all) | Average | 22.34 | 0.022 | 29.12 | 123.38 | 107.76 | 0.874 | 1.342 |
| | | $\sigma$ | 1.394 | 1.89E-03 | 0.381 | 3.561 | 3.035 | 0.031 | 0.058 |
| | | CV, % | 6.24 | 8.55 | 1.31 | 2.89 | 2.82 | 3.54 | 4.36 |

The average values of absorbed energy (*KV*), lateral expansion (*LE*) and maximum force ($F_m$) obtained in the four testing rounds are compared in Figure 2 to Figure 6. For absorbed energy, the figures also indicate the certified values and the ASTM acceptability limits corresponding to ± 1.4 J for LL-103 and ± 5 % for HH-103. For maximum force values, certified values and expanded uncertainties are indicated. We observe that:

- *KV* average values for NIST tests are lower than LNE averages for LL-103, and higher for HH-103;
- the trends shown by lateral expansion measurements are consistent with those for *KV* for LL-103 (NIST values lower than LNE), but not for HH-103;
- $F_m$ average values for NIST tests are lower than for LNE tests for both LL-103 and HH-103;
- regarding absorbed energy, NIST results are acceptable (*i.e.*, within ± 1.4 J of the certified value) for LL-103 but slightly too high for HH-103; LNE results are too high for LL-103 and acceptable for HH-103;
- regarding maximum force, only the LL-103 results from the first NIST round and the HH-103 results from the second round are within the expanded uncertainties, while all the remaining data are too high;
- a significant decrease in $F_m$ for both LL-103 (-33 %) and HH-103 (-14 %) is observed between the first NIST testing round (May 13$^{th}$, 2014) and the second NIST testing round (June 3$^{rd}$, 2014). This should be attributed to the questionable operation of the amplifier. A comparison between selected LL-103 test records from the NIST and LNE testing rounds is presented in Figure 7.

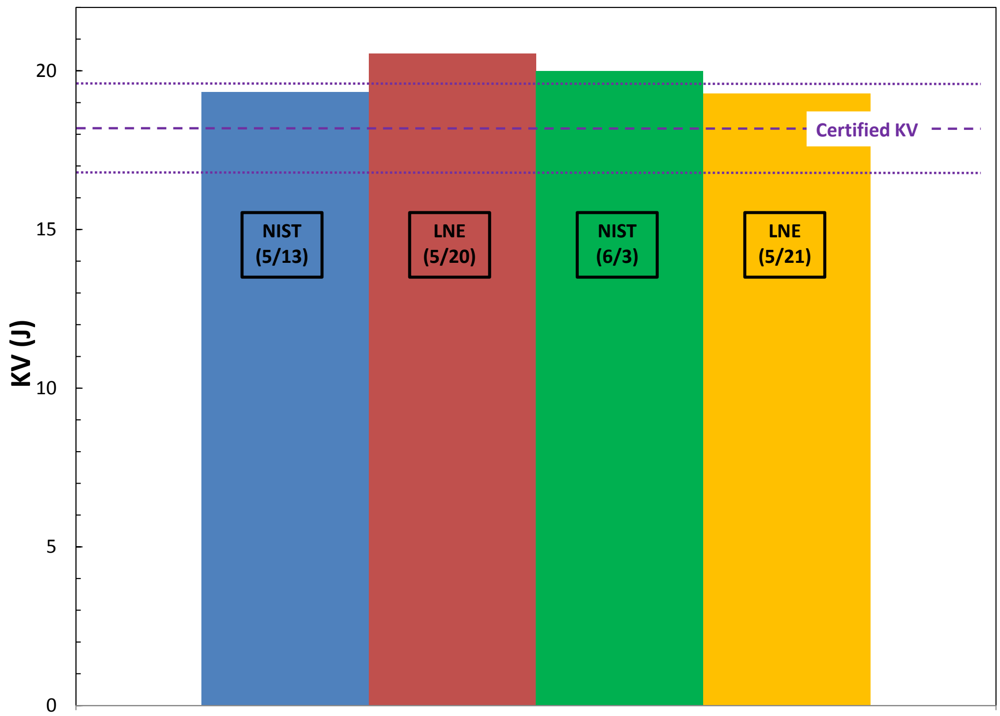


*Figure 2 - Average values of absorbed energy KV for LL-103. Dashed line and dotted lines indicate respectively certified value and bounds of ± 1.4 J (acceptability limits according to ASTM E23).*

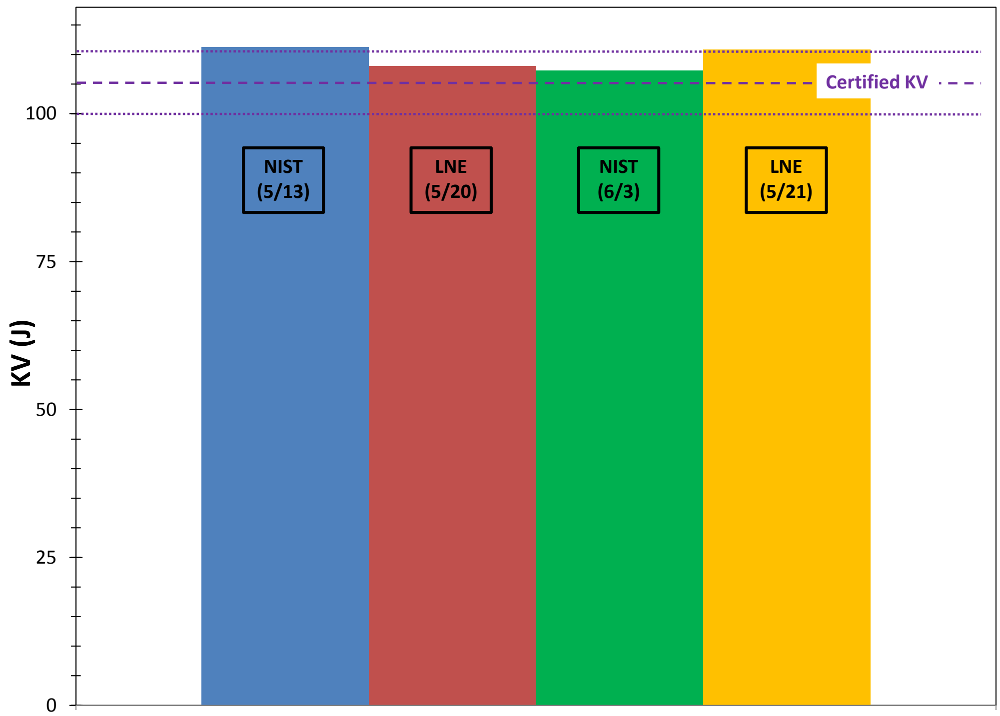


*Figure 3 - Average values of absorbed energy KV for HH-103. Dashed line and dotted lines indicate respectively certified value and bounds of ± 5 % (acceptability limits according to ASTM E23).*

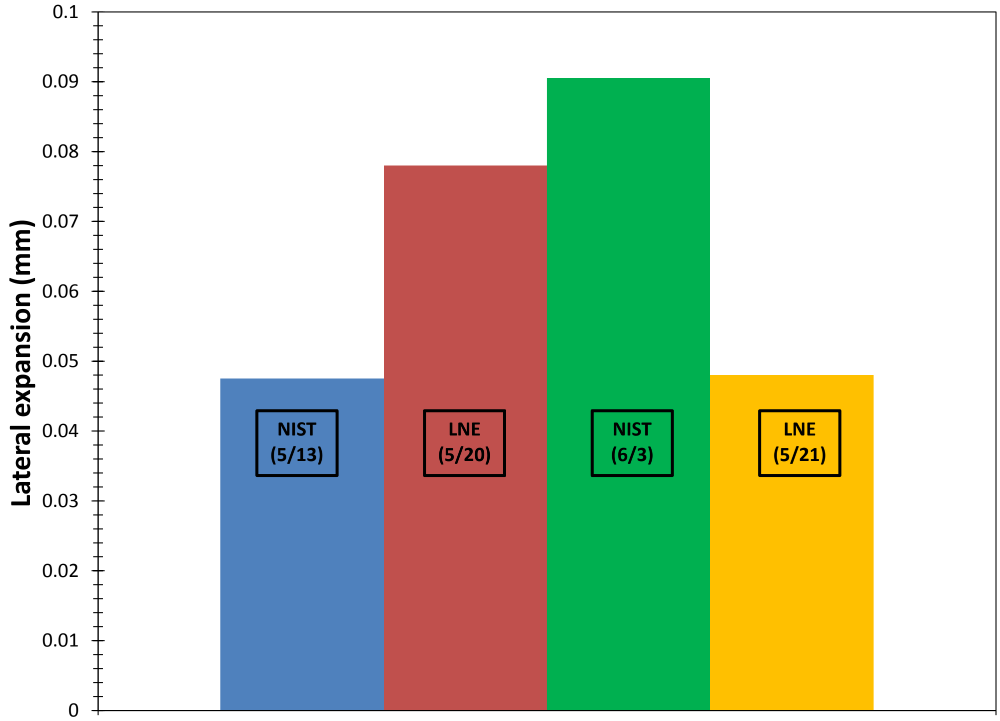


*Figure 4 - Average values of lateral expansion (LE) for LL-103.*

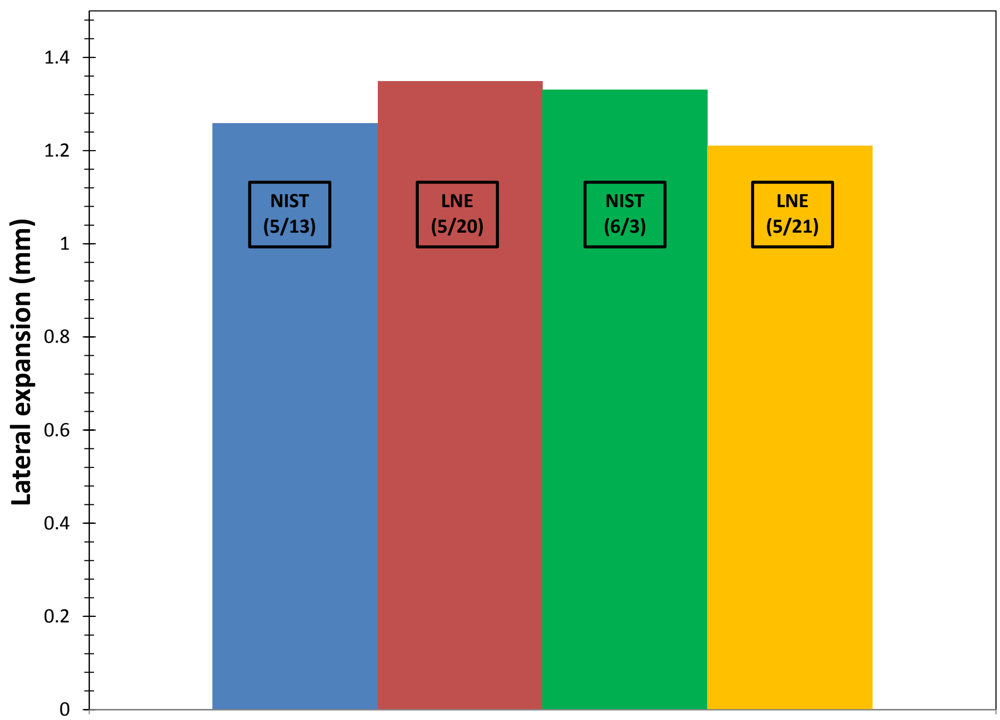


*Figure 5 - Average values of lateral expansion (LE) for HH-103.*

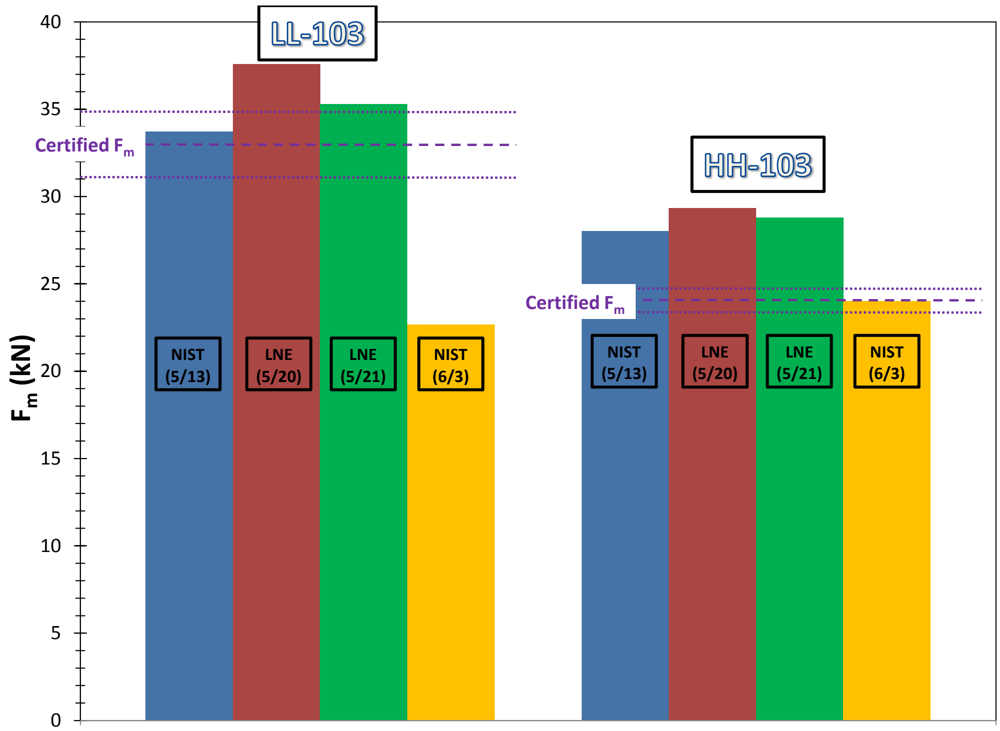


*Figure 6 - Average values of maximum force $F_m$ for LL-103 and HH-103. Dashed lines and dotted lines indicate respectively certified values and bounds of the expanded uncertainty range.*

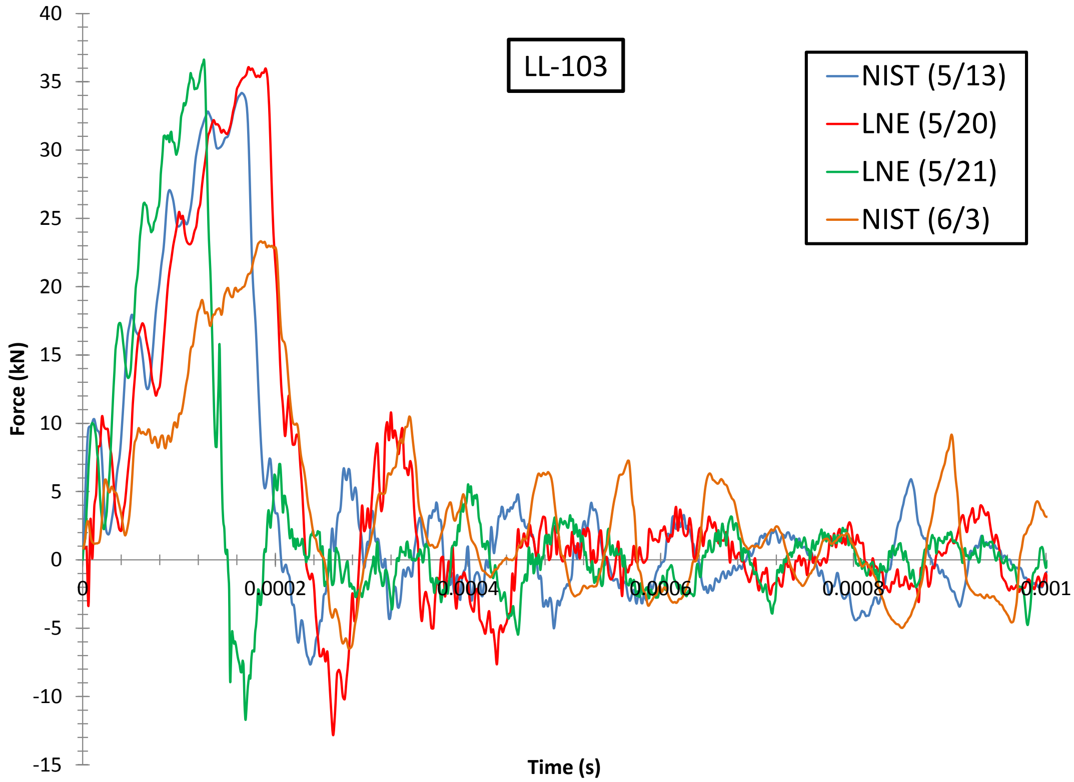


*Figure 7 – Comparison between selected LL-103 test records from NIST and LNE testing rounds (NIST, 1st round: specimen 938; LNE, 1st round: specimen 186; LNE, 2nd round: specimen 237; NIST, 2nd round: specimen 639).*

### 3.1.1 Statistical analyses of the differences between NIST and LNE

To investigate whether the observed differences between the results obtained at NIST and at LNE are statistically significant, we have applied Student's unpaired two-sample *t*-test. This is a statistical hypothesis test which is used to determine if two independent and identically distributed sets of data are significantly different from each other.

Before the *t*-test, another statistical test (*F*-test) was performed in order to establish whether the two data sets have equal or unequal variances. The method used for calculation of the *t* parameter depends on the result of the *F*-test (equal variances: homoscedastic *t*-test; unequal variances: heteroscedastic *t*-test) [11].

The results of the statistical tests on *KV*, $F_m$ and *LE* are presented in Table 4, Table 5, and Table 6 respectively. If the calculated value of *F* or *t* is smaller than the corresponding critical value, variances are not statistically different (*F*-test) or means are not statistically different (*t*-test) at a confidence level of 95 %. Result cells are color coded depending on the outcome of the *F*- or *t*-test.

*Table 4 - Statistical analyses results on KV results from LL-103 and HH-103.*

| Lot | Statistical test | Test location | Mean (J) | Variance (J) | Calculated value | Critical value | Result |
|---|---|---|---|---|---|---|---|
| **LL-103** | *F*-test | NIST | 19.18 | 0.43 | $F$ = 1.407 | $F_{crit}$ = 6.388 | *Variances **are not** statistically different* |
| | | LNE | 20.32 | 0.60 | | | |
| | *t*-test | NIST | 19.18 | 0.43 | $t$ = 2.526 | $t_{crit}$ = 2.306 | *Means **are** statistically different* |
| | | LNE | 20.32 | 0.60 | | | |
| **HH-103** | *F*-test | NIST | 111.07 | 12.41 | $F$ = 1.347 | $F_{crit}$ = 6.388 | *Variances **are not** statistically different* |
| | | LNE | 107.76 | 9.21 | | | |
| | *t*-test | NIST | 111.07 | 12.41 | $t$ = 1.592 | $t_{crit}$ = 2.306 | *Means **are not** statistically different* |
| | | LNE | 107.76 | 9.21 | | | |

*Table 5 - Statistical analyses results on $F_m$ results from LL-103 and HH-103.*

| Lot | Statistical test | Test location | Mean (kN) | Variance (kN) | Calculated value | Critical value | Result |
|---|---|---|---|---|---|---|---|
| **LL-103** | *F*-test | NIST | 29.29 | 37.43 | $F$ = 8.452 | $F_{crit}$ = 6.388 | *Variances **are** statistically different* |
| | | LNE | 36.66 | 4.43 | | | |
| | *t*-test | NIST | 29.29 | 37.43 | $t$ = 2.548 | $t_{crit}$ = 2.571 | *Means **are not** statistically different* |
| | | LNE | 36.66 | 4.43 | | | |
| **HH-103** | *F*-test | NIST | 26.40 | 5.01 | $F$ = 34.397 | $F_{crit}$ = 6.388 | *Variances **are** statistically different* |
| | | LNE | 29.12 | 0.15 | | | |
| | *t*-test | NIST | 26.40 | 5.01 | $t$ = 2.674 | $t_{crit}$ = 2.776 | *Means **are not** statistically different* |
| | | LNE | 29.12 | 0.15 | | | |

*Table 6 - Statistical analyses results on LE results from LL-103 and HH-103.*

| Lot | Statistical test | Test location | Mean (mm) | Variance (mm) | Calculated value | Critical value | Result |
|---|---|---|---|---|---|---|---|
| **LL-103** | *F*-test | NIST | 0.048 | 3.63E-05 | $F$ = 12.342 | $F_{crit}$ = 6.388 | *Variances **are** statistically different* |
| | | LNE | 0.083 | 4.48E-04 | | | |
| | *t*-test | NIST | 0.048 | 3.63E-05 | $t$ = 3.597 | $t_{crit}$ = 2.571 | *Means **are** statistically different* |
| | | LNE | 0.083 | 4.48E-04 | | | |
| **HH-103** | *F*-test | NIST | 1.252 | 0.0159 | $F$ = 4.648 | $F_{crit}$ = 6.388 | *Variances **are not** statistically different* |
| | | LNE | 1.342 | 0.0034 | | | |
| | *t*-test | NIST | 1.252 | 0.0159 | $t$ = 1.448 | $t_{crit}$ = 2.306 | *Means **are not** statistically different* |
| | | LNE | 1.342 | 0.0034 | | | |

While variances were found to be sometimes equal and sometimes unequal among the different data sets, the *t*-tests performed showed statistically significant differences between NIST and LNE for LL-103.

### 3.2 NIST certified reference specimens (LL-136 and HH-140)

The individual test results obtained at NIST and LNE on LL-136 and HH-140 are presented in Table 7 and Table 8, respectively. For each parameter average values, standard deviations and coefficients of variation (*CV*) are reported for each individual test day and considering all tests performed in one location. Note that tests performed in the first round at NIST and LNE were instrumented, while tests from the second round in both locations were non-instrumented.

*Table 7 - Results of the tests performed on LL-136.*

| Charpy lot | Lab | Specimen id | $F_{gy}$ (kN) | $C_{el}$ (mm/kN) | $F_m$ (kN) | $W_t$ (J) | $KV$ (J) | $KV/W_t$ | $LE$ (mm) |
|---|---|---|---|---|---|---|---|---|---|
| LL-136 | NIST (5/13/14) | 857 | 31.56 | 0.012 | 34.82 | 24.10 | 22.24 | 0.923 | 0.127 |
| | | 1023 | 31.77 | 0.010 | 34.82 | 22.45 | 19.80 | 0.882 | 0.087 |
| | | 1030 | 31.08 | 0.013 | 34.79 | 22.21 | 20.58 | 0.927 | 0.111 |
| | | 1193 | 33.63 | 0.013 | 34.64 | 22.80 | 20.84 | 0.914 | 0.125 |
| | | 2265 | 33.47 | 0.009 | 35.05 | 21.86 | 19.89 | 0.910 | 0.041 |
| | | Average | 32.30 | 0.011 | 34.82 | 22.68 | 20.28 | 0.908 | 0.091 |
| | | $\sigma$ | 1.168 | 1.77E-03 | 0.147 | 0.863 | 0.983 | 0.018 | 0.036 |
| | | CV, % | 3.62 | 15.52 | 0.42 | 3.80 | 4.85 | 1.94 | 39.27 |
| | LNE (5/20/14) | 706 | 21.28 | 0.020 | 38.67 | 25.29 | 23.98 | 0.948 | 0.076 |
| | | 709 | 24.63 | 0.024 | 37.87 | 24.28 | 22.13 | 0.911 | 0.099 |
| | | 1050 | 19.05 | 0.019 | 37.99 | 24.24 | 21.54 | 0.889 | 0.128 |
| | | 1114 | 24.61 | 0.020 | 36.22 | 24.33 | 22.06 | 0.907 | 0.176 |
| | | 1867 | 22.82 | 0.023 | 37.99 | 25.10 | 23.31 | 0.929 | 0.056 |
| | | Average | 22.48 | 0.021 | 37.75 | 24.65 | 22.60 | 0.917 | 0.107 |
| | | $\sigma$ | 2.371 | 2.38E-03 | 0.911 | 0.505 | 1.006 | 0.023 | 0.047 |
| | | CV, % | 10.55 | 11.19 | 2.41 | 2.05 | 4.45 | 2.47 | 43.91 |
| | LNE (5/21/14) | 782 | NON-INSTRUMENTED TESTS | | | | 21.14 | | 0.217 |
| | | 808 | | | | | 23.60 | | 0.145 |
| | | 828 | | | | | 23.67 | | 0.102 |
| | | 909 | | | | | 24.30 | | 0.107 |
| | | 1126 | | | | | 22.09 | | 0.153 |
| | | 2116 | | | | | 23.33 | | 0.130 |
| | | 2180 | | | | | 21.94 | | 0.117 |
| | | 2459 | | | | | 24.43 | | 0.128 |
| | | 2498 | | | | | 22.32 | | 0.120 |
| | | 2623 | | | | | 20.85 | | 0.117 |
| | | Average | | | | | 22.77 | | 0.134 |
| | | $\sigma$ | | | | | 1.274 | | 0.033 |
| | | CV, % | | | | | 5.60 | | 24.89 |
| | NIST (6/4/14) | 1033 | NON-INSTRUMENTED TESTS | | | | 19.98 | | 0.098 |
| | | 947 | | | | | 23.38 | | 0.068 |
| | | 384 | | | | | 21.55 | | 0.099 |
| | | 2175 | | | | | 18.85 | | 0.098 |
| | | 2143 | | | | | 19.63 | | 0.088 |
| | | 1203 | | | | | 20.59 | | 0.078 |
| | | 2177 | | | | | 20.85 | | 0.129 |
| | | 760 | | | | | 21.11 | | 0.105 |
| | | 997 | | | | | 19.55 | | 0.113 |
| | | 847 | | | | | 22.68 | | 0.112 |
| | | Average | | | | | 20.82 | | 0.099 |
| | | $\sigma$ | | | | | 1.426 | | 0.018 |
| | | CV, % | | | | | 6.85 | | 17.93 |
| | LNE (all) | | | | | Average | 22.71 | | 0.125 |
| | | | | | | $\sigma$ | 1.157 | | 0.039 |
| | | | | | | CV, % | 5.09 | | 31.15 |
| | NIST (all) | | | | | Average | 20.77 | | 0.099 |
| | | | | | | $\sigma$ | 1.260 | | 0.024 |
| | | | | | | CV, % | 6.07 | | 24.15 |

*Table 8 - Results of the tests performed on HH-140.*

| Charpy lot | Lab | Specimen id | $F_{gy}$ (kN) | $C_{el}$ (mm/kN) | $F_m$ (kN) | $W_t$ (J) | $KV$ (J) | $KV/W_t$ | $LE$ (mm) |
|---|---|---|---|---|---|---|---|---|---|
| HH-140 | NIST (5/13/14) | 552 | 24.54 | 0.010 | 28.32 | 118.58 | 101.81 | 0.859 | 1.323 |
| | | 553 | 25.01 | 0.009 | 28.50 | 118.86 | 101.62 | 0.855 | 1.384 |
| | | 556 | 23.86 | 0.011 | 28.24 | 121.82 | 106.82 | 0.877 | 1.611 |
| | | 557 | 24.00 | 0.009 | 28.10 | 119.68 | 104.64 | 0.874 | 1.433 |
| | | 558 | 24.40 | 0.009 | 28.20 | 115.99 | 100.20 | 0.864 | 1.394 |
| | | Average | 24.36 | 0.010 | 28.27 | 118.99 | 103.02 | 0.868 | 1.456 |
| | | $\sigma$ | 0.457 | 1.13E-03 | 0.150 | 2.102 | 2.666 | 0.010 | 0.109 |
| | | CV, % | 1.88 | 11.84 | 0.53 | 1.77 | 2.59 | 1.11 | 7.50 |
| | LNE (5/20/14) | 546 | 22.70 | 0.026 | 29.89 | 124.50 | 104.64 | 0.840 | 1.358 |
| | | 547 | 22.20 | 0.030 | 29.24 | 119.58 | 103.03 | 0.862 | 1.294 |
| | | 548 | 23.70 | 0.025 | 29.94 | 120.25 | 106.68 | 0.887 | 1.216 |
| | | 549 | 22.63 | 0.023 | 29.21 | 120.44 | 101.95 | 0.846 | 1.305 |
| | | 960 | 21.22 | 0.031 | 29.18 | 122.68 | 109.94 | 0.896 | 1.405 |
| | | Average | 22.49 | 0.027 | 29.49 | 121.49 | 105.25 | 0.866 | 1.316 |
| | | $\sigma$ | 0.898 | 3.50E-03 | 0.387 | 2.047 | 3.171 | 0.025 | 0.071 |
| | | CV, % | 3.99 | 12.97 | 1.31 | 1.69 | 3.01 | 2.83 | 5.41 |
| | LNE (5/21/14) | 541 | | | | | 108.98 | | 1.362 |
| | | 542 | | | | | 109.18 | | 1.387 |
| | | 543 | | | | | 105.78 | | 1.402 |
| | | 544 | | | | | N/A | | 1.331 |
| | | 545 | | | | | 107.69 | | 1.426 |
| | | 955 | **NON-INSTRUMENTED TESTS** | | | | 110.26 | | 1.565 |
| | | 956 | | | | | 100.56 | | 1.298 |
| | | 957 | | | | | 109.94 | | 1.433 |
| | | 958 | | | | | 105.00 | | 1.336 |
| | | 959 | | | | | 104.80 | | 1.412 |
| | | Average | | | | | 106.91 | | 1.395 |
| | | $\sigma$ | | | | | 3.165 | | 0.074 |
| | | CV, % | | | | | 2.96 | | 5.33 |
| | NIST (6/4/14) | 945 | | | | | 102.98 | | 1.337 |
| | | 944 | | | | | 104.97 | | 1.343 |
| | | 943 | | | | | 101.28 | | 1.248 |
| | | 942 | | | | | 101.66 | | 1.298 |
| | | 941 | | | | | 103.65 | | 1.381 |
| | | 551 | **NON-INSTRUMENTED TESTS** | | | | 100.52 | | 1.219 |
| | | 560 | | | | | 103.74 | | 1.427 |
| | | 554 | | | | | 106.01 | | 1.178 |
| | | 555 | | | | | 106.58 | | 1.123 |
| | | 559 | | | | | 100.71 | | 1.186 |
| | | Average | | | | | 103.21 | | 1.274 |
| | | $\sigma$ | | | | | 2.171 | | 0.099 |
| | | CV, % | | | | | 2.10 | | 7.75 |
| | LNE (May 14) | | | | | Average | 106.32 | | 1.369 |
| | | | | | | $\sigma$ | 3.153 | | 0.081 |
| | | | | | | CV, % | 2.97 | | 5.90 |
| | NIST (May/Jun 14) | | | | | Average | 103.15 | | 1.326 |
| | | | | | | $\sigma$ | 2.252 | | 0.124 |
| | | | | | | CV, % | 2.18 | | 9.36 |

The average values of $KV$, $LE$ and $F_m$ obtained in the four testing rounds are compared in Figure 8 to Figure 12.

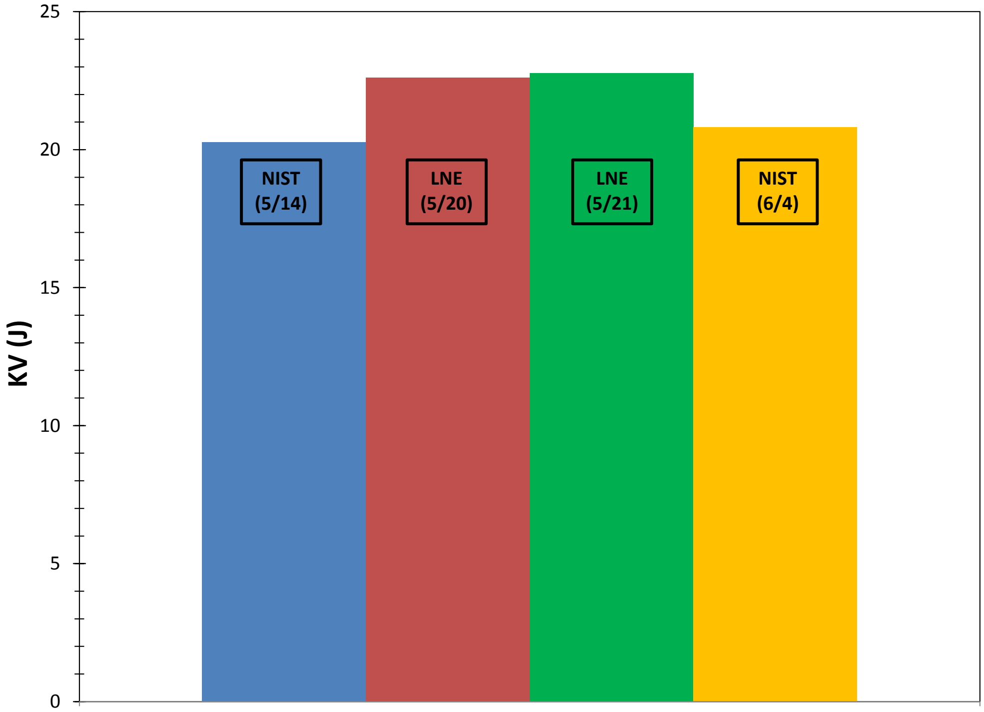


*Figure 8 - Average values of absorbed energy KV for LL-136.*

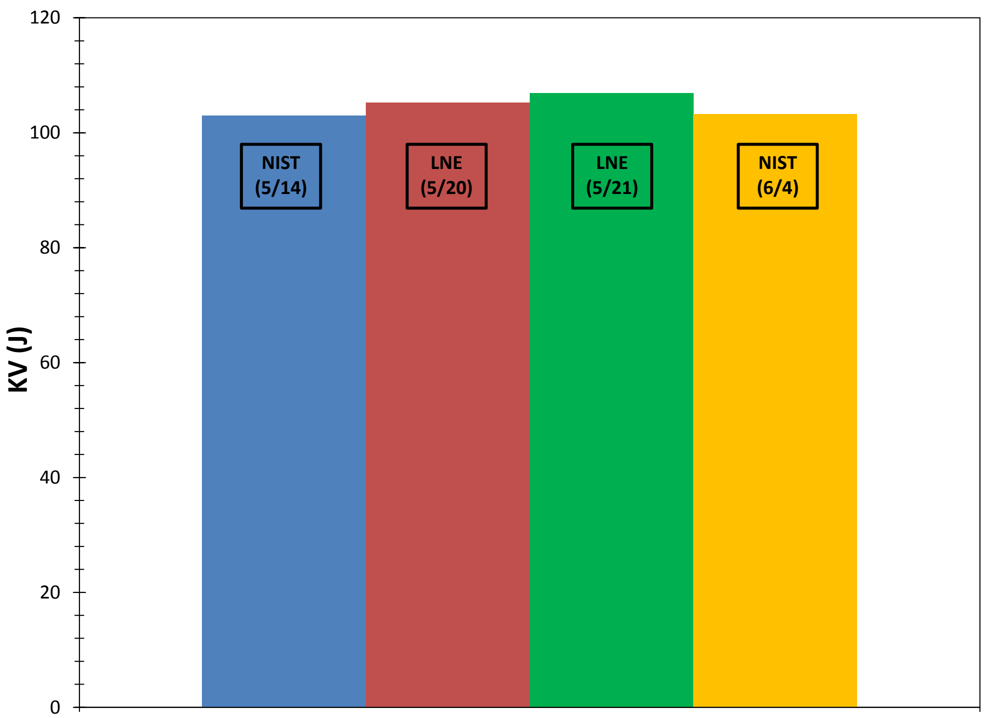


*Figure 9 - Average values of absorbed energy KV for HH-140.*

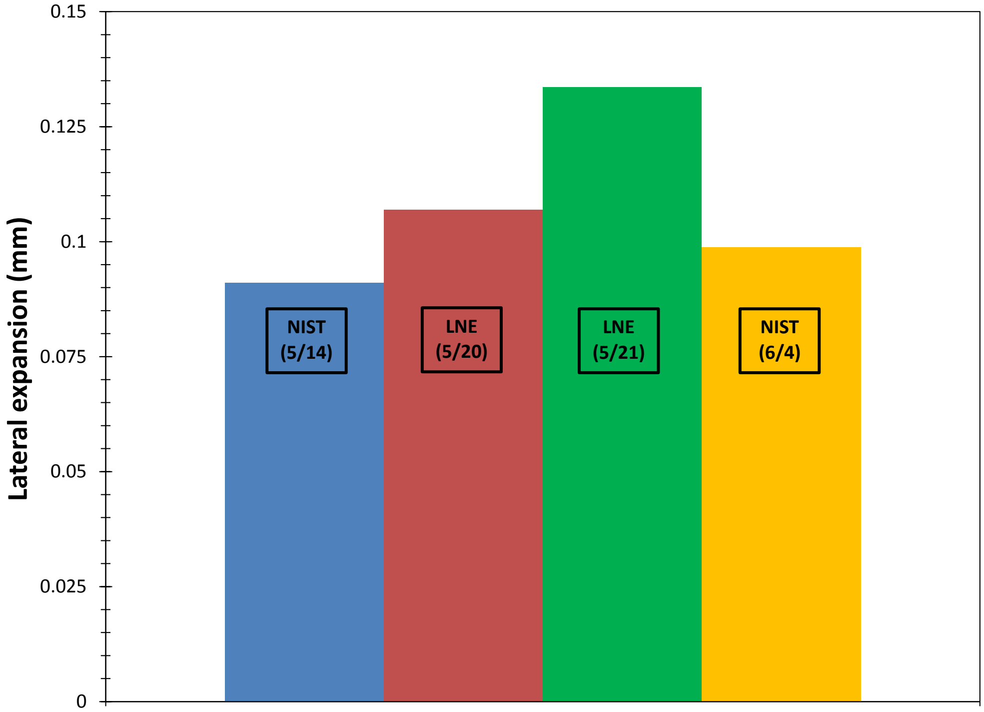

*Figure 10 - Average values of lateral expansion (LE) for LL-136.*

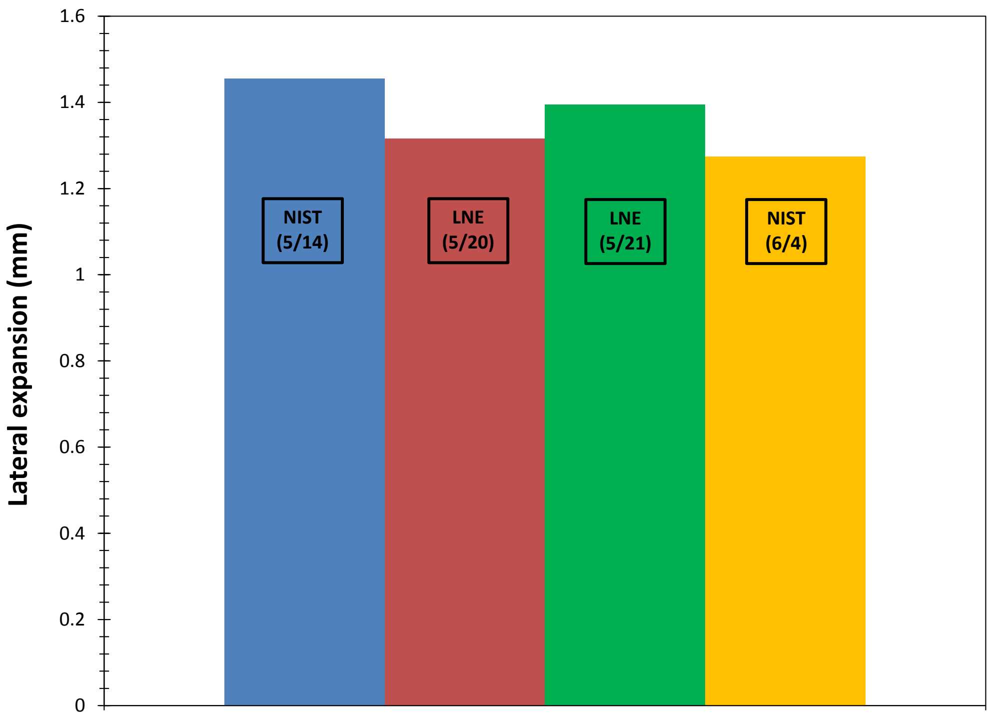

*Figure 11 - Average values of lateral expansion (LE) for HH-140.*

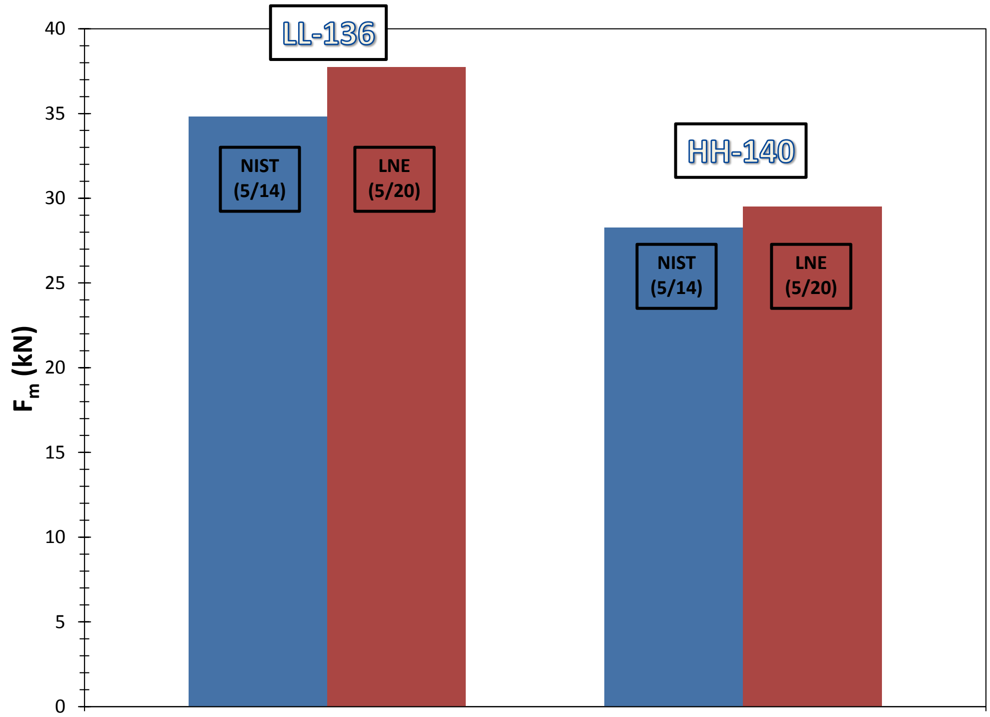


*Figure 12 - Average values of maximum force $F_m$ for LL-136 and HH-140.*

We observe that:

- average values of *KV* and $F_m$ for NIST tests are lower than LNE averages for both materials;
- the trends for maximum forces confirm those observed on LL-103 and HH-103;
- lateral expansion measurements show different trends than absorbed energy.

Selected instrumented curves for LL-136 and HH-140 tested at NIST and LNE are shown in Figure 13 and Figure 14, respectively.

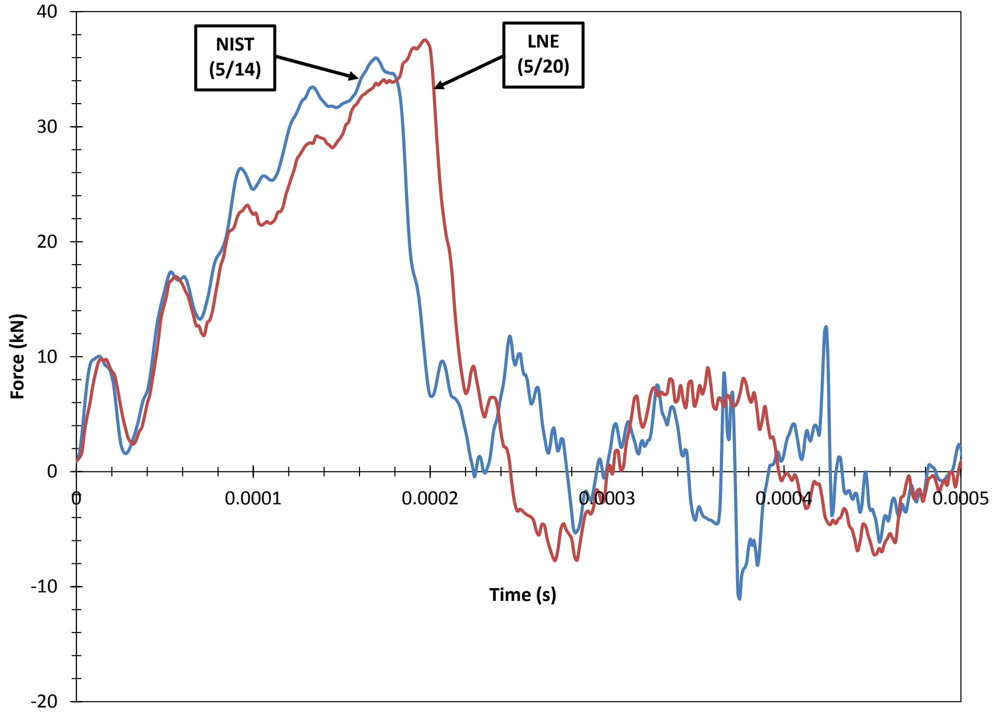


*Figure 13 - Selected instrumented curves from LL-136 tested at NIST (specimen 1030) and LNE (specimen 709).*

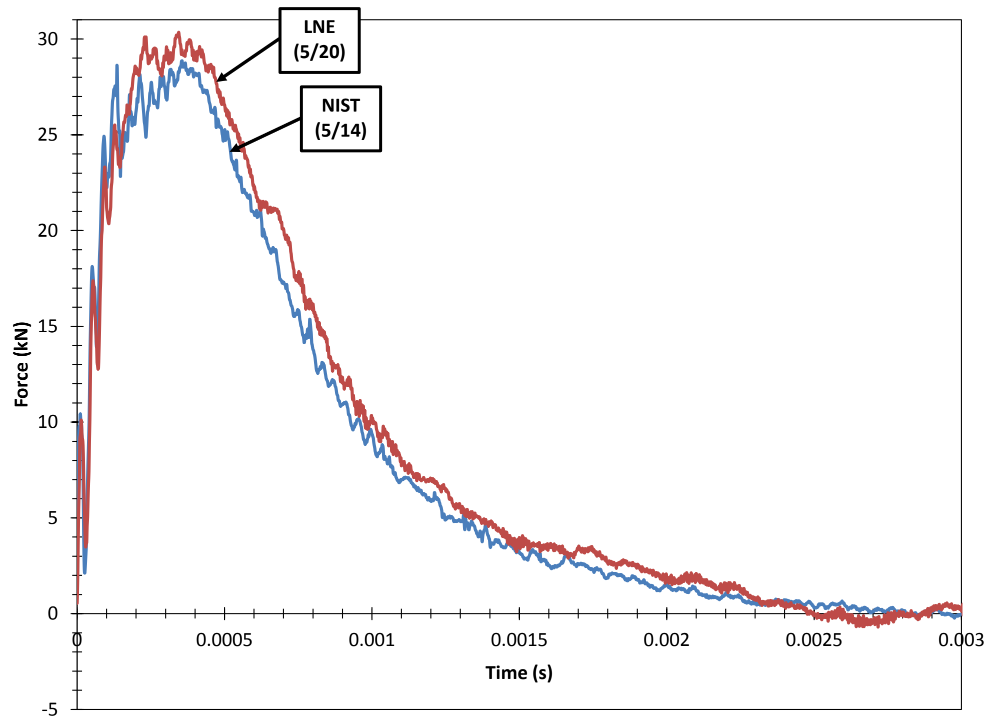


*Figure 14 - Selected instrumented curves from HH-140 tested at NIST (specimen 552) and LNE (specimen 546).*

### 3.2.1 Statistical analyses of the differences between NIST and LNE

In addition to analyzing the statistical differences between the mean values of the test results obtained at NIST and at LNE, we have also applied the same procedure (*F*-test to investigate the equality of the variances, and *t*-test for the difference between means) to test absorbed energy and lateral expansion results obtained at the same location in two different test days. The results of these preliminary analyses are listed in Table 9 (NIST tests) and Table 10 (LNE tests), which show no statistical difference between tests performed on different days.

*Table 9 - Statistical analyses on KV results obtained at NIST from LL-136 and HH-140.*

| Lot | Statistical test | Test date | Mean (J) | Variance (J) | Calculated value | Critical value | Result |
|---|---|---|---|---|---|---|---|
| **LL-136** | *F*-test | 5/13/14 | 20.67 | 0.97 | $F = 2.102$ | $F_{crit} = 5.999$ | *Variances **are not** statistically different* |
| | | 6/4/14 | 20.82 | 2.03 | | | |
| | *t*-test | 5/13/14 | 20.67 | 0.97 | $t = 0.204$ | $t_{crit} = 2.160$ | *Means **are not** statistically different* |
| | | 6/4/14 | 20.82 | 2.03 | | | |
| **HH-140** | *F*-test | 5/13/14 | 103.02 | 7.11 | $F = 1.508$ | $F_{crit} = 3.633$ | *Variances **are not** statistically different* |
| | | 6/4/14 | 103.21 | 4.72 | | | |
| | *t*-test | 5/13/14 | 111.07 | 12.41 | $t = 0.150$ | $t_{crit} = 2.160$ | *Means **are not** statistically different* |
| | | 6/4/14 | 107.76 | 9.21 | | | |

*Table 10 - Statistical analyses on KV results obtained at LNE from LL-136 and HH-140.*

| Lot | Statistical test | Test date | Mean (J) | Variance (J) | Calculated value | Critical value | Result |
|---|---|---|---|---|---|---|---|
| **LL-136** | *F*-test | 5/20/14 | 22.60 | 1.01 | $F = 1.605$ | $F_{crit} = 5.999$ | *Variances **are not** statistically different* |
| | | 5/21/14 | 22.77 | 1.62 | | | |
| | *t*-test | 5/20/14 | 22.60 | 1.01 | $t = 0.248$ | $t_{crit} = 2.160$ | *Means **are not** statistically different* |
| | | 5/21/14 | 22.77 | 1.62 | | | |
| **HH-140** | *F*-test | 5/20/14 | 106.91 | 10.02 | $F = 1.004$ | $F_{crit} = 3.838$ | *Variances **are not** statistically different* |
| | | 5/21/14 | 105.25 | 10.06 | | | |
| | *t*-test | 5/20/14 | 106.91 | 10.02 | $t = 0.941$ | $t_{crit} = 2.179$ | *Means **are not** statistically different* |
| | | 5/21/14 | 105.25 | 10.06 | | | |

The results of the statistical tests on *KV*, $F_m$ and *LE* are presented in Table 11, Table 12, and Table 13 respectively.

*Table 11 - Statistical analyses results on KV results from LL-136 and HH-140.*

| Lot | Statistical test | Test location | Mean (J) | Variance (J) | Calculated value | Critical value | Result |
|---|---|---|---|---|---|---|---|
| **LL-136** | *F*-test | NIST | 20.77 | 1.59 | $F = 1.186$ | $F_{crit} = 2.483$ | *Variances **are not** statistically different* |
| | | LNE | 22.71 | 1.34 | | | |
| | *t*-test | NIST | 20.77 | 1.59 | $t = 4.404$ | $t_{crit} = 2.048$ | *Means **are** statistically different* |
| | | LNE | 22.71 | 1.34 | | | |
| **HH-140** | *F*-test | NIST | 103.15 | 5.07 | $F = 1.961$ | $F_{crit} = 2.507$ | *Variances **are not** statistically different* |
| | | LNE | 106.32 | 9.94 | | | |
| | *t*-test | NIST | 103.15 | 5.07 | $t = 3.133$ | $t_{crit} = 2.052$ | *Means **are** statistically different* |
| | | LNE | 106.32 | 9.94 | | | |

*Table 12 - Statistical analyses results on $F_m$ results from LL-136 and HH-140.*

| Lot | Statistical test | Test location | Mean (kN) | Variance (kN) | Calculated value | Critical value | Results |
|---|---|---|---|---|---|---|---|
| **LL-136** | *F*-test | NIST | 34.82 | 0.02 | $F$ = 0.026 | $F_{crit}$ = 0.157 | *Variances **are not** statistically different* |
| | | LNE | 37.75 | 0.83 | | | |
| | *t*-test | NIST | 34.82 | 0.02 | $t$ = 7.089 | $t_{crit}$ = 2.306 | *Means **are** statistically different* |
| | | LNE | 37.75 | 0.83 | | | |
| **HH-140** | *F*-test | NIST | 28.27 | 0.02 | $F$ = 0.150 | $F_{crit}$ = 0.157 | *Variances **are not** statistically different* |
| | | LNE | 29.49 | 0.15 | | | |
| | *t*-test | NIST | 28.27 | 0.02 | $t$ = 6.570 | $t_{crit}$ = 2.306 | *Means **are** statistically different* |
| | | LNE | 29.49 | 0.15 | | | |

*Table 13 - Statistical analyses results on LE results from LL-136 and HH-140.*

| Lot | Statistical test | Test location | Mean (mm) | Variance (mm) | Calculated value | Critical value | Results |
|---|---|---|---|---|---|---|---|
| **LL-136** | *F*-test | NIST | 0.099 | 5.67E-04 | $F$ = 2.663 | $F_{crit}$ = 2.484 | *Variances **are** statistically different* |
| | | LNE | 0.125 | 1.51E-03 | | | |
| | *t*-test | NIST | 0.099 | 5.67E-04 | $t$ = 2.221 | $t_{crit}$ = 2.069 | *Means **are** statistically different* |
| | | LNE | 0.125 | 1.51E-03 | | | |
| **HH-140** | *F*-test | NIST | 1.326 | 0.015 | $F$ = 2.361 | $F_{crit}$ = 2.484 | *Variances **are not** statistically different* |
| | | LNE | 1.369 | 0.007 | | | |
| | *t*-test | NIST | 1.326 | 0.015 | $t$ = 1.125 | $t_{crit}$ = 2.048 | *Means **are not** statistically different* |
| | | LNE | 1.369 | 0.007 | | | |

Test results for absorbed energy *KV* and maximum force $F_m$ were found to be statistically different between NIST and LNE for both steels, while in terms of lateral expansion a statistically significant difference was observed for LL-136 but not for HH-140.

## 3.2 LNE certified reference specimens (1AD, 5AB, and 9E)

The individual test results obtained at NIST and LNE on lot 1AD (30 J), lot 5AB (120 J), and lot 9E (200 J) are presented in Table 14, Table 15 and Table 16, respectively. For each parameter average values, standard deviations and coefficients of variation (*CV*) are reported for each individual test day and for all tests performed in one location. Note that tests performed in the first round at NIST and LNE were instrumented, while tests from the second round in both locations were non-instrumented.

*Table 14 - Results of the tests performed on 1AD.*

| Charpy lot | Lab/Date | Specimen id | $F_{gy}$ (kN) | $C_{el}$ (mm/kN) | $F_m$ (kN) | $W_t$ (J) | $KV$ (J) | $KV/W_t$ | $LE$ (mm) |
|---|---|---|---|---|---|---|---|---|---|
| 1AD | LNE (5/20/14) | M52 | 30.70 | 0.023 | 43.28 | 33.99 | 30.57 | 0.899 | 0.163 |
| | | D59 | 26.06 | 0.024 | 42.55 | 33.51 | N/A | N/A | 0.106 |
| | | J40 | 16.94 | 0.024 | 45.26 | 31.91 | 30.01 | 0.940 | 0.086 |
| | | N38 | 27.78 | 0.022 | 44.89 | 33.96 | 30.53 | 0.899 | 0.153 |
| | | E67 | 24.61 | 0.022 | 45.15 | 34.46 | 31.38 | 0.911 | 0.146 |
| | | Average | 25.22 | 0.023 | 44.23 | 33.57 | 30.64 | 0.917 | 0.123 |
| | | $\sigma$ | 5.153 | 7.65E-04 | 1.232 | 0.985 | 0.566 | 0.019 | 0.033 |
| | | CV, % | 20.43 | 3.34 | 2.78 | 2.93 | 1.85 | 2.13 | 26.97 |
| | LNE (5/21/14) | H24 | NON-INSTRUMENTED TESTS | | | | 30.25 | | 0.092 |
| | | A65 | | | | | 30.23 | | 0.052 |
| | | P69 | | | | | 29.50 | | 0.118 |
| | | G83 | | | | | 31.15 | | 0.158 |
| | | I12 | | | | | 29.35 | | 0.093 |
| | | Average | | | | | 30.10 | | 0.103 |
| | | $\sigma$ | | | | | 0.718 | | 0.039 |
| | | CV, % | | | | | 2.39 | | 37.97 |
| | LNE (all) | | | | | Average | 30.33 | | 0.117 |
| | | | | | | $\sigma$ | 0.675 | | 0.037 |
| | | | | | | CV, % | 2.22 | | 31.86 |
| | NIST (6/3/14) | I43 | 22.95 | 0.033 | 31.08 | 25.17 | 29.62 | 1.177 | 0.144 |
| | | P25 | 23.14 | 0.031 | 27.96 | 22.56 | 28.56 | 1.266 | 0.382 |
| | | J18 | 21.77 | 0.033 | 27.13 | 20.95 | 28.64 | 1.367 | 0.131 |
| | | H89 | 24.79 | 0.033 | 27.66 | 22.64 | 29.26 | 1.292 | 0.091 |
| | | L58 | 33.10 | 0.019 | 38.07 | 29.89 | 29.26 | 0.979 | 0.141 |
| | | Average | 25.15 | 0.030 | 30.38 | 24.24 | 29.07 | 1.226 | 0.178 |
| | | $\sigma$ | 4.573 | 5.82E-03 | 4.567 | 3.500 | 0.453 | 0.149 | 0.116 |
| | | CV, % | 18.18 | 19.57 | 15.03 | 14.44 | 1.56 | 12.16 | 65.30 |
| | NIST (6/4/14) | J77 | NON-INSTRUMENTED TESTS | | | | 28.65 | | 0.050 |
| | | B75 | | | | | 28.83 | | 0.089 |
| | | K43 | | | | | 29.09 | | 0.084 |
| | | H59 | | | | | 29.27 | | 0.136 |
| | | N53 | | | | | 29.89 | | 0.032 |
| | | Average | | | | | 29.15 | | 0.078 |
| | | $\sigma$ | | | | | 0.478 | | 0.040 |
| | | CV, % | | | | | 1.64 | | 51.23 |
| | NIST (all) | | | | | Average | 29.11 | | 0.128 |
| | | | | | | $\sigma$ | 0.441 | | 0.097 |
| | | | | | | CV, % | 1.51 | | 75.99 |

*Table 15 - Results of the tests performed on 5AB.*

| Charpy lot | Lab/Date | Specimen id | $F_{gy}$ (kN) | $C_{el}$ (mm/kN) | $F_m$ (kN) | $W_t$ (J) | $KV$ (J) | $KV/W_t$ | $LE$ (mm) |
|---|---|---|---|---|---|---|---|---|---|
| 5AB | LNE (5/20/14) | P33 | 19.41 | 0.024 | 29.04 | 145.70 | 127.72 | 0.877 | 1.630 |
| | | C98 | 20.67 | 0.024 | 29.38 | 150.21 | 129.95 | 0.865 | 1.564 |
| | | K77 | 21.81 | 0.021 | 28.75 | 151.03 | 129.31 | 0.856 | 1.538 |
| | | G30 | 20.33 | 0.022 | 29.31 | 146.66 | 124.76 | 0.851 | 1.501 |
| | | N19 | 26.30 | 0.019 | 29.09 | 149.83 | 127.03 | 0.848 | 1.519 |
| | | Average | 21.70 | 0.022 | 29.11 | 148.69 | 127.76 | 0.855 | 1.531 |
| | | $\sigma$ | 2.709 | 2.19E-03 | 0.249 | 2.353 | 2.045 | 0.012 | 0.050 |
| | | CV, % | 12.48 | 9.83 | 0.85 | 1.58 | 1.60 | 1.37 | 3.28 |
| | LNE (5/21/14) | M74 | NON-INSTRUMENTED TESTS | | | | 128.82 | | 1.509 |
| | | E89 | | | | | 134.95 | | 1.714 |
| | | D14 | | | | | 127.56 | | 1.552 |
| | | L09 | | | | | 133.76 | | 1.532 |
| | | C37 | | | | | 129.15 | | 1.673 |
| | | Average | | | | | 130.85 | | 1.596 |
| | | $\sigma$ | | | | | 3.283 | | 0.091 |
| | | CV, % | | | | | 2.51 | | 5.73 |
| | LNE (all) | | | | | Average | 129.30 | | 1.573 |
| | | | | | | $\sigma$ | 3.051 | | 0.074 |
| | | | | | | CV, % | 2.36 | | 4.68 |
| | NIST (6/3/14) | J57 | 22.22 | 0.021 | 28.01 | 130.71 | 117.64 | 0.900 | 1.570 |
| | | F33 | 21.23 | 0.021 | 27.61 | 129.07 | 122.38 | 0.948 | 1.429 |
| | | K08 | 22.11 | 0.022 | 27.97 | 143.47 | 130.80 | 0.912 | 1.560 |
| | | N55 | 21.70 | 0.021 | 27.66 | 130.73 | 119.25 | 0.912 | 1.577 |
| | | G71 | 21.08 | 0.022 | 27.47 | 132.90 | 122.76 | 0.924 | 1.480 |
| | | Average | 21.67 | 0.021 | 27.74 | 133.38 | 122.57 | 0.919 | 1.523 |
| | | $\sigma$ | 0.510 | 4.12E-04 | 0.236 | 5.804 | 5.078 | 0.018 | 0.066 |
| | | CV, % | 2.35 | 1.94 | 0.85 | 4.35 | 4.14 | 1.99 | 4.30 |
| | NIST (6/4/14) | I14 | NON-INSTRUMENTED TESTS | | | | 121.93 | | 1.454 |
| | | B15 | | | | | 122.59 | | 1.557 |
| | | N73 | | | | | 119.09 | | 1.469 |
| | | D60 | | | | | 116.24 | | 1.503 |
| | | P95 | | | | | 125.81 | | 1.486 |
| | | Average | | | | | 121.13 | | 1.494 |
| | | $\sigma$ | | | | | 3.631 | | 0.040 |
| | | CV, % | | | | | 3.00 | | 2.66 |
| | NIST (all) | | | | | Average | 121.85 | | 1.509 |
| | | | | | | $\sigma$ | 4.230 | | 0.053 |
| | | | | | | CV, % | 3.47 | | 3.54 |

*Table 16 - Results of the tests performed on 9E.*

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 9E | LNE (5/20/14) | J36 | 26.86 | 0.023 | 39.63 | 225.66 | 197.32 | 0.874 | 2.126 |
| | | M33 | 29.69 | 0.020 | 38.87 | 222.14 | 191.85 | 0.864 | 1.837 |
| | | L56 | 32.15 | 0.021 | 38.85 | 202.47 | 185.33 | 0.915 | 1.949 |
| | | H52 | 27.55 | 0.021 | 38.72 | 225.92 | 202.36 | 0.896 | 1.841 |
| | | B55 | 25.24 | 0.021 | 38.32 | 197.86 | 191.29 | 0.967 | 1.905 |
| | | Average | 28.30 | 0.021 | 38.88 | 214.81 | 193.63 | 0.910 | 1.883 |
| | | $\sigma$ | 2.681 | 9.63E-04 | 0.475 | 13.550 | 6.468 | 0.041 | 0.118 |
| | | CV, % | 9.47 | 4.54 | 1.22 | 6.31 | 3.34 | 4.48 | 6.28 |
| | LNE (5/21/14) | H70 | **NON-INSTRUMENTED TESTS** | | | | 192.49 | | 1.720 |
| | | F41 | | | | | 184.58 | | 1.857 |
| | | K28 | | | | | 179.84 | | 1.822 |
| | | M61 | | | | | 179.91 | | 1.837 |
| | | I01 | | | | | 189.73 | | 1.857 |
| | | Average | | | | | 185.31 | | 1.819 |
| | | $\sigma$ | | | | | 5.716 | | 0.057 |
| | | CV, % | | | | | 3.08 | | 3.14 |
| | LNE (all) | | | | | Average | 189.47 | | 1.875 |
| | | | | | | $\sigma$ | 7.235 | | 0.106 |
| | | | | | | CV, % | 3.82 | | 5.65 |
| | NIST (6/3/14) | I34 | 29.60 | 0.023 | 38.36 | 198.95 | 182.91 | 0.919 | 1.717 |
| | | J69 | 29.97 | 0.024 | 38.21 | 210.43 | 186.18 | 0.885 | 1.752 |
| | | M19 | 29.46 | 0.024 | 38.65 | 215.42 | 194.39 | 0.902 | 1.781 |
| | | A33 | 29.47 | 0.023 | 38.68 | 209.96 | 186.45 | 0.888 | 2.015 |
| | | C43 | 29.54 | 0.024 | 38.82 | 206.66 | 183.18 | 0.886 | 1.901 |
| | | Average | 29.61 | 0.024 | 38.54 | 208.28 | 186.62 | 0.890 | 1.833 |
| | | $\sigma$ | 0.210 | 6.31E-04 | 0.251 | 6.085 | 4.642 | 0.015 | 0.123 |
| | | CV, % | 0.71 | 2.64 | 0.65 | 2.92 | 2.49 | 1.66 | 6.71 |
| | NIST (6/4/14) | G08 | **NON-INSTRUMENTED TESTS** | | | | 173.59 | | 1.421 |
| | | F51 | | | | | 177.63 | | 1.583 |
| | | B15 | | | | | 187.02 | | 1.924 |
| | | A45 | | | | | 181.11 | | 1.984 |
| | | C81 | | | | | 171.47 | | 1.617 |
| | | Average | | | | | 178.16 | | 1.706 |
| | | $\sigma$ | | | | | 6.187 | | 0.239 |
| | | CV, % | | | | | 3.47 | | 14.03 |
| | NIST (all) | | | | | Average | 182.39 | | 1.770 |
| | | | | | | $\sigma$ | 6.816 | | 0.192 |
| | | | | | | CV, % | 3.74 | | 10.82 |

The average values of *KV*, *LE* and $F_m$ obtained in the four testing rounds are compared in Figure 15 to Figure 21. For absorbed energy, Figure 15 to Figure 17 also indicate the certified values of *KV* and the acceptability limits in accordance with ISO 148:2, *i.e.*, ± 4 J (below 40 J) and ± 15 % (above 40 J). Comparisons between selected instrumented curves from tests performed at LNE and NIST are given in Figure 22 (1AD), Figure 23 (5AB), and Figure 24 (9E).

Although clear and consistent trends are not visible, a general tendency is observed for average values obtained at LNE to be higher than average values obtained at NIST. The largest discrepancy can be noted for $F_m$ values measured on 1AD (see Figure 21 and Figure 22).

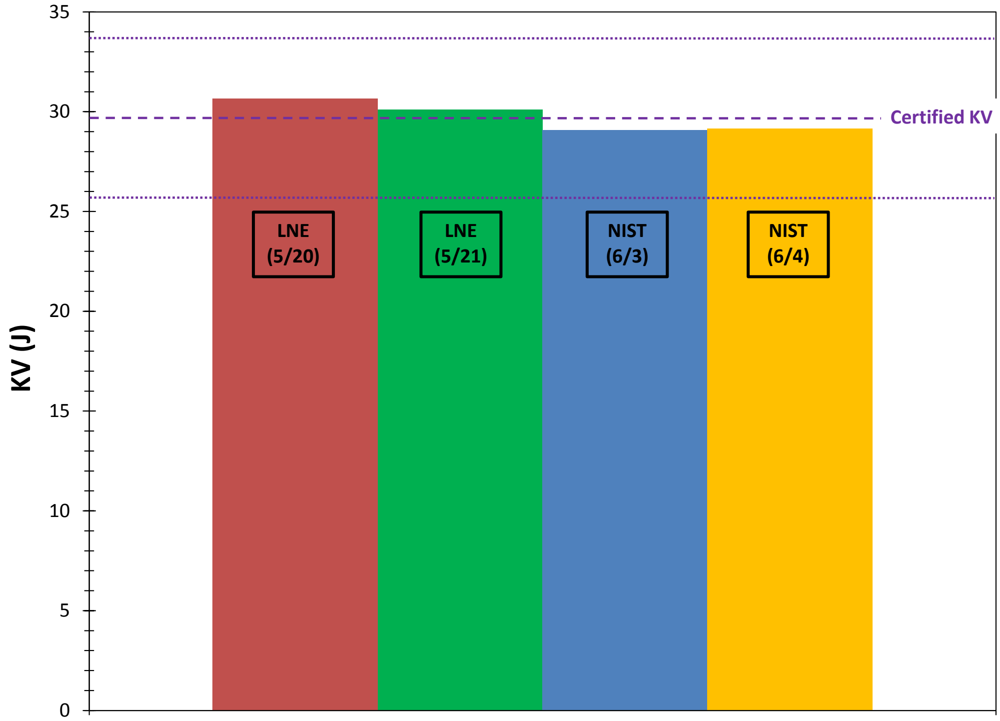


*Figure 15 - Average values of absorbed energy (KV) for 1AD. Dashed line and dotted lines indicate respectively the certified value and ± 4 J bounds (acceptability limits according to ISO 148:2).*

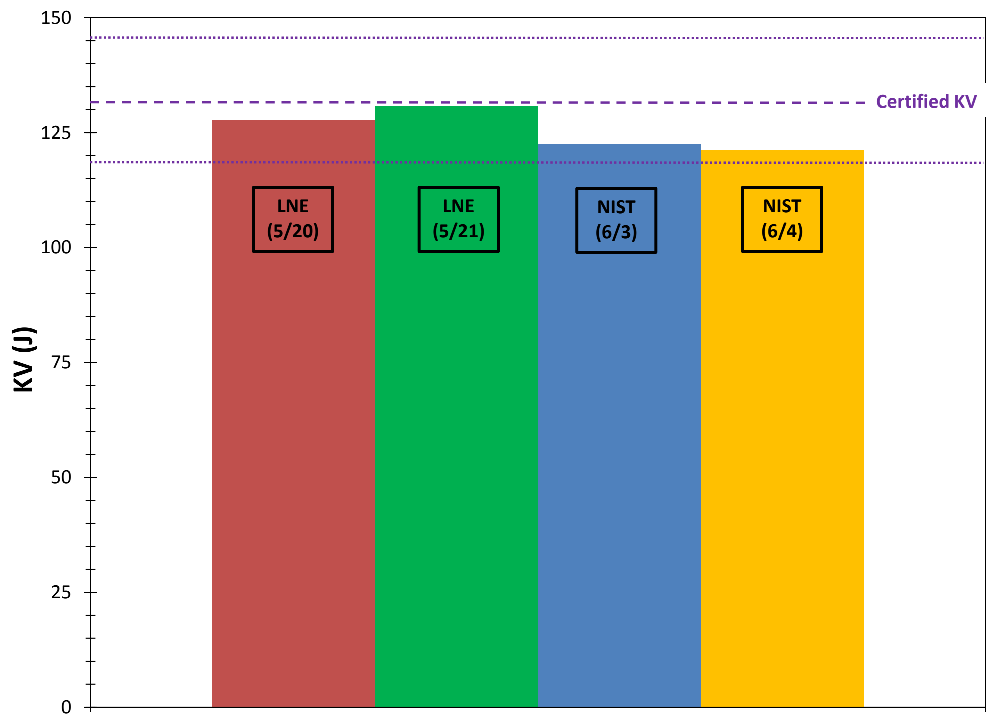


*Figure 16 - Average values of absorbed energy (KV) for 5AB. Dashed line and dotted lines indicate respectively the certified value and ± 10 % bounds (acceptability limits according to ISO 148:2).*

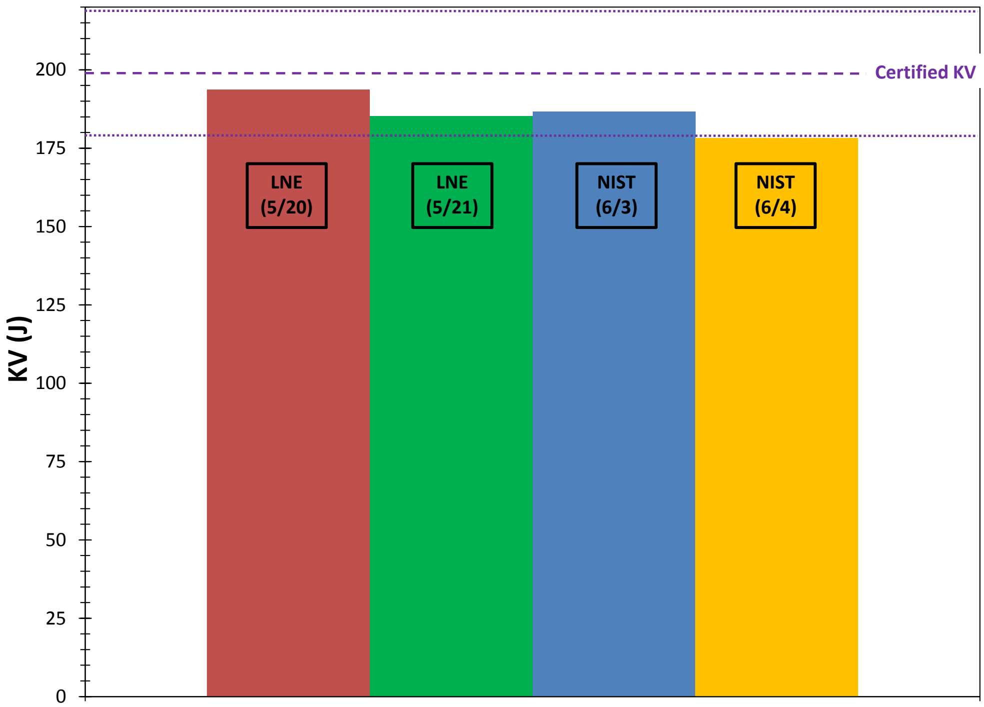


*Figure 17 - Average values of absorbed energy (KV) for 9E. Dashed line and dotted lines indicate respectively the certified value and ± 10 % bounds (acceptability limits according to ISO 148:2).*

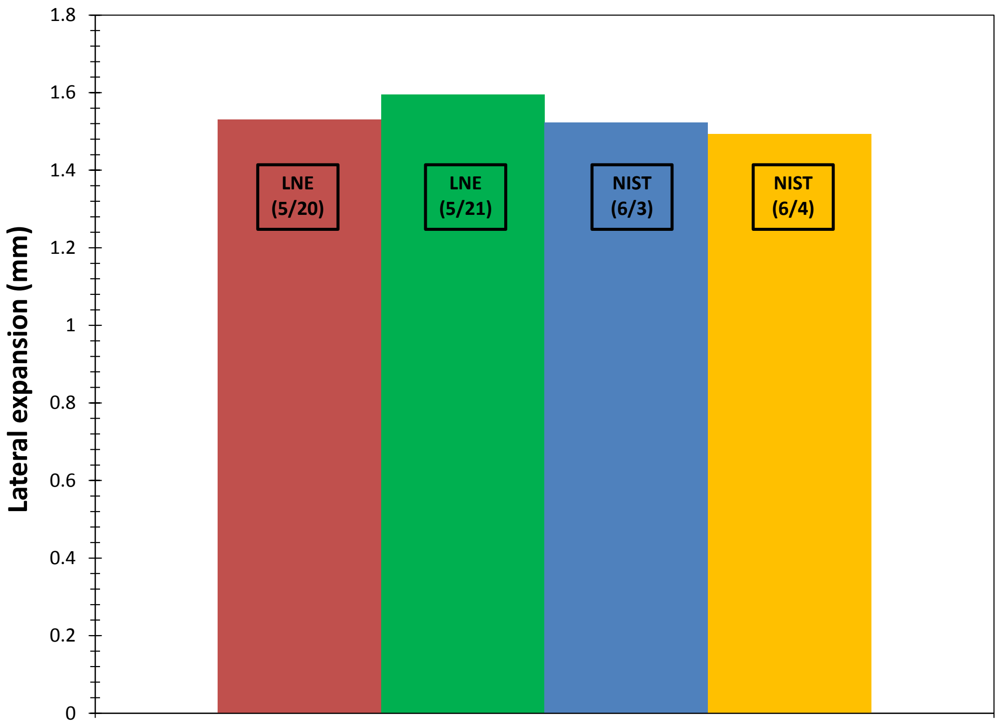


*Figure 18 - Average values of lateral expansion (LE) for 1AD.*

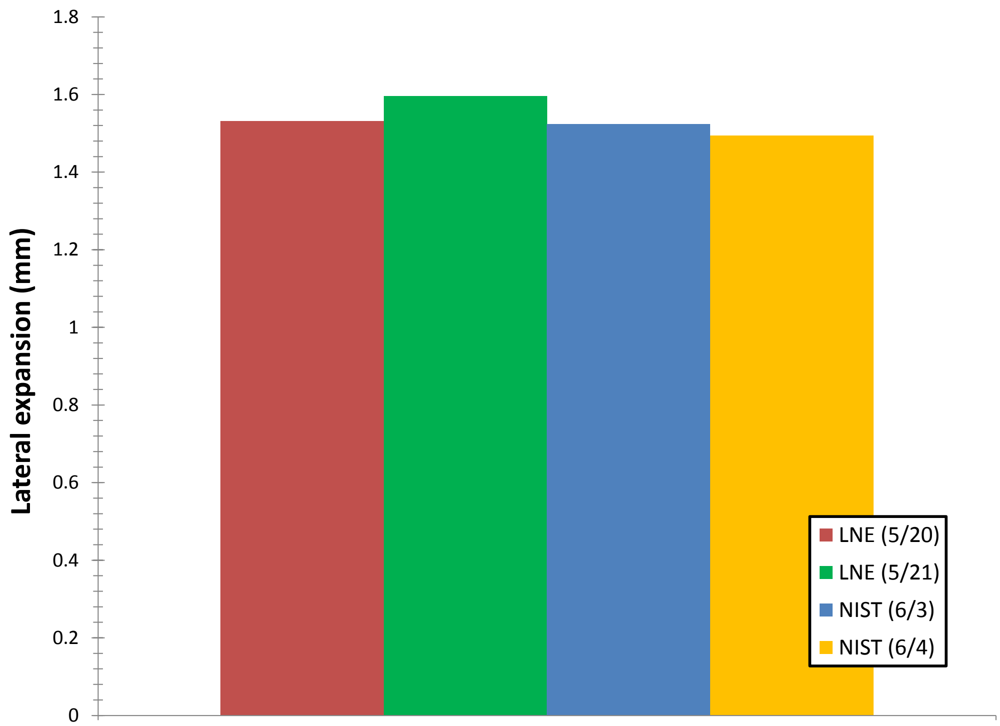


*Figure 19 - Average values of lateral expansion (LE) for 5AB.*

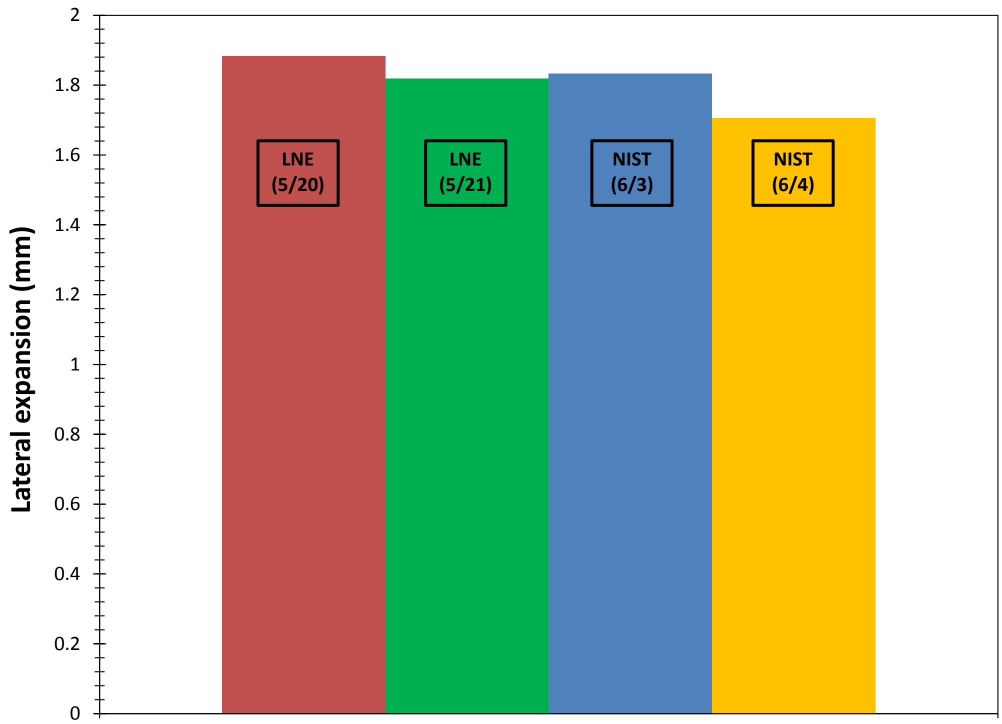


*Figure 20 - Average values of lateral expansion (LE) for 9E.*

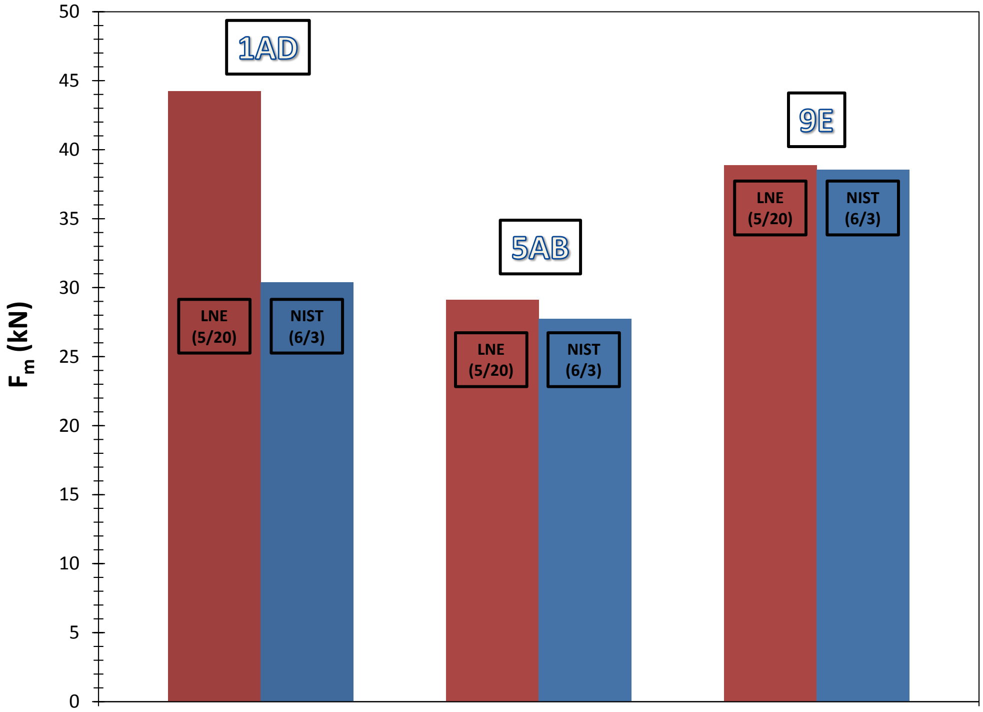


*Figure 21 - Average values of maximum force ($F_m$) for 1AD, 5AB and 9E.*

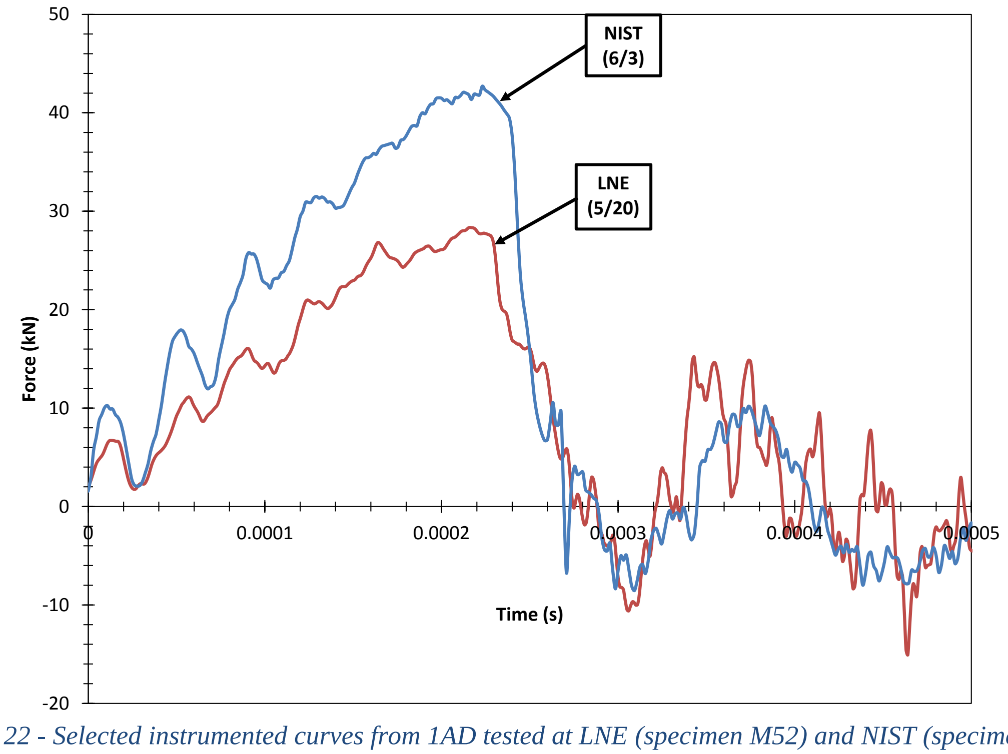


*Figure 22 - Selected instrumented curves from 1AD tested at LNE (specimen M52) and NIST (specimen H89).*

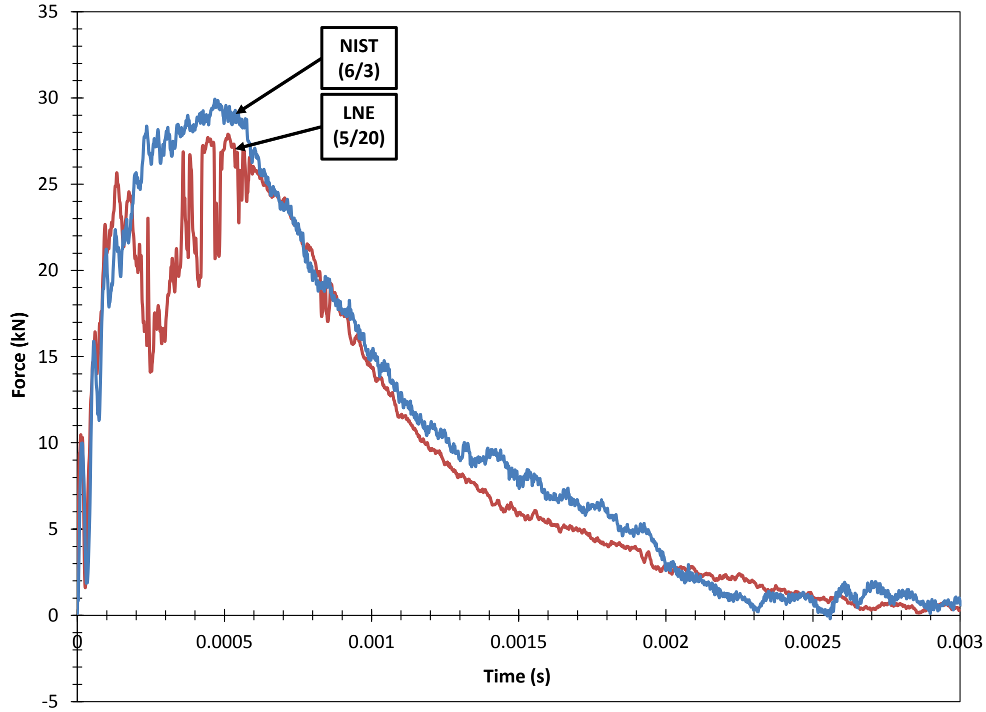


*Figure 23 - Selected instrumented curves from 5AB tested at LNE (specimen P33) and NIST (specimen G71). NOTE: the shape of the LNE test record indicates a malfunction of the acquisition system.*

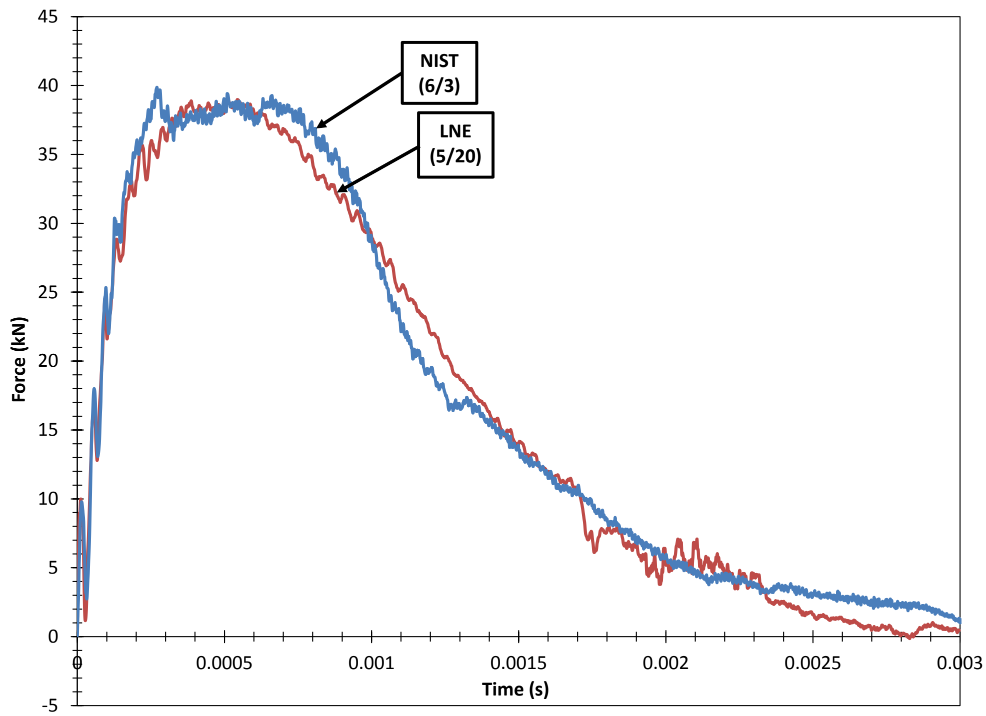


*Figure 24 - Selected instrumented curves from 9E tested at LNE (specimen M33) and NIST (specimen A33).*

### 3.3.1 Statistical analyses of the differences between NIST and LNE

The results of the statistical tests (*F*-test and *t*-test) conducted to establish possible differences between absorbed energy values obtained in the first and second day at LNE and NIST are shown in Table 17 and Table 18, respectively. Only in one case (lot 9E tested at NIST) were the mean values obtained in the two testing rounds statistically different.

*Table 17 - Statistical analyses on KV results obtained at LNE from 1AD, 5AB, and 9E.*

| Lot | Statistical test | Test date | Mean (J) | Variance (J) | Calculated value | Critical value | Results |
|---|---|---|---|---|---|---|---|
| 1AD | *F*-test | 5/20/14 | 30.62 | 0.32 | $F$ = 1.612 | $F_{crit}$ = 9.117 | *Variances **are not** statistically different* |
| | | 5/21/14 | 30.10 | 0.52 | | | |
| | *t*-test | 5/20/14 | 30.62 | 0.32 | $t$ = 1.194 | $t_{crit}$ = 2.365 | *Means **are not** statistically different* |
| | | 5/21/14 | 30.10 | 0.52 | | | |
| 5AB | *F*-test | 5/20/14 | 127.75 | 4.18 | $F$ = 2.577 | $F_{crit}$ = 6.388 | *Variances **are not** statistically different* |
| | | 5/21/14 | 130.85 | 10.78 | | | |
| | *t*-test | 5/20/14 | 127.75 | 4.18 | $t$ = 1.789 | $t_{crit}$ = 2.306 | *Means **are not** statistically different* |
| | | 5/21/14 | 130.85 | 10.78 | | | |
| 9E | *F*-test | 5/20/14 | 193.63 | 41.84 | $F$ = 1.128 | $F_{crit}$ = 6.388 | *Variances **are not** statistically different* |
| | | 5/21/14 | 185.31 | 32.68 | | | |
| | *t*-test | 5/20/14 | 193.63 | 41.84 | $t$ = 2.155 | $t_{crit}$ = 2.306 | *Means **are not** statistically different* |
| | | 5/21/14 | 185.31 | 32.68 | | | |

*Table 18 - Statistical analyses on KV results obtained at NIST from 1AD, 5AB, and 9E.*

| Lot | Statistical test | Test date | Mean (J) | Variance (J) | Calculated value | Critical value | Results |
|---|---|---|---|---|---|---|---|
| 1AD | *F*-test | 6/3/14 | 29.07 | 0.20 | $F$ = 1.116 | $F_{crit}$ = 6.388 | *Variances **are not** statistically different* |
| | | 6/4/14 | 29.15 | 0.23 | | | |
| | *t*-test | 6/3/14 | 29.07 | 0.20 | $t$ = 0.268 | $t_{crit}$ = 2.306 | *Means **are not** statistically different* |
| | | 6/4/14 | 29.15 | 0.23 | | | |
| 5AB | *F*-test | 6/3/14 | 122.57 | 25.78 | $F$ = 1.955 | $F_{crit}$ = 6.388 | *Variances **are not** statistically different* |
| | | 6/4/14 | 121.13 | 13.19 | | | |
| | *t*-test | 6/3/14 | 122.57 | 25.78 | $t$ = 0.514 | $t_{crit}$ = 2.306 | *Means **are not** statistically different* |
| | | 6/4/14 | 121.13 | 13.19 | | | |
| 9E | *F*-test | 6/3/14 | 186.62 | 21.55 | $F$ = 1.776 | $F_{crit}$ = 6.388 | *Variances **are not** statistically different* |
| | | 6/4/14 | 178.16 | 38.28 | | | |
| | *t*-test | 6/3/14 | 186.62 | 21.55 | $t$ = 2.455 | $t_{crit}$ = 2.306 | *Means **are** statistically different* |
| | | 6/4/14 | 178.16 | 38.28 | | | |

The results of the statistical tests on *KV*, $F_m$ and *LE* are presented in Table 19, Table 20, and Table 21 respectively.

*Table 19 - Statistical analyses on KV results from 1AD, 5AB, and 9E.*

| Lot | Statistical test | Test location | Mean (J) | Variance (J) | Calculated value | Critical value | Results |
|---|---|---|---|---|---|---|---|
| **1AD** | *F*-test | LNE | 30.33 | 0.46 | $F = 2.341$ | $F_{crit} = 3.230$ | *Variances **are not** statistically different* |
| | | NIST | 29.11 | 0.19 | | | |
| | *t*-test | LNE | 30.33 | 0.46 | $t = 4.725$ | $t_{crit} = 2.110$ | *Means **are** statistically different* |
| | | NIST | 29.11 | 0.19 | | | |
| **5AB** | *F*-test | LNE | 129.30 | 17.89 | $F = 1.922$ | $F_{crit} = 3.179$ | *Variances **are not** statistically different* |
| | | NIST | 121.85 | 9.31 | | | |
| | *t*-test | LNE | 129.30 | 17.89 | $t = 4.518$ | $t_{crit} = 2.110$ | *Means **are** statistically different* |
| | | NIST | 121.85 | 9.31 | | | |
| **9E** | *F*-test | LNE | 189.47 | 52.35 | $F = 1.127$ | $F_{crit} = 3.179$ | *Variances **are not** statistically different* |
| | | NIST | 182.39 | 46.46 | | | |
| | *t*-test | LNE | 189.47 | 52.35 | $t = 2.251$ | $t_{crit} = 2.110$ | *Means **are** statistically different* |
| | | NIST | 182.39 | 46.46 | | | |

*Table 20 - Statistical analyses on $F_m$ results from 1AD, 5AB, and 9E.*

| Lot | Statistical test | Test location | Mean (kN) | Variance (kN) | Calculated value | Critical value | Results |
|---|---|---|---|---|---|---|---|
| **1AD** | *F*-test | LNE | 44.23 | 20.86 | $F = 0.073$ | $F_{crit} = 0.157$ | *Variances **are not** statistically different* |
| | | NIST | 30.38 | 1.52 | | | |
| | *t*-test | LNE | 44.23 | 20.86 | $t = 6.545$ | $t_{crit} = 2.306$ | *Means **are** statistically different* |
| | | NIST | 30.38 | 1.52 | | | |
| **5AB** | *F*-test | LNE | 29.11 | 0.06 | $F = 1.116$ | $F_{crit} = 6.388$ | *Variances **are not** statistically different* |
| | | NIST | 27.74 | 0.06 | | | |
| | *t*-test | LNE | 29.11 | 0.06 | $t = 8.940$ | $t_{crit} = 2.306$ | *Means **are** statistically different* |
| | | NIST | 27.74 | 0.06 | | | |
| **9E** | *F*-test | LNE | 38.88 | 0.23 | $F = 1.127$ | $F_{crit} = 3.179$ | *Variances **are not** statistically different* |
| | | NIST | 38.54 | 0.06 | | | |
| | *t*-test | LNE | 38.88 | 0.23 | $t = 1.390$ | $t_{crit} = 2.306$ | *Means **are not** statistically different* |
| | | NIST | 38.54 | 0.06 | | | |

*Table 21 - Statistical analyses on LE results from 1AD, 5AB, and 9E.*

| Lot | Statistical test | Test location | Mean (mm) | Variance (mm) | Calculated value | Critical value | Results |
|---|---|---|---|---|---|---|---|
| **1AD** | *F*-test | LNE | 0.117 | 1.38E-03 | $F = 6.843$ | $F_{crit} = 3.179$ | *Variances **are** statistically different* |
| | | NIST | 0.128 | 9.46E-03 | | | |
| | *t*-test | LNE | 0.117 | 1.38E-03 | $t = 0.343$ | $t_{crit} = 2.179$ | *Means **are not** statistically different* |
| | | NIST | 0.128 | 9.46E-03 | | | |
| **5AB** | *F*-test | LNE | 1.573 | 5.42E-03 | $F = 1.899$ | $F_{crit} = 3.179$ | *Variances **are not** statistically different* |
| | | NIST | 1.509 | 2.85E-03 | | | |
| | *t*-test | LNE | 1.573 | 5.42E-03 | $t = 2.250$ | $t_{crit} = 2.101$ | *Means **are** statistically different* |
| | | NIST | 1.509 | 2.85E-03 | | | |
| **9E** | *F*-test | LNE | 1.875 | 1.12E-02 | $F = 3.272$ | $F_{crit} = 3.179$ | *Variances **are not** statistically different* |
| | | NIST | 1.770 | 3.67E-02 | | | |
| | *t*-test | LNE | 1.875 | 1.12E-02 | $t = 1.526$ | $t_{crit} = 2.145$ | *Means **are not** statistically different* |
| | | NIST | 1.770 | 3.67E-02 | | | |

In most cases, the test results obtained at NIST and LNE were found to be statistically different, with the exception of $F_m$ for lot 9E and *LE* for lots 1AD and 9E.

# 4. Discussion

Table 22 summarizes the comparison between NIST and LNE, based on average values of $F_m$, $KV$, and $LE$ for all the reference materials tested. In Table 22, the cells corresponding to the largest average value between NIST and LNE are shaded in light blue and in **bold** font.

*Table 22 - Summary of the comparison between NIST and LNE in terms of maximum force, absorbed energy and lateral expansion.*

| Specimen lot | Testing lab | $F_m$ (kN) | | $KV$ (J) | | $LE$ (mm) | |
|---|---|---|---|---|---|---|---|
| LL-103 | NIST | 29.29 | *Statistically* | 19.18 | *Statistically* | 0.048 | *Statistically* |
| | LNE | **36.66** | ***DIFFERENT*** | **20.32** | ***DIFFERENT*** | **0.083** | ***DIFFERENT*** |
| HH-103 | NIST | 26.40 | Statistically | **111.07** | Statistically | 1.252 | Statistically |
| | LNE | **29.12** | **NOT DIFFERENT** | 107.76 | **NOT DIFFERENT** | **1.342** | **NOT DIFFERENT** |
| LL-136 | NIST | 34.82 | *Statistically* | 20.77 | *Statistically* | 0.099 | *Statistically* |
| | LNE | **37.75** | ***DIFFERENT*** | **22.71** | ***DIFFERENT*** | **0.125** | ***DIFFERENT*** |
| HH-140 | NIST | 28.27 | *Statistically* | 103.15 | *Statistically* | 1.326 | Statistically |
| | LNE | **29.49** | ***DIFFERENT*** | **106.32** | ***DIFFERENT*** | **1.369** | **NOT DIFFERENT** |
| 1AD | NIST | 30.38 | *Statistically* | 29.11 | *Statistically* | **0.128** | Statistically |
| | LNE | **44.23** | ***DIFFERENT*** | **30.33** | ***DIFFERENT*** | 0.117 | **NOT DIFFERENT** |
| 5AB | NIST | 27.74 | *Statistically* | 121.85 | *Statistically* | 1.509 | *Statistically* |
| | LNE | **29.11** | ***DIFFERENT*** | **129.30** | ***DIFFERENT*** | **1.573** | ***DIFFERENT*** |
| 9E | NIST | 38.54 | Statistically | 182.39 | *Statistically* | 1.770 | Statistically |
| | LNE | **38.88** | **NOT DIFFERENT** | **189.47** | ***DIFFERENT*** | **1.875** | **NOT DIFFERENT** |

Examination of the information presented in Table 22 leads to the following observations.

(1) Maximum force, $F_m$: for all the materials considered, $F_m$ values from NIST tests are lower than those from LNE tests. Statistically, the difference is significant in all cases but two (HH-103 and 9E). In two cases, the difference is large (7.37 kN for LL-103, 13.85 kN for 1AD).

(2) Absorbed energy, $KV$: average values of $KV$ for NIST tests are lower than for LNE tests except in one case (HH-103). However, this is the only instance when the difference is statistically not significant. Therefore, we can state that the LNE machine tends to provide higher absorbed energy values than the NIST machine.

(3) Lateral expansion, $LE$: similar to $KV$, NIST average values of lateral expansion are systematically lower than LNE average values, except in one case (1AD). However, in most cases (4 lots out of 7), differences are not statistically different.

## 4.1 Instrumented parameters

For instrumented parameters, Table 23 shows the comparison of average values for two characteristic force values ($F_{gy}$ and $F_m$), the elastic slope of the instrumented test record ($C_{el}$), and the absorbed energy calculated under the force-displacement curve ($W_t$). Again, the largest average values for each parameter are shaded in light blue and in **bold** font.

No systematic trend can be observed in Table 23. Only 4 out of 7 lots (57 %) have the same relation between NIST and LNE average force values for both $F_{gy}$ and $F_m$ (*i.e.*, NIST < LNE or vice versa). Furthermore, since overestimating forces has a relatively minor effect on displacements[6], and time values are assumed identical, one would expect that higher $F_{gy}$ always corresponds to a lower elastic slope, $C_{el}$: based on Table 23, this is true in 71 % of cases (5 out of 7), the exceptions being lots 5AB and 9E. However, for these two latter lots NIST and LNE average values are only marginally different ($|\Delta F_{gy}|$ = 0.03 kN and $|\Delta C_{el}|$ = 0.00105 mm/kN for lot 5AB; $|\Delta F_{gy}|$ = 1.31 kN and $|\Delta C_{el}|$ = 0.00269 mm/kN for lot 9E).

Considering that:

- all tests used the same instrumented striker (with the same calibration function, see Figure 1), the same acquisition system (amplifier/conditioner, A/D converter, PC) and the same acquisition software; and
- all tests were analyzed by the same person by means of the same analysis software,

the observed behavior and differences (in terms of instrumented parameters) cannot be easily explained. However, the malfunctioning of the acquisition system during the tests performed at LNE (already mentioned in section 2.3), might have been the cause of the erratic behavior observed.

*Table 23 - Comparison between NIST and LNE instrumented impact tests in terms of force at general yield, maximum force, elastic slope and calculated absorbed energy.*

| Specimen lot | Testing lab | $F_{gy}$ (kN) | $F_m$ (kN) | $C_{el}$ (mm/kN) | $W_t$ (J) |
|---|---|---|---|---|---|
| LL-103 | NIST | 23.92 | 29.29 | **0.02528** | 19.09 |
| | LNE | **30.05** | **36.66** | 0.02131 | **22.90** |
| HH-103 | NIST | 19.93 | 26.40 | **0.02820** | **124.66** |
| | LNE | **22.34** | **29.12** | 0.02216 | 123.88 |
| LL-136 | NIST | **32.30** | 34.82 | 0.01139 | 22.68 |
| | LNE | 22.48 | **37.75** | **0.02123** | **24.65** |
| HH-140 | NIST | **24.36** | 28.27 | 0.00957 | 118.99 |
| | LNE | 22.36 | **29.49** | **0.02701** | **121.49** |
| 1AD | NIST | 25.15 | 30.38 | **0.02973** | 24.24 |
| | LNE | **25.22** | **44.23** | 0.02292 | **33.57** |
| 5AB | NIST | 21.67 | 27.74 | 0.02125 | 133.48 |
| | LNE | **21.70** | **29.11** | **0.02230** | **148.69** |
| 9E | NIST | **29.61** | 38.54 | **0.02389** | 208.28 |
| | LNE | 28.30 | **38.88** | 0.02120 | **214.81** |

## 4.2 Absorbed energy

For absorbed energy, we already remarked that the tendency is for LNE values to be higher than NIST values. From Table 24, the same tendency is also observed for average calculated energy values, $W_t$. Also, the difference in terms of $W_t$ is mostly larger than for $KV$, which would indicate larger forces and displacements. However, the ratio between $\Delta W_t$ and $\Delta KV$ ranges from a minimum of 0.4 (lot HH-103) to a maximum of 5.9 (lot 1AD), with an average of 2.4. This confirms the erratic behavior already remarked above.

[6]Displacement values are calculated by double numerical integration of force and time measurements.

*Table 24 - Differences between average values of absorbed (KV) and calculated ($W_t$) energy for NIST and LNE tests.*

| **Specimen lot** | $KV_{LNE}$ - $KV_{NIST}$ **(J)** | $W_{t,LNE} - W_{t,NIST}$ **(J)** |
|---|---|---|
| LL-103 | 1.14 | 3.82 |
| HH-103 | -3.31 | -1.29 |
| LL-136 | 2.33 | 1.96 |
| HH-140 | 2.23 | 2.50 |
| 1AD | 1.57 | 9.32 |
| 5AB | 5.20 | 15.31 |
| 9E | 7.01 | 6.53 |
| Average | 2.31 | 5.45 |

Although the NIST and LNE impact machines were nominally identical and the same instrumented striker was used for all the tests, the anvil/support blocks were different between the two labs, since NIST tests in accordance with ASTM E23 and LNE tests in accordance with ISO 148. The two standards feature different requirements only in terms of:

- angle of taper of the anvils (10 ° ± 2 ° for ASTM, 11 ° ± 1 ° for ISO – see also Section 2.2);
- surface finish of the anvils and supports ($R_a$ 0.1 µm or better for ASTM, not specified for ISO).

All other characteristics (*i.e.*, anvil radius and anvil spacing or span) are identical between the two standards.

The influence of the angle of taper of the anvils on the absorbed energy of Charpy specimens of three energy levels (30 J, 100 J, and 160 J) was investigated by Yamaguchi and coworkers [12]. They concluded that *KV* tends to decrease with increasing angle of taper at all energy levels, even though the effect is statistically significant (at 95 % confidence level) only at 100 J and 160 J. However, in our investigation the opposite effect was observed for 6 of the 7 lot tested (*KV* is higher for LNE, that uses 11 °, than for NIST, that uses 10 °). Therefore, the angle of taper of the anvils cannot explain the trends observed.

Regarding surface finish (roughness) of the anvils and supports, its influence on Charpy absorbed energy was studied by Ruth and coworkers [13]. They observed that for low-energy specimens ($KV \approx 17$ J), which tend to exit the machine in a direction opposite to the pendulum swing, the effect of surface finish is negligible because the broken specimen halves have limited contact with anvils, supports and striker. On the contrary, high-energy specimens ($KV \approx 90$ J) exit the machine in the same direction of the pendulum swing and the friction between specimen, anvils and supports increases with increasing roughness and tends to produce higher absorbed energy. NIST anvils and supports were in compliance with ASTM E23 ($R_a \leq 0.1$ µm), whereas it is possible that the roughness of LNE anvils/supports was higher at the time the interlaboratory tests were performed. According to Ruth *et al.*, the average difference in *KV* at the high-energy level between polished ($R_a$ = 0.05 µm) and unpolished ($R_a$ = 0.25 µm) anvils/supports is in the order of 0.4 J (approximately 0.44 % of 90 J). The differences we observed in our investigation were typically much higher, and therefore surface finish could explain only a small part of the differences between NIST and LNE.

## 4.3 Lateral expansion

Absorbed energy and lateral expansion are two of the fundamental test parameters commonly measured from a conventional (*i.e.*, non-instrumented) Charpy test, along with Shear Fracture Appearance. Both quantities are related to the amount of ductility exhibited by the material at the test temperature, and many correlations between *KV* and *LE* have been published, showing that the two parameters are linearly correlated for a given material, see for example [14-16].

One would therefore expect to find a reasonable correlation between $\Delta KV_{\text{LNE-NIST}}$ and $\Delta LE_{\text{LNE-NIST}}$ for the seven reference lots investigated. Figure 25 shows that a strong positive linear relationship (coefficient of correlation $r$ = 0.84) is obtained when HH-103 is excluded. The correlation coefficient drops to 0.23 (weak linear relationship) when HH-103 is included. Note that HH-103 was also the only lot for which average energy values were higher for NIST tests than LNE tests, albeit with a statistically insignificant difference (see Table 22).

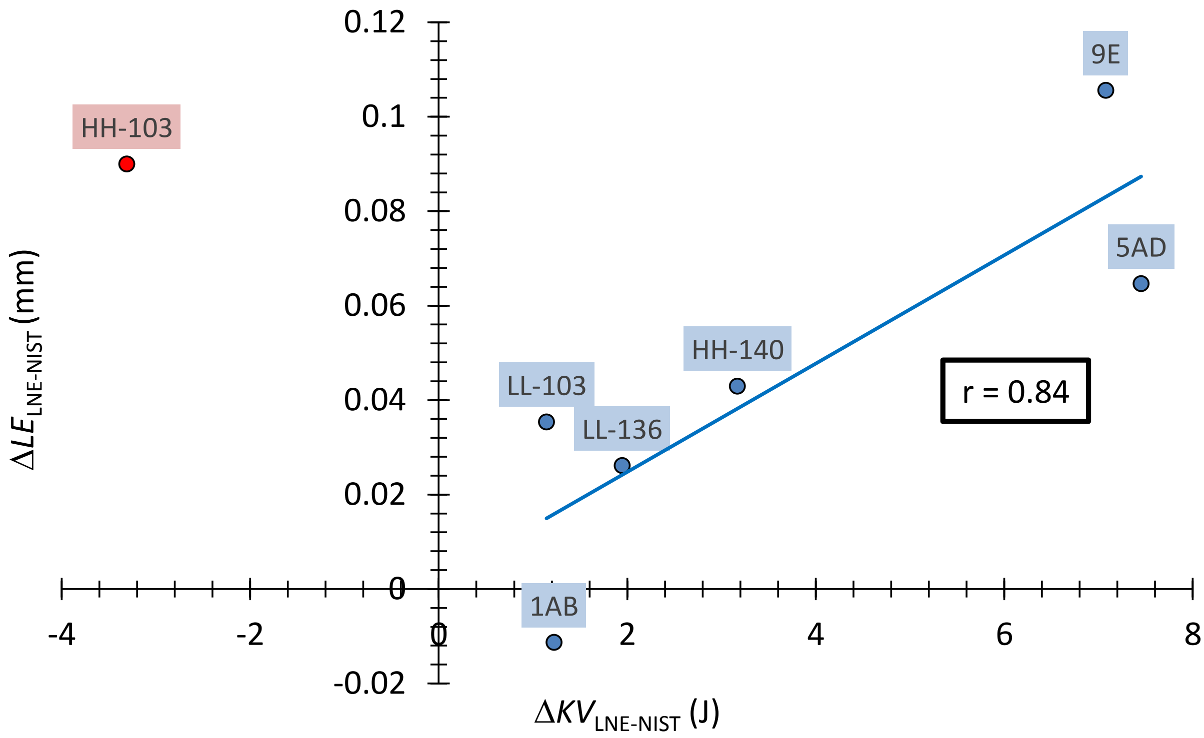


*Figure 25- Relationship between differences in absorbed energy and lateral expansion between NIST and LNE tests.*

## 5. Conclusions

In the framework of a collaborative effort aimed at establishing an international scale for instrumented impact testing, NIST and *Laboratoire National de métrologie et d'Essai* (LNE, France) performed instrumented Charpy tests on seven certified reference materials, produced by both institutes. The tests were carried out at both locations (Boulder, Colorado and Trappes, France) on two nominally identical impact machines equipped with the same instrumented striker and the same signal conditioning and acquisition system.

The results from the tests performed at NIST and LNE were compared in terms of both non-instrumented parameters (absorbed energy, *KV*, and lateral expansion, *LE*) and instrumented parameters (maximum force, $F_m$, and calculated energy, $W_t$). The statistical significance of the differences between average values obtained at NIST and LNE on each material was assessed by means of the unpaired two-sample *t*-test.

While no significant difference was observed between tests performed on different days at the same location, most of the differences between NIST and LNE in terms of $F_m$ and *KV* were found to be statistically significant at the 95 % confidence level. For all reference lots except HH-103, for which results were not statistically different between the two institutes, tests performed at LNE exhibit systematically higher maximum forces and higher absorbed energies. This confirms results from previous intercomparisons, where LNE absorbed energies were found to be systematically higher than NIST absorbed energies, even when striker, anvil and supports for the LNE machine were in compliance with ASTM E23 [17]. The bias in terms of $W_t$ showed a similar trend, although the magnitude of the difference was typically larger than for *KV*. On the other hand, measurements of lateral expansion were generally equivalent between NIST and LNE and no specific trend was observed.

The source of the disagreement between the two sets of results is unclear. The difference in the angle of taper of the anvils (10 ° for NIST, 11 ° for LNE) is unlikely to affect the results significantly, and according to a published study, a larger taper angle should induce a decrease, rather than an increase of absorbed energy. In addition, a possible difference in the surface finish of machine anvils and supports might be invoked, considering that the LNE machine complies with ISO 148, which does not require a specific surface finish, whereas NIST complies with ASTM E23, which prescribes a surface finish of 0.1 µm or better. Rougher anvils and supports cause more energy dissipation due to greater friction for ductile specimens that exit the machine in the same direction of the pendulum swing. This factor, however, appears insufficient to fully explain the observed bias. Furthermore, for 3 of the 7 lots investigated (low-energy specimens), friction is not expected to play any role.

Even though the reasons of the observed differences are not apparent, some discrepancies between Charpy results from different reference specimen producers have already been reported [17]. The results presented here reinforce the need for further collaborations among National Institutes, with the aim of establishing an international scale for instrumented Charpy testing.

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