TENSILE AND IMPACT TESTING OF AN
HFBR CONTROL ROD FOLLOWER

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ABSTRACT

The Materials Technology Group of the Department of Nuclear Energy (DNE) at Brookhaven National Laboratory (BNL) undertook a program to machine and test specimens from a control rod follower from the High Flux Beam Reactor (HFBFR). Tensile and Charpy impact specimens were machined and tested from non-irradiated aluminum alloys in addition to irradiated 6061-T6 from the HFBFR. The tensile test results on irradiated material showed a two-fold increase in tensile strength to a maximum of 100.6 ksi. The impact resistance of the irradiated material showed a six-fold decrease in values (3 in-lb average) compared to similar non-irradiated material. Fracture toughness ($K_{max}$) specimens were tested on an unirradiated compositionally and dimensionally similar (to HFBFR follower) 6061 T-6 material with $K_{max}$ values of 24.8±1.0 Ksi/in (average) being obtained.

The report concludes that the specimens produced during the program yielded reproducible and believable results and that proper quality assurance was provided throughout the program.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>SECTION</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>iii</td>
</tr>
<tr>
<td>LIST OF FIGURES AND TABLES</td>
<td>vii</td>
</tr>
<tr>
<td>1. INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>2. MATERIALS TESTED</td>
<td>1</td>
</tr>
<tr>
<td>3. FRACTURE TOUGHNESS TESTING</td>
<td>3</td>
</tr>
<tr>
<td>4. MACHINING OF IMPACT AND TENSILE SPECIMENS</td>
<td>4</td>
</tr>
<tr>
<td>5. SIZE OF IMPACT SPECIMENS/IMPACT TESTER USED</td>
<td>4</td>
</tr>
<tr>
<td>6. CALIBRATION OF EQUIPMENT</td>
<td>4</td>
</tr>
<tr>
<td>7. QUALITY ASSURANCE</td>
<td>10</td>
</tr>
<tr>
<td>8. RESULTS OF TESTING</td>
<td>10</td>
</tr>
<tr>
<td>9. CONCLUSIONS</td>
<td>15</td>
</tr>
<tr>
<td>APPENDIX 1</td>
<td>23</td>
</tr>
<tr>
<td>APPENDIX 2</td>
<td>39</td>
</tr>
<tr>
<td>APPENDIX 3</td>
<td>45</td>
</tr>
<tr>
<td>APPENDIX 4</td>
<td>55</td>
</tr>
<tr>
<td>APPENDIX 5</td>
<td>69</td>
</tr>
<tr>
<td>APPENDIX 6</td>
<td>71</td>
</tr>
<tr>
<td>APPENDIX 7</td>
<td>73</td>
</tr>
<tr>
<td>APPENDIX 8</td>
<td>75</td>
</tr>
<tr>
<td>APPENDIX 9</td>
<td>81</td>
</tr>
<tr>
<td>APPENDIX 10</td>
<td>91</td>
</tr>
</tbody>
</table>
LIST OF FIGURES AND TABLES

FIGURE 1  Tolerances in Accordance with ASTM Requirements . 5
FIGURE 2  Measurements Taken Along Length of Control Rod
  Follower to Determine Condition of "As Received"
  Material. 6-7
FIGURE 3  Charpy Impact Sample. 8
FIGURE 4  Control Blade Sample. 17
FIGURE 5  Tensile Test Chart for Specimen T-C 18
FIGURE 6  Tensile Test Chart for Specimen T-1 19
FIGURE 7  Tensile Test Chart for Specimen T-2 20
FIGURE 8  Tensile Test Chart for Specimen T-3 21
FIGURE 9  Tensile Test Chart for Specimen T-4 22

LIST OF TABLES

TABLE 1  Chemical Analysis of Test Specimen. 2
TABLE 2  Fracture Toughness Testing of Unirradiated
  Aluminum Samples. 3
TABLE 3  Results of Impact Tests of Machined "Full
  Size" Specimens 9
TABLE 4  Unirradiated Charpy Testing 11-13
TABLE 5  Results of Irradiated Impact Testing 14
TABLE 6  HFBR Tensile Test Results 16
1. INTRODUCTION

In October 1988, the Reactor Division (RD) of Brookhaven National Laboratory contracted with the Materials Technology Group of the Department of Nuclear Energy (DNE) to machine and test specimens from an HFBR control rod follower.

The purpose of the program was twofold:

a) Four tensile specimens were required to be machined and tested (HFBR Technical Specification Requirement).

b) The Shewmon committee had requested BNL to perform evaluations of the fracture toughness of the HFBR beam tube materials. After extended discussions with the Structural Analysis Division of DNE, it was decided that charpy impact specimens would be machined and tested.

Charpy impact specimens were chosen because they could be reproducibly machined and tested in the BNL Metallurgical Hot Cell with the equipment and personnel available at the time of program inception.

2. MATERIALS TESTED

Four commercially available aluminum alloys were procured for this test program: 6061 T-6, 4032, 1100 and 5052.

The 6061 T-6 alloy corresponded to the original materials used in fabricating the HFBR Beam Tubes.

The 4032 alloy is similar to 6061 T-6 with the exception of its silicon content which in the case of the alloy used in the test program was 11.60%.

An essentially pure, annealed aluminum (1100) was also tested in addition to a 5052 alloy.

Two size/shapes of the 6061 alloy were tested. A thick walled (schedule 80) and a thin walled (schedule 40) tube of approximately 1 inch in diameter were procured. These specimens were used to approximate the control rod follower dimensions for both machining and testing purposes.

The 4032 material was purchased in a 2 inch diameter rod. Tubing could not be procured for this alloy.

The 1100 and 5052 were purchased as sheet stock.

All of the materials used were chemically analyzed by an independent laboratory which had been previously audited (for QA practices, standards traceability, etc.) by members of the Materials Technology Group. The independent chemical analyses are shown in Table 1.

After initial machining/testing operations were performed, the alloys used for the test program were the thick walled 6061 T-6 Tube and Alloy 4032 rod.
### TABLE 1
Chemical Analysis of Test Specimens

<table>
<thead>
<tr>
<th>Element</th>
<th>6061 T-6 Thin wall tube</th>
<th>6061 T-6 Thick wall tube</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
<td>0.32</td>
<td>0.31</td>
</tr>
<tr>
<td>Mn</td>
<td>0.059</td>
<td>0.03</td>
</tr>
<tr>
<td>Si</td>
<td>0.48</td>
<td>0.49</td>
</tr>
<tr>
<td>Cu</td>
<td>0.20</td>
<td>0.21</td>
</tr>
<tr>
<td>Cr</td>
<td>0.052</td>
<td>0.046</td>
</tr>
<tr>
<td>Mg</td>
<td>1.05</td>
<td>0.93</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Element</th>
<th>4032</th>
<th>1100</th>
<th>5052</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
<td>0.30</td>
<td>0.55</td>
<td>0.29</td>
</tr>
<tr>
<td>Mn</td>
<td>0.03</td>
<td>0.015</td>
<td>0.07</td>
</tr>
<tr>
<td>Si</td>
<td>11.60</td>
<td>0.20</td>
<td>0.13</td>
</tr>
<tr>
<td>Cu</td>
<td>0.90</td>
<td>0.07</td>
<td>0.05</td>
</tr>
<tr>
<td>Cr</td>
<td>0.01</td>
<td>&lt;0.01</td>
<td>0.17</td>
</tr>
<tr>
<td>Mg</td>
<td>0.92</td>
<td>&lt;0.01</td>
<td>2.35</td>
</tr>
<tr>
<td>Ni</td>
<td>0.94</td>
<td>0.02</td>
<td>0.015</td>
</tr>
</tbody>
</table>

Note: Testing performed by Long Island Testing Laboratories, Inc., North Babylon, New York. Composition, wt%.
3. FRACTURE TOUGHNESS TESTING

Samples of the 6061 T-6 tube and 4032 rod were sent to an independent laboratory for fracture toughness testing to American Society for Testing of Materials (ASTM) E399 as modified by ASTM:B645 and B646 (aluminum alloys).

Appendix 1 is a copy of the report from the independent laboratory (Lucius Pitkin, Inc., NYC). Four specimens from each shape (alloy) were tested.

Table 2 lists the results of these tests.

Due to the shape/size of the material sent to the lab, the plane strain fracture toughness ($K_{jc}$) measurements were not considered valid. However, the $K_{max}$ measurements of both alloys is a realistic representation of that product form's fracture toughness measurement.

**TABLE 2**

Fracture Toughness Testing of Unirradiated Aluminum Samples

<table>
<thead>
<tr>
<th>Specimen</th>
<th>$K_{max}$ (Ksi/in)</th>
<th>$K_{ic}$ (Ksi/in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6061 T-6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>24.9</td>
<td>not valid</td>
</tr>
<tr>
<td>2</td>
<td>23.2</td>
<td>not valid</td>
</tr>
<tr>
<td>3</td>
<td>25.0</td>
<td>not valid</td>
</tr>
<tr>
<td>4</td>
<td>26.0</td>
<td>not valid</td>
</tr>
<tr>
<td></td>
<td>$24.8 \pm 1.0$</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Specimen</th>
<th>$K_{max}$ (Ksi/in)</th>
<th>$K_{ic}$ (Ksi/in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4032</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>16.4</td>
<td>not valid</td>
</tr>
<tr>
<td>2</td>
<td>15.5</td>
<td>not valid</td>
</tr>
<tr>
<td>3</td>
<td>15.2</td>
<td>not valid</td>
</tr>
<tr>
<td>4</td>
<td>15.8</td>
<td>not valid</td>
</tr>
<tr>
<td></td>
<td>$15.7 \pm 0.4$</td>
<td></td>
</tr>
</tbody>
</table>
4. MACHINING OF IMPACT AND TENSILE SPECIMENS

An intensive program was initiated to evaluate the accuracy and reproducibility of machining charpy impact specimens and tensile specimens in the BNL Metallurgical Hot Cell. The machining steps were recorded in a detailed procedure for each operation performed in the hot cell. Appendix 2 and Appendix 3 are the procedures used for machining impact specimens (Appendix 2) and tensile specimens (Appendix 3).

These procedures were reviewed by the RD QA Group during the actual machining operations in the cell.

Figure 1 is a sketch of the nominal dimensions and configuration of the tensile specimens machined from the control rod follower in the hot cell facility.

Prior to any work commencing on the follower, measurements were taken along its length with a micrometer to determine if an "out of round" condition existed.

Figure 2 is a sketch of the follower with these measurements recorded. It was apparent that the tube was relatively round throughout its length.

5. SIZE OF IMPACT SPECIMENS/IMPACT TESTER USED

Since the actual control rod follower dimensions would not allow a standard charpy impact specimen to be machined, subsized specimens were machined. Figure 3 is a sketch of the specimen used. This size specimen conforms to the subsized requirements of the ASTM Standard.

During the initial phases of the program, some impact specimens (shop machined 6061 T-6 and 4032 subsize specimens) were tested by the Material Science Division of the Department of Applied Science (DAS). The results were 6061 T-6 1.75 ft-lb (average of 3 tested) and 4032 1.0 ft-lb (average of 3 tested). The scale used on the impact tester was in 0.5 ft-lb increments and 1.0 ft-lb increments which was considered to be too large to produce meaningful and accurate results.

It was then decided (Materials Technology Group) to calibrate and modify a Tinius Olsen impact tester (used for plastic testing) for accommodating aluminum alloys remotely in the hot cell facility.

Appendix 4 outlines the steps taken to qualify the impact tester for this program. Extensive discussions took place between BNL personnel and the manufacturer in order to obtain the correct striker head and fixtures for performing uniform and reproducible tests on the subsized aluminum specimens.

6. CALIBRATION OF EQUIPMENT

The tensile test machine manufacturer (MTS Systems, Inc.) was contacted and a technician came to calibrate the tensile test load cell in situ at the hot cell. Appendix 5 and 6 are the calibration sheets for the unit traceable to the National Bureau of Standards.
Tolerances in accordance with ASTM Requirements.
Measurement in inches.

2x Scale
Figure 2 Measurements taken along length of control rod follower to determine condition of "as received" material.
Figure 2 Measurements taken along length of control rod follower to determine condition of "as received" material.
MEASUREMENT IN INCHES

Figure 3
Calibrated test specimens (charpy "V" notch) were ordered from the U.S. Army (NBS traceable) for the impact tester. Appendix 7 is the calibration sheet for the specimens.

When the first full sized calibration specimen was tested in the impact machine, it would not break. In order to test the low range specimens in the modified impact tester, it was necessary to machine subsized specimens from the original "full size" specimens.

Two full size specimens were machined in the BNL metal shop and cut down to two subsize specimens each (total of four specimens). These were then tested in the modified impact tester on three different scales of the unit.

Table 3 gives the results of the testing. These values are considered consistent with those expected of subsized specimens tested in this manner.

Various sets/sizes of calibrated (to NBS) gage blocks were used to verify the calibration of micrometers, gages and verniers/calipers in the hot cell. The calibration certifications were checked during the RD QA audit and are on file at the hot cell.

**TABLE 3**

Results of Impact Tests of Machined "Full Size" Specimens

<table>
<thead>
<tr>
<th></th>
<th>Specimen cut from #LL-12-0821</th>
<th>Scale: 200 in-lb</th>
<th>Temp.: -40°F</th>
<th>Result: 36 in-lb, 3.0 ft-lb</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Specimen cut from #LL-12-0821</td>
<td>Scale: 50 in-lb</td>
<td>Temp.: -40°F</td>
<td>Result: 38 in-lb, 3.2 ft-lb</td>
</tr>
<tr>
<td>3</td>
<td>Specimen cut from #LL-12-1091</td>
<td>Scale: 50 in-lb</td>
<td>Temp.: -40°F</td>
<td>Result: 38.5 in-lb, 3.2 ft-lb</td>
</tr>
<tr>
<td>4</td>
<td>Specimen cut from #LL-12-1091</td>
<td>Scale: 100 in-lb</td>
<td>Temp.: -40°F</td>
<td>Result: 36 in-lb, 3.0 ft-lb</td>
</tr>
</tbody>
</table>

Note: in-lb and ft-lb are in-lbf and ft-lbf
7. QUALITY ASSURANCE

The assurance of quality in both machining and testing of the HFBR materials was maintained by the following:

A. A limited number of personnel (4) were involved with the machining and testing operations.

B. Extensive discussions with RD personnel resulted in a cutting and orientation marking procedure for the rod follower (Appendix 8).

C. All equipment was calibrated (either to NBS or by ASTM Methods).

D. All specimens were segregated in discrete envelopes and separated in 9 lead containers.

E. All operations were audited by RD QA personnel (Appendix 9).

8. RESULTS OF TESTING

In order to verify that the machining/test methods would produce consistent results, various unirradiated impact specimens were tested (both 6061 T-6 and 4032 material).

Table 4 lists the various tests conditions imposed and the results of the testing. Some specimens were machined remotely in the hot cell. All impact tests were performed on the modified impact tester.

The different test conditions imposed (shop or hot cell machining) did not appear to significantly alter the results. The scatter obtained was probably due to the expected machining variations between samples.

A total of twelve impact samples were machined from the irradiated follower. Eight specimens were machined from the area of peak fluence (as determined by RD personnel) and four were machined from an area (on the follower) outside the peak fluence regime.

Two specimens from the area outside the high fluence area were tested at room temperature. Three specimens were each tested (area of peak fluence) at 210°F and room temperature (Appendix 10). Table 5 lists the results from all eight specimens tested. The average of specimens C-B and C-C (outside highest fluence area) was 3.0 in-lbf while the average of the three tested at room temperature (highest fluence area) was 3.0 in-lbf and those at 210°F (highest fluence area) averaged 2.75 in-lbf.

A total of eight tensile specimens were machined from the follower (four from area of highest fluence and four from outside this area). Six specimens were tensile pulled on the MTS equipment in the hot cell facility. Control rod blade follower sample orientation requirements, Figure 4, was provided by P. Tichler of the Reactor Division.
### TABLE 4

Unirradiated Charpy Testing

**A. Machine shop machined** (6061 T-6), 71°F

<table>
<thead>
<tr>
<th>Specimen #</th>
<th>Impact Energy (in-lbf)</th>
<th>Impact Energy (ft-lbf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18.5</td>
<td>1.54</td>
</tr>
<tr>
<td>2</td>
<td>22.0</td>
<td>1.83</td>
</tr>
<tr>
<td>3</td>
<td>20.0</td>
<td>1.67</td>
</tr>
<tr>
<td>4</td>
<td>18.25</td>
<td>1.52</td>
</tr>
<tr>
<td>5</td>
<td>19.50</td>
<td>1.63</td>
</tr>
</tbody>
</table>

Average 1,4,5 (18.75 ± 0.66) (1.56 ± 0.06)

- Testing done outside of Hot Cell -

**B. Machine shop machined** (6061 T-6), 73°F

<table>
<thead>
<tr>
<th>Specimen #</th>
<th>Impact Energy (in-lbf)</th>
<th>Impact Energy (ft-lbf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>22.25</td>
<td>1.85</td>
</tr>
<tr>
<td>2</td>
<td>22.25</td>
<td>1.85</td>
</tr>
<tr>
<td>3</td>
<td>21.00</td>
<td>1.75</td>
</tr>
</tbody>
</table>

Average 21.83 ± 0.72 1.82 ± 0.06

- Testing done in Hot Cell -

**C. Hot Cell Machined** (6061 T-6), 74°F

<table>
<thead>
<tr>
<th>Specimen #</th>
<th>Impact Energy (in-lbf)</th>
<th>Impact Energy (ft-lbf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>21.75</td>
<td>1.81</td>
</tr>
<tr>
<td>2</td>
<td>19.75</td>
<td>1.65</td>
</tr>
<tr>
<td>3</td>
<td>17.25</td>
<td>1.44</td>
</tr>
</tbody>
</table>

Average 19.58 ± 2.25 1.63 ± 0.19

- Testing done in Hot Cell -
### TABLE 4 (cont.)

Unirradiated Charpy Testing

**D. Machine shop machined (4032), 71°F**

<table>
<thead>
<tr>
<th>Specimen #</th>
<th>Impact Energy (in-lbf)</th>
<th>Impact Energy (ft-lbf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (50 in-lb scale)</td>
<td>9.75</td>
<td>0.81</td>
</tr>
<tr>
<td>2 (50 in-lb scale)</td>
<td>11.25</td>
<td>0.94</td>
</tr>
<tr>
<td>3 (50 in-lb scale)</td>
<td>9.75</td>
<td>0.81</td>
</tr>
</tbody>
</table>

Average 10.25 ± 0.9 0.85 ± 0.08

- Testing done in Hot Cell -

**E. Machine shop machined (6061 T-6), 210°F**

<table>
<thead>
<tr>
<th>Specimen #</th>
<th>Impact Energy (in-lbf)</th>
<th>Impact Energy (ft-lbf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (50 in-lb scale)</td>
<td>23.50</td>
<td>1.96</td>
</tr>
<tr>
<td>2 (50 in-lb scale)</td>
<td>20.75</td>
<td>1.73</td>
</tr>
<tr>
<td>3 (50 in-lb scale)</td>
<td>21.00</td>
<td>1.75</td>
</tr>
</tbody>
</table>

Average 21.75 ± 1.5 1.81 ± 0.13

- Testing done in Hot Cell -

**F. Hot Cell Machined (6061 T-6), 210°F**

<table>
<thead>
<tr>
<th>Specimen #</th>
<th>Impact Energy (in-lbf)</th>
<th>Impact Energy (ft-lbf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 (50 in-lb scale)</td>
<td>18.75</td>
<td>1.56</td>
</tr>
<tr>
<td>6 (50 in-lb scale)</td>
<td>18.00</td>
<td>1.50</td>
</tr>
<tr>
<td>7 (50 in-lb scale)</td>
<td>19.00</td>
<td>1.58</td>
</tr>
</tbody>
</table>

Average 18.58 ± 0.52 1.53 ± 0.05

- Testing done in Hot Cell -
### TABLE 4 (cont.)

**Unirradiated Charpy Testing**

<table>
<thead>
<tr>
<th>Specimen #</th>
<th>Impact Energy (in-lbf)</th>
<th>Impact Energy (ft-lbf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (50 in-lb scale)</td>
<td>12.00</td>
<td>1.00</td>
</tr>
<tr>
<td>2 (50 in-lb scale)</td>
<td>9.50</td>
<td>0.79</td>
</tr>
<tr>
<td>3 (50 in-lb scale)</td>
<td>11.00</td>
<td>0.92</td>
</tr>
</tbody>
</table>

Average 10.8 ± 1.3 0.90 ± 0.11

- Testing done in Hot Cell -
TABLE 5
Results of Irradiated Impact Testing

Outside Area of Highest Fluence

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Temperature (°F)</th>
<th>Impact Energy (in-lbf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-B</td>
<td>74</td>
<td>3.0</td>
</tr>
<tr>
<td>C-C</td>
<td>74</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Average = 3.0 in-lbf

Area of Highest Fluence

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Temperature (°F)</th>
<th>Impact Energy (in-lbf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-1</td>
<td>75</td>
<td>3.0</td>
</tr>
<tr>
<td>C-2</td>
<td>76</td>
<td>3.25</td>
</tr>
<tr>
<td>C-3</td>
<td>76</td>
<td>2.75</td>
</tr>
</tbody>
</table>

Average = 3.0 in-lbf

C-4          210°F  2.0
C-5          210°F  3.25
C-6          210°F  3.00

Average = 2.75 in-lbf
Table 6 depicts the results of the tensile tests. All specimens averaged above 90,000 psi ultimate strength. Figures 5-9 are reduced copies of the charts generated from the tests. Note: Due to loading pin damage, the chart and results from tensile specimen T-B are omitted.

In order to account for "give" (softness) in the linkage of the tensile testing system, five unirradiated tensile specimens were tested (on the MTS unit) with a known gage length marked on their reduced cross section. These were then compared (after testing) to the total elongation recorded by the load cell. The average ratio (measured gage to total extension) of the five specimens was .785 with the lowest ratio obtained being .706. This value of .706 was multiplied by the values for total extension in order to give the most conservative estimate of the actual elongation of the specimens in a one inch gage length. The minimum elongation observed was .064 inch with a maximum in the area of highest fluence of .079 inch.

9. CONCLUSIONS

- The Materials Technology Group of DNE has successfully machined and tested tensile and charpy impact specimens for the RD from a highly irradiated control rod follower.

- The specimens produced reproducible and believable results.

- Adequate quality assurance was provided throughout all phases of the program.
TABLE 6
HFBR Tensile Test Results

<table>
<thead>
<tr>
<th>SPEC. #</th>
<th>TENSILE STRESS (PSI)</th>
<th>TOTAL ELONGATION (IN.)</th>
<th>CONVERTED ELONGATION (IN.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>NOT IN AREA OF INTEREST</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T-C</td>
<td>93,042.8</td>
<td>.120</td>
<td>.085</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>AREA OF INTEREST</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T-1</td>
<td>99,206.3</td>
<td>.105</td>
<td>.074</td>
</tr>
<tr>
<td>T-2</td>
<td>96,659.8</td>
<td>.100</td>
<td>.071</td>
</tr>
<tr>
<td>T-3</td>
<td>100,608.5</td>
<td>.112</td>
<td>.079</td>
</tr>
<tr>
<td>T-4</td>
<td>99,447.6</td>
<td>.091</td>
<td>.064</td>
</tr>
</tbody>
</table>
Figure 5  Tensile Test Chart for Specimen T-C.
Figure 6. Tensile Test Chart for Specimen T-1.
Figure 8 Tensile Test Chart for Specimen T-3.
Figure 9 Tensile Test Chart for Specimen T-4.
REPORT NO. M-9852

FRACTURE TOUGHNESS TESTING OF ALUMINUM ALLOYS

BROOKHAVEN NATIONAL LABORATORY
Brookhaven National Laboratory
Bldg. 703
Upton, New York, 1193-5000

Attention: Mr. Tom Roberts

Subject: FRACTURE TOUGHNESS TESTING OF ALUMINUM ALLOYS

Lucius Pitkin, Inc. was requested to perform fracture toughness tests on 6061 T6 aluminum alloy tube and 4032 aluminum alloy bar materials. One 1-5/6 in. diameter by 5/16 in. thick wall by 36 in. long tube and one 2-in. diameter by 30 in. long bar were submitted to LPI for testing. We were advised that the yield strength for both submitted materials was 40,000 psi. Specifically, we were requested to machine a minimum of three longitudinally oriented fracture toughness specimens from each sample and test these specimens at room temperature according to ASTM: E 399 as modified by ASTM: B 645 and B 646.

To this end, four longitudinally oriented single edge notched bend (SE(B)) specimens were prepared from the submitted tube and bar samples with notches oriented in the transverse direction. The width and thickness of the SE(B) specimens are given in Table I, appended. All test specimens were precracked at room temperature according to ASTM: E 399 to crack depth-to-width ratios (a/w) of 0.50 to 0.60. Final precracking was conducted at a stress intensity factor range (ΔK) of 8 ksi √in.

Fracture toughness testing and fatigue precracking were conducted on an Instron servo-hydraulic test frame using a 1.0 kip load cell with an accuracy of ± 0.1 percent over all load ranges. Crack opening displacement (COD) was measured using a double cantilever clip displacement gage with ± 0.1 percent linearity. A Compaq 386 personal computer with a 16 bit Harrier interface system and an X-Y pen plotter were used for data acquisition and test...
control. All tests were conducted in ram stroke control at loading rates which varied from 70 to 100 ksi in/min.

The stress intensity factors, $K_Q$, $K_{\text{max}}$, and $K_{\text{IC}}$ (ksi in.) were evaluated for the SE(B) specimens according to the following equation:

$$K_Q, K_{\text{max}}, K_{\text{IC}} = \frac{PQS}{BW^{3/2}} \cdot f(a/W)$$

where:

$$f(a/W) = \frac{3(a/W)^{1/2}(1.99 - (a/W)(1-a/W))}{x(2.15 - 3.93a/W + 2.7a^2/W^2)}$$

$$2(1 + 2a/W)(1 - a/W)^{3/2}$$

$PQ$ = load determined in 9.1.1 of E 399, kips
$B$ = specimen thickness, in.
$S$ = span, in.
$W$ = specimen depth (width), in.
$a$ = crack length as determined in 8.2.2. of E 399, in.

In addition, for the bend specimens the specimen strength ratio (a dimensionless quantity) was calculated as follows:

$$R_{sb} = \frac{6P_{\text{max}} W}{B(W-a)^{2} \sigma_{y}}$$

where:

$P_{\text{max}}$ = maximum load sustained by the specimen, lb.
$\sigma_{y}$ = yield strength, psi

Tables II and III, appended, give the fracture toughness test results for the 6061 T6 aluminum tube and 4032 aluminum bar materials. Plane strain fracture toughness, $K_{\text{IC}}$, values could not be obtained from the test specimens as calculated according to ASTM: E 399. Although most of the test specimens satisfied the precracking requirements, none of the fracture toughness specimens met the $P_{\text{max}}/PQ \leq 1.10$ requirement specified in E 399. Further, the 6061 T6 aluminum tube material specimens conformed to the minimum thickness and final crack length requirements of this specification. The load versus COD curves for each fracture toughness specimen are appended herewith.

Results of the fracture toughness tests on the 6061 T6 aluminum tube and 4032 aluminum bar materials indicated that valid
plane strain fracture toughness (K_{IC}) values, as determined according to ASTM: E 399, could not be obtained from the size specimens tested herein. The average K_{max} values for the 6061 T6 and 4032 materials were measured to be 24.8 ksi\(\sqrt{\text{in}}\) (standard deviation equals \(\pm 1.0\)) and 15.7 ksi\(\sqrt{\text{in}}\) (standard deviation equals \(\pm 0.4\)), respectively. Since the scatter (standard deviation) in these results was considered to be small, the K_{max} values are considered meaningful for structural components whose thicknesses are comparable with the specimen sizes tested herein.

Respectfully submitted.

LUCIUS PITKIN, INC

Robert S. Vecchio, Ph.D.
Engineer

Approved: A. J. Vecchio, P.E.
Vice President

RSV/pm/2
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>6061 T 6 Tube Material (a)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A 1</td>
<td>0.476</td>
<td>0.135</td>
<td>0.225</td>
</tr>
<tr>
<td>A 2</td>
<td>0.477</td>
<td>0.130</td>
<td>0.265</td>
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<tr>
<td>A 3</td>
<td>0.468</td>
<td>0.132</td>
<td>0.238</td>
</tr>
<tr>
<td>A 4</td>
<td>0.478</td>
<td>0.139</td>
<td>0.224</td>
</tr>
<tr>
<td>4032 Bar Material (b)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B 1</td>
<td>1.248</td>
<td>0.651</td>
<td>0.750</td>
</tr>
<tr>
<td>B 2</td>
<td>1.235</td>
<td>0.625</td>
<td>0.700</td>
</tr>
<tr>
<td>B 3</td>
<td>1.241</td>
<td>0.630</td>
<td>0.690</td>
</tr>
<tr>
<td>B 4</td>
<td>1.239</td>
<td>0.624</td>
<td>0.680</td>
</tr>
</tbody>
</table>

Notes: (a) - Test Span, S = 2.6 in.  
(b) - Test Span, S = 5.0 in.
**TABLE II**

**FRACTURE TOUGHNESS TEST RESULTS**

**6061 T6 ALUMINUM ALLOY TUBE MATERIAL**

<table>
<thead>
<tr>
<th>Specimen Ident.</th>
<th>( P_Q, \text{lb} )</th>
<th>( P_{\text{max}}, \text{lb} )</th>
<th>( K_Q, \text{kSI/in.} )</th>
<th>( K_{\text{max}}, \text{kSI/in.} )</th>
<th>( K_{IC}, \text{kSI/in.} )</th>
<th>Specimen Strength Ratio ( R_{sb} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>140</td>
<td>175</td>
<td>20.0</td>
<td>24.9</td>
<td>Not valid</td>
<td>1.47</td>
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<tr>
<td>A2</td>
<td>86</td>
<td>122</td>
<td>16.4</td>
<td>23.2</td>
<td>Not valid</td>
<td>1.49</td>
</tr>
<tr>
<td>A3</td>
<td>110</td>
<td>148</td>
<td>18.6</td>
<td>25.0</td>
<td>Not valid</td>
<td>1.49</td>
</tr>
<tr>
<td>A4</td>
<td>140</td>
<td>176</td>
<td>20.6</td>
<td>26.0</td>
<td>Not valid</td>
<td>1.50</td>
</tr>
</tbody>
</table>

Note: (a) Fracture toughness and specimen strength ratio calculated per ASTM: E 399-83
TABLE III

FRACTURE TOUGHNESS TEST RESULTS

4032 ALUMINUM ALLOY ROD MATERIAL

<table>
<thead>
<tr>
<th>Specimen Ident.</th>
<th>$P_Q$, lb</th>
<th>$P_{max}$, lb</th>
<th>$K_Q$, ksi/in.</th>
<th>$K_{max}$, ksi/in.</th>
<th>$K_{IC}$, ksi/in.</th>
<th>Specimen Strength Ratio $R_{sb}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>650</td>
<td>780</td>
<td>13.6</td>
<td>16.4</td>
<td>Not valid</td>
<td>0.92</td>
</tr>
<tr>
<td>B2</td>
<td>680</td>
<td>830</td>
<td>12.7</td>
<td>15.5</td>
<td>Not valid</td>
<td>0.85</td>
</tr>
<tr>
<td>B3</td>
<td>600</td>
<td>830</td>
<td>11.0</td>
<td>15.2</td>
<td>Not valid</td>
<td>0.83</td>
</tr>
<tr>
<td>B4</td>
<td>710</td>
<td>865</td>
<td>13.0</td>
<td>15.8</td>
<td>Not valid</td>
<td>0.85</td>
</tr>
</tbody>
</table>

Note: (a) Fracture toughness and specimen strength ratio calculated per ASTM: E 399-83
Material: 6061 T6 AL  Specimen: A1

Load, lbs.

- Peak = 175 lbs.
- \( P_{	ext{max}} = 140 \text{ lbs.} \)

COD, in.
Material: 4032 AL

Specimen: 81

Load, lbs.

$P_{max} = 780 \text{ lb}$

$P_o = 690 \text{ lb}$
Material: 4032 AL
Specimen: 83

Load, lbs.

- 0 lb. to 1200 lb.
- 0.01 to 0.10 lb.
- 0.05 lb. increments

Graph showing load vs. material properties.
APPENDIX 2

MATERIALS TECHNOLOGY GROUP

HOT CELL HFBR CHARPY IMPACT MACHINING PROCEDURE

Written by: Tom Roberts
Approved by: M. H. Schuster
Approved by: C. J. Czajkowski

Revision 0

1. Position tube in vise with approx. 3" exposed.
2. Install 1/2" end mill with 3/8" shank.
3. Spray layout fluid on top and end of tube.
4. Position cross direction handwheel at .100, top center of tube. To verify correct number of revolutions, vise will align with bed indexing mark which is approx. 25/64" in from bed.
5. Raise end mill above tube. (ccw)
6. Position tube under end mill near end.
7. Turn milling machine on.
8. Slowly lower end mill until it touches tube 1 vertical dial.
9. Raise end mill 1 rev. to clear tube. (ccw)
10. Move tube to the right of end mill. (cw)
11. Lower end mill 7 revs. (6 revs. = .375 + 1 rev. to clear tube)
12. Move tube into cutter (ccw) to trim end of tube 2 longitudinal dial. (ccw)

Reposition cross dial .100 top center of tube.
13. Raise end mill (ccw) 7 revs.
14. Move tube to left (ccw) 2.25" sample length + .500" dia. of end mill + 2 longitudinal start = 3 revs + .500" + 2 = 3 revs. (ccw) + 3 longitudinal dial.
15. Install left stop.
16. Move tube (cw) to the right of the end mill.
17. Lower end mill 1 rev., top of tube.
18 Lower end mill approx. .010" at a time until lowered a total of .034".
19 Move tube to left stop (ccw).
20 Return tube to right of end mill. (cw)
21 Lower end mill approx. .010".
22 Move tube to left stop (ccw) cutting slowly.
23 Return tube to right of end mill.
24 Lower end mill \[ \frac{1}{4} + .034" = \frac{3}{4} \text{ vertical dial.} \]
25 Move tube to left stop (ccw) cutting slowly.
26 Return tube to right of end mill.
27 Move cross dial 4 revs. + .194 cross dial. Front sample width. (.394" + 2 = .197" + .250 (.500 + 2) = .447", 4 revs. = .400" + (.047" x 2).094\textsuperscript{D} + .100\textsuperscript{D} = .194\textsuperscript{D})
28 Note handwheel position on vertical dial at .____\textsuperscript{4}.
29 Lower end mill approx. .010" at a time and cut across sample length from left to right until at total of 3 revs. (cw) on vertical dial complete. Front split.
30 With tube on right side of end mill, raise end mill 3 revs. (ccw)
31 Move cross dial (ccw) 8 revs. + .004 cross dial. Back sample width. (.394" + .500" = .894", 8 revs. = .800" + .188\textsuperscript{D}(.094" x 2) - .194\textsuperscript{D}, .194\textsuperscript{D} - .188\textsuperscript{D} = .006\textsuperscript{D} - .002\textsuperscript{D}(.001" x 2 handwheel backlash) = .004\textsuperscript{D})
32 Repeat steps 28, 29, 30. Back split.
33 Raise end mill above tube. (ccw)
34 Move tube to the left (ccw) to rest at left stop.
35 Lock longitudinal direction.
36 Position tube under end mill, cross direction cw.
37 With milling machine on, lower end mill until cutting begins.
38 Turn cross dial ccw the dia. of tube.
39 Return end mill to front of tube.
40 Lower end mill approx. .010".
41 Turn cross dial ccw the dia. of tube.
42 Return end mill to front of tube.
43 Lower and cut until sample parted, holding sample with left tong when last cut made.
44 Unlock longitudinal direction + left stop.
45 Move vise to the right (cw) clear of end mill.
46 Unlock vise and rotate tube 90°
47 Repeat steps 1–46 for samples 2, 3, 4.
48 Remove tube from vise.
49 Deburr 4 samples with 320 silicon carbide polishing paper and wipe with kimwipe.
50 Spray I.D. of 4 sample with layout fluid.
51 Place sample #1 in sample holding section of vise jaws with trimmed end against stop and flat side down.
52 Raise end mill above sample.
53 Position sample under end mill. Top center of sample will be approx. 21/64" vise in from bed of milling machine.
54 Lower end mill until cutting begins.
55 Turn longitudinal dial ccw across sample length.
56 Return sample to the right of end mill.
57 Lower end mill approx. .010" at a time to the point of removing concave portion of sample. Vertical dial ___
58 With felt marker label sample left of center.
59 Remove sample from vise and measure with micrometer sample thickness at 3 locations, left, center, right. Note readings.
60 Place sample back in vise with label in proper positon.
61 Tighten vise.
62 With hammer and wooden ruler, gently tap sample to fully seat sample in vise.
63 Verify readings with digital indicator with those of micrometer to insure proper seating.
With felt marker cover top of sample.

With milling machine on, move sample under end mill the length of sample.

Return sample to the right of end mill.

Determine amount to lower vertical dial from lowest micrometer reading and required thickness \(0.118 \pm 0.001\).

Lower end mill and cut across sample length.

Return sample to right of end mill.

Lower end mill 4 revs.

Move sample to the left (longitudinal dial ccw) until cutting begins.

Move cross dial ccw the sample width.

Trim sample until end square longitudinal dial \(6\).

Position sample in front of end mill.

Measure sample length with digital caliper.

Determine amount to remove for required sample length \(2.165^{+0.00}.0.01\).

Remove sample from vise.

Measure and record data for sample thickness, width, length.

Repeat steps 51–78 for samples 2, 3, 4.

Deburr samples with 320 silicon carbide polishing paper.

Remove collet holder from milling machine and install 45° double angle cutter with holder.

Rotate head of milling machine 90° using scale on side.

Place sample #1 in vise and tighten.

Gently tap sample for proper seating.

Verify with digital indicator sample is seated.

Mark sample with felt marker in notch area.

Position vise so notch cutter is in notch of vise jaw. 0.390 ccw longitudinal dial.

Raise cutter above sample.
89 Position sample under cutter so vise is 21/64" in from bed of milling machine. Top center of sample.

90 Slowly lower cutter until scratch felt marker. Vertical dial _____

91 Determine amount to lower vertical dial for required notch depth of .024±.001".

92 Repeat steps 83–91 for sample 2, 3, 4.
1 Position vise at rightstop and verify longitudinal handwheel is at zero.
2 Install 3/8" long end mill.
3 Install tube in vise with approx. 4" exposed to cutter.
4 Position tube end near cutter.
5 Lower end mill until the full diameter of tube can be trimmed.
6 Trim end of tube square.
7 Move vise to the right, clear of cutter.
8 Install 1/4" drill.
9 Raise drill above tube.
10 Position cross direction handwheel at .100, top center of tube. To verify correct number of revolutions, vise will align with bed indexing mark. Also the vise will be approx. 25/64" in from bed of milling machine.
11 Position drill above tube in alignment with indexing pin.
12 Move vise to the right (cw) 3 revs. + .7125 longitudinal dial.
13 Lower drill the diameter of tube.
14 Loosen tube in vise and slide tube until resting on drill. Tighten.
15 Raise drill above tube.
16 Move vise to the left (ccw). .540 longitudinal dial. Hole #1.
17 Lock longitudinal direction.
18 Slowly drill hole.
19 Raise drill above tube.
Unlock vise and move to left (ccw) 2 revs. + .290 longitudinal dial. #2 pin hole.

Lock longitudinal direction.

Slowly drill hole.

Raise drill above tube.

Unlock vise, move to the right (cw) clear of cutter.

Install 3/8" end mill.

Position end mill on top of tube near #1 hole. _____ vertical dial.

Raise end mill 1 rev. to clear tube.

Position end mill at end of tube .650 cw .665 ccw longitudinal dial.

Move vise to the left (ccw) 1 rev. + .290 longitudinal dial. This is the left gage length start.

Install right stop on bed.

Move vise to the left (ccw) 1" = 1 rev. + .540 longitudinal dial. This is the right gage length stop.

Install left stop on bed.

Check handwheel numbers for left and right stops.

Adjust if necessary. Return to right stop.

Move vise back (cw) 5 revs. + .125 cross dial. This is the start of the gage width.

Count revs. into tube. Note handwheel position.

With vise against right stop, turn milling machine and vacuum cleaner on.

Lower end mill (cw) 5 revs. + ____ vertical dial.

Turn longitudinal dial (ccw) to the left stop.

Return to right stop.

Move tube into end mill (ccw) with cross dial approx. .025".

Turn longitudinal dial (ccw) to the left stop.

Return to the right stop.

Repeat steps 41-43 until 2 revs. (ccw) + .125 cross dial complete.
45  Raise end mill (ccw) 5 revs. + _____ vertical dial.
46  Return to top center of tube from gage width end on the front side. Turn cross dial (ccw) 3 revs. + .100.
47  Turn cross dial (ccw) 5 revs. + .075 to start gage width back side.
48  Note handwheel position, count revs.
49  With vise against left stop, turn milling machine, vacuum on.
50  Lower end mill (cw) 5 revs. + _____ vertical dial.
51  Turn longitudinal dial (cw) to the right stop.
52  Move tube into end mill (cw) with cross dial approx. .025".
53  Turn longitudinal dial (cw) to the right stop. Return to left stop.
54  Return to the left stop.
55  Repeat steps 52–54 until 2 revs. + .075 cross dial complete.
56  Raise end mill (ccw) 5 revs. + _____ vertical dial.
57  Return to top center of tube from gage width end on backside. Turn cross dial (cw) 3 revs. + .100 cross dial.
58  Remove stops.
59  Move vise to the right, clear of end mill.
60  Loosen vise and rotate tube aligning indexing pin.
61  Tighten vise.
62  Install 1/4" drill.
63  Raise drill above tube.
64  Position tube to the right of drill.
65  Move vise to left (ccw) .540 longitudinal dial. Hole #1.
66  Repeat steps 17–64 until 4 tensile gages machined.
67  Move vise to the right, clear of cutter.
68  Install 1/8" end mill.
69  Position tube end near end mill.
70 Raise end mill with vertical dial above tube.
71 Position end mill between tube end and first hole.
72 Lower end mill (cw) to rest on tube. vertical dial.
73 Raise end mill (ccw) 1 rev. to clear tube.
74 Position tube to the right of end mill (cw) .025 longitudinal dial.
75 Front split position, turn cross dial (cw) 3 revs. + .075.
76 Move vise to the left (ccw) 4 revs. + .025 longitudinal dial.
77 Install left stop, sample length.
78 Move vise to the right and back to left stop to verify longitudinal dial stop.
79 Adjust if necessary.
80 Move tube to the right of end mill.
81 A total of 6 revs. vertical dial.
82 Note vertical handwheel position, count revs.
83 Lower end mill (cw) vertical dial until a light cut is made.
84 Move vise from right to left stop.
85 Return tube end to right of end mill.
86 Lower and cut until 6 rev. + vertical dial or sample complete.
87 Raise end mill 6 revs. +.
88 Move tube forward (ccw) 3 rev. + .100 cross dial. Top center of tube.
89 Back split position, turn cross dial (cww) 3 revs. + .125.
90 Repeat steps 81-87.
91 Lock longitudinal direction against left stop.
92 Position tube under end mill. Turn cross dial (cw) 3 revs. + .100.
93 Note vertical handwheel position. Count revs. 6 needed.
94 Lower end mill until a light cut is made.
95 Turn cross dial (ccw) the diameter of tube.
96 Return end mill to front of tube.
97 Lower end mill and cut with cross dial until 6 revs. + ___ of vertical dial complete.
98 Hold sample when last cut is made.
99 Raise end mill above tube (ccw) 6 revs.
100 Unlock vise and rotate tube aligning indexing pin.
101 Tighten vise.
102 Repeat step 10 for top center of tube.
103 Move tube to the right of end mill.
104 Repeat steps 74–87 for samples 2, 3, 4.
105 Repeat steps 91–99 for sample #2.
106 Repeat steps 100–105 for sample #3.
107 Unlock vise and rotate tube.
108 Tighten vise.
109 Position end mill along side of tube from previous sample length cuts.
110 Raise end mill above tube.
111 Position tube under end mill.
112 Repeat steps 94–98 for sample #4.
REFERENCE

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<tr>
<th>Longitudinal Dial</th>
<th>Cross Dial</th>
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<tr>
<td>Left Right</td>
<td>Forward Back</td>
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<td>.750&quot; = 1 rev.</td>
<td>.100&quot; = 1 rev.</td>
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<td>1 div. = .010&quot;</td>
<td>1 rev. = 200 divisions</td>
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<td>ccw handwheel moves sample left</td>
<td>ccw handwheel moves sample forward</td>
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<tr>
<td>#’s increase</td>
<td>#’s decrease</td>
</tr>
<tr>
<td>cw handwheel moves sample right</td>
<td>cw handwheel moves sample back</td>
</tr>
<tr>
<td>#’s decrease</td>
<td>#’s increase</td>
</tr>
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<td>&quot; reading &lt; .100 x 2 = dial number</td>
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</table>

<table>
<thead>
<tr>
<th>Vertical Dial</th>
<th>Indexing Pin</th>
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<tr>
<td>Up — Down</td>
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<td>.0625 = 1 rev.</td>
<td>Longitudinal dial ccw .290</td>
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<td>1 div. = .0005&quot;</td>
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<td>cw handwheel cutter moves down</td>
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<td>CW handwheel cutter moves up</td>
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<tr>
<td>#’s decrease</td>
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<td></td>
<td>CW handwheel moves up</td>
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</table>
CALCULATION

Step 12 2.000" + .4375" + .125" (.250 + 2) - .275D (dial cw), 3 revs. = 2.25" + (.3125" - .275D = .0375D) (.750D - .0375D = .7125D), 3 revs. + .7125D cw .7275D ccw longitudinal dial.


Step 28 .7125D cw (1/4 drill) - .0625" (difference 1/4 drill + 3/8 end mill) = .650D cw .665D ccw longitudinal dial.


Step 31 Move ccw 1", 1 rev. = .750 + .250 + .290 dial, 1 rev. + .250 + .290 = 1 rev. + .540 ccw longitudinal dial.

Step 35 Move cross dial cw .325" (.650 + 2) + .1875" (3/8 + 2) + .100 dial = .5125" + .100 dial = 5 revs. (.100 x 5) + .025D (.0125" x 2) + .100 dial = 5 revs. + .125 cw cross dial.

Step 38 1 rev. to touch tube, 4 revs. = .250".

Step 44 Move a total .200" ccw = 2 revs. + .125 dial gage width stop position cross direction front side.

Step 45 4 revs. position top of tube, 1 rev. to clear tube.

Step 46 .125" (1/2 gage width) + .1875" (1/2 end mill) = .3125", 3 revs. = .300" + .025D (.0125" x 2), .125D (present positon) - .025D (final position) = .100, 3 revs. + .100 ccw cross dial.

Step 47 Move ccw cross dial .325" (.650 + 2) + .1875" (3/8 + 2) + .100 dial = .5125" + .100 dial = 5 revs. (.100 x 5) + .025 (.0125 x 2) + .100 dial = .100D - .025D = .075 + 5 revs. ccw cross dial.
Step 50  Same as step 38.

Step 55  Cross dial start position \(0.075^D\), move cw cross dial a total \(0.200'' = 2\) revs. + \(0.075\) cross dial gage width stop position, backside.

Step 56  Same as step 45.

Step 57  \(0.125'' (1/2'' gage width) + 0.1875'' (1/2 end mill) + 0.075\) dial = \(0.3125'' + 0.075\) dial, 3 revs. = \(0.300 + 0.025^D (0.0125'' \times 2) + 0.075^D\), 3 revs. + \(0.075 + 0.025 = 0.100\), 3 revs. + \(0.100 \text{cw cross dial, top center of tube.}\)

Step 65  Same as step 16.

Step 74  \(0.7125^D\) (position with \(1/4''\) drill) + \(0.0625''\) (difference \(1/4''\) drill + \(1/8''\) end mill) = \(0.7750 - 0.750 = 0.025\) cw longitudinal dial.

Step 75  \(0.325'' (0.650 + 2) + 0.0625'' (0.125 + 2) - 0.100^D = 0.3875'' - 0.100\) dial = 3 revs. + \(0.175^D (0.0875'' \times 2) - 0.100\) dial = \(0.175^D - 0.100^D = 0.075^D\) 3 revs. + \(0.075\) cw cross dial.

Step 76  4 revs. = \(3.000'' (2.875'' \text{ sample length} + 0.125''\) dia. of end mill).

Step 81  1 rev. to touch tube, 5 revs. = \(0.3125'' (0.3125'' + 0.3125'' + 0.650'' = 1.275'').\)

Step 88  \(0.325'' (0.650 + 2) + 0.0625'' (0.125 + 2) = 0.3875'' - 0.075\) cross dial, \(0.3875'' = 3\) revs. + \(0.175^D (0.0875'' \times 2) - 0.075^D = 3\) revs. ccw + \(0.100\) cross dial.

Step 89  \(0.325'' (0.650'' + 2) + 0.0625'' (0.125'' + 2) = 0.3875'' + 0.100\) dial, 3 revs. = \(0.300 + 0.175^D (0.0875'' \times 2) + 0.100\) dial, \(0.100^D - 0.175^D = 0.075^D\), \(0.200^D - 0.075^D = 0.125\) cross dial + 3 revs. ccw.

Step 92  \(0.325'' (0.650'' + 2) + 0.0625'' (0.125'' + 2) = 0.3875'' + 0.125\) dial, 3 revs. = \(0.300 + 0.175^D (0.0875'' \times 2) + 0.125^D, 0.200^D (\text{max cross dial}) - 0.175^D = 0.025^D, 0.125^D - 0.025^D = 0.100 + 3\) revs. cw cross dial.
MTS TENSILE TEST PROCEDURE

PROCEDURE:

1. Check that no sample is in the grips

2. Zero the output of the load channel (XDCR #2 ZERO adjust)

3. Zero the Y-channel of the X.Y. plotter

4. Turn on the water

5. Start the pump

6. Use the SET POINT (406 controller) to move the actuator in order to install the test sample

7. When the test sample is installed in the grips engage the pen of the X.Y. recorder

8. Push the START pushbutton on the Model 410 Function Generator

9. When the sample breaks, push HOLD on the Model 410 Function Generator

10. Remove the test sample

11. Push RETURN TO ZERO on the 410 Function Generator

12. Push the HOLD button on the Function Generator to take the unit out of HOLD
1. APPARATUS

1.1 General Requirements - (As Per Method E-23)

1.1.1 (E-23: Section 4.1.2)

The impact tester was levelled to within 3:1000 as specified in the Standard. However, this was achieved with the use of minor shimming. Figure 1 describes the dimensions and results concerning the use of these shims. In addition, level measurements had to be performed using the anvil/supports (two directions) because the machined surface used to establish levelness had a high-spot (corrosion) on the middle of the block which made level determination difficult. The impact tester is firmly secured to a steel-constructed table.

1.1.2 (E-23: Section 4.1.3)

The scale is graduated in energy units with these scale markings for the lowest energy readings accurate only to 1% of the full range of the scale, i.e., 0.25/25 in-lbf x 100 = 1%. Increments can be estimated to one-half unit if necessary, thus enabling one to read to 0.5% of full scale. The specification requires readings to be made to within 0.25%, but this is for ft-lbf measurements.

Figure 1 Shims used to level the support/anvils (Left Support Only).

Top View of Shim (not actual size)

![Shim Diagram]

One shim had the above dimensions and a thickness of 0.001 in. A second shim placed to the far left and on top of the above shim measured ~25mm in length and is 0.002 in. thick.

Result: Support/anvils are level in both directions to ~0.001 in. (Level used was a L.S. Starrett Co. No. 199 Master Precision Level with 1 division = 0.0005 in./1 foot).
Section 3.1.4.2 of this report describes the results achieved following E-23: Section 5.27. The standard requires that the error in the scale reading not exceed 0.2% of the range or 0.4% of the reading whichever is larger. Table 4 shows the values achieved and although many are close and others fall within the specification, others do not. It should be noted that these are very difficult values to ascertain because of three critical variables, the calculated initial potential energy, an accurate height measurement of one free swing and the friction loss value. If just one of these variables is not close to the expected value, all subsequent calculations are affected. For example, the expected initial potential energy for the 25 in-lbf scale of course should be 25 in-lbf, however, it was measured and calculated to be 24.75 in-lbf. Although this value if reasonable (within 1% of the expected value), the impact on subsequent calculations could be considerable.

1.1.3 Friction Losses (E-23: Section 4.1.4)

This particular measurement was performed on each impact scale range (25, 50, 100 and 200 in-lbf). Friction losses were discussed in Section 3.1.3 of this report. The standard requires that these losses not exceed 0.75% of the scale capacity. The results indicate that total friction and windage losses for the 25 in-lbf scale slightly exceeded this requirement (0.93%). Each of the other scale ranges 50 (0.48%) and the 100 and 200 (0) fall within the acceptable range. Note that no energy loss from friction in the indicating mechanism could be measured (see Section 3.1.3) or for that matter distinguishable from pendulum friction losses (the Standard requires that friction losses in the indicating mechanism shall not exceed 0.25% of the scale range capacity).

1.1.4 Center of Strike and Percussion (E-23: Section 4.1.5)

There is a 1.1% difference (see Section 3.1.2.6 of this report) between the measured center of percussion compared to the center of strike as described in this section of the standard (the Standard requires this relationship to be within 1%). It should be noted that a blueprint of this particular impact machine (Model 66, Charpy/Izod Impact Machine for Plastics) shows that the center of percussion is 16.0 inches in which case there is essentially no error. Also note, this center of percussion measurement was performed only on the 25 in-lbf impact scale range.

The striking edge of the free hanging pendulum falls well within the 2.5 mm (0.10 in) limit of the position where it would just touch the test specimen. It would appear, based on the results of Sections 2.1.2.1 and 2.1.2 of this report, that the plane of the swing of the pendulum is perpendicular to the transverse axis of the Charpy anvils.

1.1.5 (E-23: Section 4.1.6)

The transverse play of the pendulum cannot be measured by this standard since the impact machine is equipped with a much thinner pendulum shaft than the one sited in E-23 (the impact tester was constructed to meet Method D-256 and as such, if necessary, the pendulum arm could be measured for transverse play via these requirements). The impact velocity falls within the range of the Standard which requires a velocity between 3-6 m/s (10-20 ft/s). Section 3.1.2.5 of this report calculates the impact velocity to be ~3.45 m/s.
1.1.6 (E-23: Section 4.1.7)

The Method states that:

"Before release, the height of the center of strike above its free hanging position shall be within 0.4% of the range capacity divided by the pendulum weight."

An example of the calculation is shown below:

The height of the pendulum before release equals - 24.0 in.
The scale range capacity - 25 in-lbf
The pendulum weight - 467.8 g

Calculation: 24.00 in. should be within 0.4% of \(\frac{25 \text{ in-lbf}}{467.8 \text{ g} \times \frac{1 \text{ lb}}{453.59 \text{ g}}} = 24.24\text{ in.}\);

\[
\frac{24.24\text{ in.} - 24.00\text{ in.}}{24.00\text{ in.}} \times 100 = 1.0\%
\]

Note that 0.4% of 24.00 in. equals 0.096 in.; theoretically the calculated value could not exceed 24.10 in. (24.00 in. + 0.096 in.). All other values are shown in Table 1 and except for the 25 in-lbf scale range (1% error) all were within the Standard requirement.

<table>
<thead>
<tr>
<th>Scale (in-lbf)</th>
<th>Pendulum Weight (g)</th>
<th>Calculated Value (in.)</th>
<th>Percent Difference from 24 in.</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>467.8</td>
<td>24.24</td>
<td>1.0</td>
</tr>
<tr>
<td>50</td>
<td>945</td>
<td>24.04</td>
<td>0.2</td>
</tr>
<tr>
<td>100</td>
<td>1890</td>
<td>23.98</td>
<td>0.1</td>
</tr>
<tr>
<td>200</td>
<td>3796</td>
<td>23.90</td>
<td>0.4</td>
</tr>
</tbody>
</table>
2. CHARPY APPARATUS

2.1 (E-23: Sections 4.3.1 and 4.3.3)

Centering of both the notched sample specimen and striker edge to specification tolerances was performed simultaneously. Self-centering tongs were used to verify the mid-point between the anvils (E-23: Section 4.3.1) by simultaneously holding a V-notched specimen in the appropriate position and gluing angular support edges (which will center specimens) to the right angle support blocks. Next the striker edge was brought in contact with a specimen and two lines were scribed down the sides of the striker edges onto the metal specimen. By measuring these lines with a dial caliper and subtracting the results from half the length of the sample enabled specification verification (see below for method description). The standard (E-23: Section 4.3.3) requires the striking edge to be within 0.40 mm (0.016 in.) of the midpoint of the specimen sample.

![Scribe lines](image)

Scribe line length measurements: left side - 25.25 mm; right side 25.35 mm, subtracting each value from 27.50 mm (1/2 full length) results in values of 2.25 mm and 2.15 mm, respectively. This places the strike within 0.1 mm (0.0039 in.) of the center of the sample and well within the specification.

2.1.1 (E-23: Section 4.3.3)

With a specimen held against the anvil the striking edge was observed to be parallel within 1:1000 using a piece of shim stock of identical thickness. It was difficult to measure whether the striking edge is perpendicular to the longitudinal axis of the specimen to 5:1000. Consequently, a method described in Method D-256, Sections XI.8 and XI.9 which uses a thin film of oil on the striker edge and then requires gently contact with the specimen was used. The expected and uniform contact across the surface of the specimen sample was observed.

2.1.2 (E-23: Section 4.3.4)

Using shim stock and a small machinists square, the specimen supports were measured and square with the anvil faces to within 2.5:1000. A parallel bar and shim stock was used to verify that the specimen supports were coplanar within 0.125 mm (0.005 in.) and parallel within 2:1000 (E-23: Section 4.3.4). All specifications were acceptable in the area of interest and although larger disparities occur towards the very end of the supports, these areas also fell within the standard requirements.
3. **INSPECTION (E-23: Sections 5.1 - 5.2.2)**

3.1 **Critical Parts (E-23: Section 5.1.1)**

3.1.1 The standard requires that the bolts associated with the removal parts of the impact tester are to be refastened according to the manufacturers specifications. The parts of concern and the bolt tightening specifications are as follows:

- **Striking Bit** - 35 in. lbs.
- **Circular calibration weights** - 170 in. lbs.
- **Charpy impact specimen anvil and supports** - 300 in. lbs.

3.1.2 **Pendulum Striking Edge** (Compliance with E-23: Sections 5.1.2 and 4.3.3 [for Charpy tests]).

3.1.3 **Potential Energy Determination (E-23: Sections 5.2.3 and 5.2.3.1)**

3.1.3.1 A subsize specimen was used to perform these measurements rather than the half-width specimen (10 by 5 mm) specified in the standard. In addition, the tight working space beneath the U-shaped pendulum made scribing a line on the striker edge not only difficult, but the correct positioning of this scribed mark questionable. Therefore, the method used to find the center of the strike on the striking edge was simply the use of a half-height specimen (subsize). Scribing a line on a piece of tape attached to the striker edge would then be at the center of the strike. Measuring from this scribe mark to each end of the tup gave the following values 19/64 in. and 21/64 in. which equals 5/8 in. (the length of the striking edge).

3.1.3.2 **Center of Strike** (E-23: Section 5.2.3.1)

The height of pendulum arm from the center of axis rotation to the top edge of a half-height specimen is considered the center of strike.

The following measurements were performed to obtain the center of strike:

- **axis of rotation shaft** - measured with micrometer was 0.500 inches (32/64 in.) 1/2 this value gives 0.250 inches (16/64 in.) which represents the center of the shaft.

- From below the shaft to the top edge of 1/2 in. piece of metal stock was measured in the following manner; using a machinists ruler fastened to a carpenters square and situated on a levelled metal flat stock a small machinists square was placed on the top portion of the carpenters square to form the perpendicular necessary to measure the bottom of the pendulum shaft. The value was 15 26/64 in.
the last measurement taken was from the top edge of a half-height specimen (represents center of strike) to the top surface of the flat stock. Using a machinists ruler to measure and the small square to form the perpendicular a value of 20/64 in. was obtained.

adding the three measurements gives the following pendulum arm length:

\[
16/64 + 20/64 + 15 26/64 = 15 62/64 \text{ in. or } 15.969 \text{ in. and therefore is assumed to be 16 inches.}
\]

3.1.3.3 Pendulum weight measurements (E-23: Section 5.2.3.3)

A sturdy apparatus was constructed to support and level a top loader balance (Sartorius - 5 kg capacity). The entire procedure sited in ASTM Standard E-23, Section 5.2.3.3 was followed except no support was used at the center of rotation since erroneous measurements were being produced. Pendulum weight measurements were performed at each of the four scale range weight capacities. The values are shown in Table 2.

3.1.3.4 Measuring the Height of the Pendulum Drop (E-23: Section 5.2.3.4)
(See Section 1.1.6 of this report for additional insight)

Since our impact test will be performed using subsize specimens (55 mm x 10 mm x 3 mm), no half-width (55 mm x 25 mm x 12.5 mm) or full-sized (55 mm x 25 mm x 25 mm) specimens were used as described by the E-23 Standard.

The height of the center of strike in the elevated position to the top edge of a half-height specimen was measured as follows:

- a piece of 1/2 in. metal stock had one end placed on the specimen support and the other end on a small screw-jack which was levelled in two directions.

- with the pendulum in the elevated and locked position of the release mechanism, a carpenters square with a machinists ruler held tightly against it was used to create a vertical plane. A perpendicular plane was formed on this vertical by using a small machinists square which was then positioned on the center of the striker. A measurement of 23 42/64 in. was recorded.

- the distance between the top-edge of a half-height specimen to the top of the 1/2 in. metal stock was measured using a machinists ruler and square giving a 20/64 in. value.

- the addition of the two measurements (23 42/64 + 20/64) equals 23 62/64 (23.969) inches. Since this measurement is so close to 24 in., it is assumed that this is the actual height value and thus, was used in all calculations.
3.1.3.5 The potential energy of the system is determined in the following manner (E-23: Section 5.2.3.5) using the 25 in-lbf scale.

Formula: Height from which pendulum falls x weight of pendulum = Initial Potential Energy.

Example Calculation: (based on 25 in-lbf scale)

\[ 24 \text{ in.} \times 467.8\text{g} \times \frac{1\text{ lb}}{453.59\text{g}} = 24.75 \text{ in-lbf}. \]

Since the scale capacity is 25 in-lbf and the calculated result is 24.75 in-lbf, the difference can be attributed to only two possible factors; insufficient pendulum weight or frictional losses. Table 2 shows the calculated results for the other three capacity scale ranges.

<table>
<thead>
<tr>
<th>Scale Capacity (in-lbf)</th>
<th>Pendulum Arm Weight (g)</th>
<th>Calculated Potential Energy (in-lbf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>467.8</td>
<td>24.75 (% difference - 1%)</td>
</tr>
<tr>
<td>50</td>
<td>945.2</td>
<td>50</td>
</tr>
<tr>
<td>100</td>
<td>1890</td>
<td>100</td>
</tr>
<tr>
<td>200</td>
<td>3797</td>
<td>200.9 (% difference - 0.5%)</td>
</tr>
</tbody>
</table>

3.1.3.6 Impact Velocity (v) Determination - Neglecting Friction (E-23: Section 5.2.4)

Equation: \( v = \sqrt{2gh} \)

where:

\( v = \) velocity, m/s (or ft/s)  
\( g = \) acceleration of gravity, m/s\(^2\) (or ft/s\(^2\)) = 9.80 m/s\(^2\)  
\( h = \) initial elevation of the striking edge m (or ft)
Conversion of elevated striker edge to meters:

\[ 24.00 \text{ in.} \times \frac{1 \text{ m}}{39.37 \text{ in.}} = 0.61 \text{ m} \]

\[ v = \sqrt{2 (9.8 \text{ m/s}^2) (0.61 \text{ m})} = 11.95 \text{ m/s} \]

\[ = 3.46 \text{ m/s or } 3.46 \text{ m/s} \times \frac{3.281 \text{ ft}}{\text{m}} = 11.35 \text{ ft/s} \]

Note, according to ASTM Standard D-256, the vertical height of fall of the striking edge should be 610 mm ± 2 mm (24.0 ± 0.1 in.). Since the measurement difference (24.00 in. - 23.97 in. (actual) = 0.03 in.) is less than ± 0.1 in. the impact machine fell well within the acceptable range. The calculated result produces a velocity at the moment of impact of 3.46 m (11.35 ft)/s.

The Standard (E-23: Section 4.1.6) states that the impact velocity at the center of strike shall not be less than 3 nor more than 6 m/s (not less than 10 nor more than 20 ft/s). This impact tester meets this requirement.

3.1.3.7 Center of Percussion (determined as per instruction in E-23: Sections 5.2.5, 5.2.5.1, and 5.2.5.2.

(E-23: Section 5.2.5.1) One hundred (100) complete cycles (to and fro) of a swinging pendulum through a total angle not greater than 15° was measured with a stop watch. Four determinations were recorded and the mean value was used to perform the calculation. This procedure was followed only on the 25 in-lbf scale.

<table>
<thead>
<tr>
<th>Determinations</th>
<th>Time of 100 Complete Cycles(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>128</td>
</tr>
<tr>
<td>2</td>
<td>125</td>
</tr>
<tr>
<td>3</td>
<td>126</td>
</tr>
<tr>
<td>4</td>
<td>127.6</td>
</tr>
</tbody>
</table>

\[ \bar{\text{X}} = 126.65 \pm 1.4 \text{ seconds} \]

(E-23: Section 5.2.5.2) The center of percussion is calculated by the following equation:

\[ I = 0.2484 \text{ p}^2, \text{ to determine } I \text{ in meters} \]

\[ I = 0.821 \text{ p}^2, \text{ to determine } I \text{ in feet.} \]
where:

\[ \ell = \text{distance from the axis to the center of percussion, m (or ft)}, \]

\[ p = \text{time of a complete cycle (to and fro) of the pendulum, s}. \]

One (1) complete cycle of the pendulum equals:

\[
\frac{126.65 \text{ sec.}}{100 \text{ complete cycles}} = 1.2665 \text{ s} = 1.267 \text{ s}
\]

Length Feet = \[\ell = 0.821 \ p^2\]
\[= 0.821 \ (1.267)^2\]
\[= 1.318 \text{ ft. (15.82 in.) = center of percussion}\]

The standard states (E-23: Section 4.1.5) that "the center of percussion shall be at a point within 1% of the distance from the axis of rotation to the center of strike in the specimen."

Calculation:

Center of percussion - 15.82 in.
Center of strike - 16.00 in. (actual measurement - 15.97 in.)

\[
\frac{16.00 \text{ in.} - 15.82 \text{ in.}}{16.00 \text{ in.}} \times 100 = 1.13\%
\]

Notice that the slightest variation in the time (secs.) variable when measuring the 100 complete cycles (and therefore the average of one complete cycle) can have considerable effect on the results when comparing the center of percussion and strike. It appears, however, that this requirement is within the tolerances of the Standard specifications.

3.1.4 Friction

3.1.4.1 Determining Energy Losses due to Friction (E-23: Sections 5.2.6 and 5.2.6.1)

Frictional losses were tested at each of the four energy range capacities available - 25, 50, 100 and 200 in-lbf. If frictional losses have been corrected by the manufacturer, all values should indicate zero. The results of releasing the pendulum for one free swing from its starting position are shown in Table 3.
The vertical distance between the raised pendulum and the center of strike to the top of a half-height specimen positioned on the anvil/supports was measured. (Note: no half-width specimen was used as per Standard requirement). Pendulum height after one free swing was measured for each scale range. Results are indicated on Table 3.

Following the vertical height of one free swing measurement, each scale range was multiplied by its pendulum weight. The Initial Potential Energy (IPE) minus this value (see Table 2) gives the total energy loss in the pendulum and indicator combined. An example calculation using the 25 in-lbf scale is as follows:

\[
23.77 \text{ in.} \times 467.8g \times \frac{1 \text{ lb.}}{453.59g} = 24.52 \text{ in-lbf}
\]

IPE = 24.75 in-lbf

\[
24.75 \text{ in-lbf} - 24.52 \text{ in-lbf} =
\]

Energy Loss Due to Friction = 0.23 in-lbf.

\[
\text{Percent Frictional Losses: } \frac{0.23 \text{ in-lbf}}{24.75 \text{ in-lbf}} \times 100 = 0.93\%
\]

All calculated frictional losses for each scale capacity are given in Table 3.

Another test used to isolate frictional losses due solely to the pendulum or indicator mechanism was performed. The procedure includes not resetting the pointer and repeatedly releasing the pendulum and observing for further pointer movement. No further pointer movement was observed (Note: only the 25 in-lbf scale was tested). Apparently, it is not possible to distinguish between frictional losses due to the pendulum and the indicator alone based on the subsequent steps enumerated in Section 5.2.6.1 of E-23. Since the Standard imposes a 0.7554 upper limit on the total friction and windage losses of the scale range capacity, the 25 in-lbf capacity appears to be the only scale range that does not fall within that requirement (0.93%). However, this scale range value does not exceed the standard specification significantly.

3.1.4.2 Indicating Mechanism (E-23: Section 5.2.7)

A check was performed to verify that the scale is reasonably linear (recording accurately) over the entire range. Graduation marks corresponding to 0, 20, 40, 60 and 80% of each range were tested. (Note: it has already been established by the free swing test method that both the 25 and 50 in-lbf scales do not result in a reading of zero.) Pendulum height measurements were performed at each of the stated scale increments as per the directions in E-23: Section 5.2.7. The method states that the pendulum height should be multiplied by its weight and if necessary corrected for friction and windage losses and then subtracted from the potential energy determinations as calculated in Section 3.1.3.5 of this report.
Table 3
Pendulum Free Swing Values and Their Respective Height Measurements and Frictional Losses as Measured by the Indicating Mechanism

<table>
<thead>
<tr>
<th>Scale Capacity (in-lbf)</th>
<th>One Free Swing Frictional Energy Values (in-lbf)</th>
<th>Pendulum Vertical Height Following One Free Swing (inches)</th>
<th>Total Calculated Energy Loss in Pendulum and Indicator Combined (in-lbf)</th>
<th>Percent Frictional Losses</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>0.19 to 0.25</td>
<td>23.77</td>
<td>0.23</td>
<td>0.93</td>
</tr>
<tr>
<td>50</td>
<td>0.167(^a)</td>
<td>23.88</td>
<td>0.24</td>
<td>0.48</td>
</tr>
<tr>
<td>100</td>
<td>0</td>
<td>24.00</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>200</td>
<td>0</td>
<td>24.00</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

\(^a\)One division on this scale equals 0.50 in-lbf and the one free swing was measured to read one-third of a division. This equals \(\approx 0.167\) in-lbf.

Table 4 shows the calculated results obtained for each scale range. Where applicable, values were derived for both friction and no friction losses. A variety of results are obtained (some within the limits, some close and others excessive) and depending how you interpret the results, they can be poor to acceptable (Note: the largest errors are associated with the 0 scale reading). Section 1.1.2 of this report gives an explanation for this conclusion. A sample calculation is performed using measurements obtained for the 25 in-lbf scale.

Indicating Mechanism Linearity Example Calculation (as described in E-23: Section 5.2.7)

Using the 25 in-lbf scale at 20% scale range capacity should give a calculated value of 5 in-lbf.

Pendulum:

- height - measured 19.20 in. when pointer on the indicator mechanism was at 5 in-lbf.
- weight - 467.8g
No Friction Loss Applied:

Initial Potential Energy (IPE) = 24.75 in-lbf (should be 25 in-lbf)

Calculations:

\[
19.20 \text{ in.} \times 467.8 \text{g} \times \frac{1 \text{ lb}}{453.59 \text{g}} = 19.80 \text{ in-lbf}
\]

and

\[
24.75 \text{ in-lbf} - 19.80 \text{ in-lbf} = 4.95 \text{ in-lbf};
\]

\[4.95 \text{ in-lbf} \neq 5.00 \text{ in-lbf}\]

Percent Difference:

\[
\frac{5.0 \text{ in-lbf} - 4.95 \text{ in-lbf}}{5.0 \text{ in-lbf}} \times 100 = 1\%
\]

Friction Loss Applied:

(Friction Loss as calculated in Section 3.1.4.1 of this report equals 0.23 in-lbf)

IPE = 24.75 in-lbf

Calculations:

\[
19.80 \text{ in-lbf} + 0.23 \text{ in-lbf} = 20.03 \text{ in-lbf}
\]

and

\[
24.75 \text{ in-lbf} - 20.03 \text{ in-lbf} = 4.72 \text{ in-lbf};
\]

\[4.72 \text{ in-lbf} \neq 5.00 \text{ in-lbf}\]

Percent Difference:

\[
\frac{5.0 \text{ in-lbf} - 4.72 \text{ in-lbf}}{5.0 \text{ in-lbf}} \times 100 = 5.6\%
\]
Table 4
Indicating Mechanism

<table>
<thead>
<tr>
<th>Percent of each Scale Range</th>
<th>Percent Difference From Actual Scale Readings</th>
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<tbody>
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<td>20°C</td>
<td>1.0</td>
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<td>40°C</td>
<td>0.3</td>
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</tr>
<tr>
<td>80°C</td>
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</table>

*a* No Friction Loss Applied (No-FLA)
*b* Friction Loss Applied (FLA)
*c* Example calculation

3.1.5 Impact Specimen Heating

In addition, to calibrating the impact tester using ASTM Method E-23, two other determinations were necessary that were not considered in the Standard. This included being capable of impact testing samples at an elevated temperature of 210°F and ensuring that the front, back and sides of the specimens were being heated homogeneously, especially in the area of interest (~1/2 in. either side of the notch).

In order to ensure the specimen would be consistently impacted at 210°F, the sample had to initially be heated to 215°F. This temperature was chosen primarily by initial testing that showed rapid heat loss following the removal of the aluminum insulating box surrounding the impact specimen, as well as, the time it takes to trigger the pendulum release mechanism. A fixed thermocouple in contact with the impact sample and a stop watch enabled an accurate temperature measurement to be performed following the removal of the insulating box cover. It was determined that it took ~3.5 seconds for the specimen temperature to decrease from 215 to 210°F. Table 5 shows the 25 separate determinations and their average value.

The noticeable decrease of time with each successive determination can be attributed to the impact base/anvil/support heat loss. With each subsequent test, the stored heat energy in the base was slowly losing its retention ability every time the insulating box was removed. This was occurring even though the impact sample was accurately being measured for its decrease in temperature from 215 to 210°F.
To ensure impact sample heating, homogeneity testing was performed by positioning two thermocouple wires; one in front and the second in the back of a specimen (the sides of the specimen were also measured in a similar manner). The heat sources were turned on and the temperature monitored. The results show that wire heating tape/heat gun heating is an acceptable means for raising the temperature of these particular impact specimens. The temperature gradient on either side of the sample was measured to be $215 \pm 2^\circ F$. Side measurements in the area of interest, 1/2 inch on either side of the notched specimen indicated similar results although the temperature at the extreme ends of the specimen were as much as 5°F lower than temperatures recorded at the center.

Further information concerning impact specimen heating can be obtained from the "Hot Cell HFBR Heating and Impact Testing Procedure" which was written specifically for these impact tests.

Table 5
Impact Specimen Heat Loss Determinations

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<th>Determination No.</th>
<th>Time (seconds)</th>
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<tr>
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$x \ 3.41 \pm 0.26$
## APPENDIX 5

### TRANSUDER CONDITIONER CALIBRATION CERTIFICATE

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### CUSTOMER: BROOKHAVEN NATIONAL LABS

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### CUSTOMER: MTS SYSTEMS CORPORATION

14000 TECHNOLOGY DRIVE
EDEN PRAIRIE, MN 55334

### MTS MEASUREMENT STANDARDS APE TRACI

PERFORMED BY: [Signature]

DATE: 2/17/89

HE NATIONAL BUREAU OF STANDARDS

FORM NO.: MTS033-11
## Transducer Calibration Certificate

**Customer:** Brookhaven Natl. Labs  
**Transducer Type:** LVDT  
**System No.:** 976.20-53  
**Conditioner Model:** 405.11  
**DVM I.D. No.:** 11448  
**Indicator Unit I.D. No.:** 544  
**Standardizer I.D. No.:** 4577

### Calibration Details

- **DVM Type**: 458AC
- **Lab Temp.:** 65°F

### Module Output and Errors

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<th>Module Output</th>
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### Notes

- **Date:** 2/6/89
- **Performer:** [Signature]

**MTS Measurement Standards are Traceable**

**National Bureau of Standards**
Your check for charpy impact specimens has been received. One (s) of the questionnaire and wrapping instructions are enclosed with this letter. One set (s) of 10 specimens (5 each of the LL12 low energy and 5 each of the MM9 high energy series specimens).

Prior to testing, your machine should be checked to assure compliance with Sections 4 and 5 of ASTM Standard E-23. Specimens are to be tested at -40°F in accordance with the testing procedures outlined by ASTM (Sections 11.2.1 and 11.2.3.1 of E-23). An accurate machine will produce values within 1.0 ft-lb or 5.0% (of the nominal values), whichever is greater. The nominal values for the above specimen series are (1) LL12 - series - 11.6 ft-lb and (2) MM9 - series - 71.1 ft-lb.

Because the cause or causes of erroneous values at one energy level may not be the cause at the other level, calibration or correction curves should not be used.

This Laboratory will, if requested, evaluate the results of your tests and return a report of the findings to your facility. If your machine produces values outside the nominal values, this report will suggest changes in machine design, repair or replacement of machine parts, a change in testing techniques, etc. Facilities desirous of the evaluation must return the broken specimens and completed questions to the Director, Materials Technology Laboratory, ATTN: SLO-MRM-MTG Watertown, MA 02172-0001. Shipping charges (Airline service or shipping changes) for the return of the broken specimens and completed questionnaire are the responsibility of the customer. Overseas shipments should be shipped parcel post only. We can no longer pickup airfreight shipments. Airfreight shipments will be returned by Customs.

Sincerely,

ROBERT E. PASTERNAK
Materials Engineer

2 Enclosures
1. Questionnaire
1. Wrapping Instructions
PROCEDURE FOR PROCESSING AUXILIARY CONTROL ROD BLADE AO-2
FOR METALLURGICAL EVALUATION

1.0 PURPOSE

To establish a method for cutting auxiliary control rod AO-2 follower for metallurgical evaluation.

2.0 POLICY

This procedure must be performed by a certified Shift Supervisor and with Health Physics present. An identification mark indicating orientation of rod in the core will be provided and follower will be cut in appropriate locations for machining metallurgical samples from areas of highest thermal neutron fluence.

3.0 SCOPE

This procedure has been prepared for auxiliary control rod AO-2.

4.0 REFERENCES

BNL Safety Manual, Section 3.0, Radiation Safety
HFBR OPM Section 10.0, Canal Area Operating Procedures
High Dose TLD Control Rod AO-2 Measurements dated 4/23/89 (attached).

5.0 DEFINITIONS

None.
6.0 PROCEDURE

NOTE: Health Physics coverage is required for all of the following steps of this procedure. Review procedure with Health Physics and determine appropriate monitoring and other protective measures.

6.1 Place the canal work table with cutting fixture attached in support tube at a depth of at least 7 feet below the water surface and position all 4 clamp arms toward the south.

6.2 Using 2 (two) twenty foot long canal rods with 2" ID open hooks attached, lift the control rod as shown in Sketch #1 positioning the hooks on the stainless steel portions of the control rod assembly only.
6.3 Holding the control rod horizontally, and using the traveling bridge move the control rod to the east end of the canal while keeping it at least 12-15 feet under water. When in position near the work table slowly raise it to approximately 6 feet below the water surface while Health Physics monitors the action. Place it on the cutting fixture as shown in Sketch #2 observing correct orientation.

**SKETCH #2**
6.4 Using the ball hex key attached to a 10 ft. canal rod, swing all 4 clamp arms clockwise to their respective stops. See Photos #1 and #2.

6.5 After observing that the rod blade is fully against the western stop and blade support, tighten the clamps from west to east finger tight.

6.6 Using the hack saw on a 10 ft. canal rod make a 1/8" deep cut (approximately 10 strokes) at the eastern edge of the western saw guide. See Photo #1.
PROCEDURE FOR PROCESSING AUXILIARY CONTROL ROD BLADE AO-2
FOR METALLURGICAL EVALUATION

6.7 Next make a complete cut (approximately 150 strokes) at the eastern edge of the eastern saw guide, see Photo #2.

6.8 The final cut is also a complete cut at the western edge of the western saw guide, see Photo #1.

6.9 While holding the rod coupling end with a suitable tool unclamp the eastern most clamp and remove the coupling to the storage box to the east of the uncut fuel storage rack.

6.10 Now holding the blade end unclamp the western most clamp and place the blade end in the storage box.

6.11 With close Health Physics attention unclamp the two (2) remaining clamps and raise the follower tube slowly toward the surface, keeping it horizontal. Stop if the radiation levels approach 1 R/hr at the canal edge and return it to the cutting fixture. Estimate the distance of the follower to the surface of the water at 1 R/hr. Distance of follower to surface of the water.

6.12 Take timed TLD exposures at each end and the middle.

6.13 Place the lifting wire in the follower tube and place the prepared piece of plastic pipe over the follower tube. Then place this assembly into the Medical Reactor Fuel Cask.

6.14 Properly sign off the cask with contents and radiation levels as necessary.

6.15 Enter a description of activities performed in HFBR Canal Logbook.

__________________________
Shift Supervisor

__________________________
Date

5/09/89
DATE: July 25, 1989
TO: G. C. Kinne
FROM: J. Detweiler
SUBJECT: RD QA Audit Report 89-9

The attached audit report on HFBR Fracture Toughness Testing is submitted for your information and any action you deem appropriate. The chairman of the RSC is also requested to independently appraise the contents of this report to determine if RSC action would be appropriate. Corrective action measures required to satisfy any significant adverse findings will be scheduled and tracked by RD management following procedures contained in the RD QA Manual.

The RD QA Group will verify that corrective action measures were satisfactorily completed. Audit records will be maintained in the RD QA Office where they are available for review. If no response regarding this audit is received by me within thirty days of distribution, it will be interpreted as signifying approval of its contents.

JD/DD

cc: RD
J. Barkwill
M. Brooks
W. Brynda
J. Costanzo
R. DeRocher
S. Golden
H. Hauptman
O. Jacobi
L. Junker
V. Lettieri
W. Morrison
J. Petro
A. Queirolo
R. Reyer
D. Rorer
D. Stonebridge
R. Taneus
M. Verderosa
QA Audit Files(6)

RSC
J. Hendrie, Chairman
J. Carew
C. Czajkowski
W. Gunther
R. Hall
T. Prach, Secretary
N. Rohrig
P. Tichler
M. Todosow

Other
M. Schuster
M. Shear
RD Quality Assurance Audit Report

of

HFBR Fracture Toughness Testing

Performed by:

R. V. DeRocher

Date Submitted: June 23, 1989

Audit No. RD-89-9
1.0 PURPOSE
This audit was performed to evaluate the fracture toughness testing of a control rod follower being performed for the Reactor Division by the Department of Nuclear Engineering.

2.0 SCOPE
This audit reviewed the fracture toughness testing activities of the Department of Nuclear Energy during the period from May 31, 1989 to June 21, 1989. Discussions were held with cognizant personnel to determine if the testing was being performed in accordance with the applicable sections of the QA Manual. In addition, all aspects of the machining and subsequent testing of the impact and tensile test specimens was witnessed.

3.0 SUMMARY
The personnel involved in the HFBR Fracture Toughness Testing were well prepared and performed the testing in an effective manner.

It was evident that there had been an extensive effort in planning for the testing. Separate procedures for the machining and testing of the impact and tensile specimens were developed. Non-irradiated specimens were machined and tested in the hot cell to verify that the testing could be performed as planned. This preparation also provided excellent training for the individuals who would be performing the testing of the irradiated specimens. The machining and testing of the irradiated samples was performed in a controlled and timely manner. When minor changes to the test set-up were required due to the physical characteristics of the irradiated specimens, the experience of the individuals involved enabled them to make the changes without disrupting the testing schedule.

Although no QA requirements had been specified by the Reactor Division, the QA controls implemented by the Department of Nuclear Engineering were more than adequate. There were no significant differences between the QA controls implemented and the applicable sections of the RD QA Manual.

4.0 FINDINGS AND OBSERVATIONS
There were no adverse findings identified during this audit. One observation was identified. Details are provided below.
4.1 OBSERVATION NO. 1

The impact and tensile test requirements were developed in a series of memos between P. Tichler of the RD and C. Czajkowski of the Department of Nuclear Engineering (DNE). QA/QC procedures were mentioned in several of the memos but specific requirements to be complied with were not specified. Although no discrepancies were noted in the activities reviewed during this audit, this may not always be the case.

While the services being provided by DNE were not assigned a Quality Level, the results of the tests are certainly important to reactor operation. If this work had been performed by an outside contractor, the purchase request would have been reviewed by RD personnel to ensure that the appropriate RD requirements, including QA requirements were included.

It is suggested that work performed for the RD by DNE or other BNL Departments/Divisions receive the same level of review as work sent to outside contractors.

5.0 AUDIT RESOLUTION

An audit close-out meeting was held on 7/24/89 with M. Brooks, D. Rorer, L. Junker, M. Verderosa and J. Detweiler in attendance. The audit indicated that all aspects of the fracture toughness testing activity were in compliance with RD QA requirements and, therefore, there were no findings. However, the observation that the instructions to DNE from the RD for this testing service did not include specific QA requirements (although they were discussed orally) and that these instructions did not receive normal RD review was deemed a serious concern by the audit resolution group. The following corrective action measure will be added to the RD Commitments List.

5.1 J. Detweiler shall review and revise as necessary the procedures used to control outside services in support of RD activities to assure that appropriate review and approval controls are in place. This item is assigned RD commitment tracking number 552.

6.0 ATTACHMENTS

1. Audit Plan
2. Audit Checklist
3. Personnel Contacted
1. Prepare an audit checklist to evaluate the HFBR fracture toughness testing program. The checklist should be written to determine if the work being performed by the Department of Nuclear Engineering is in accordance with the applicable sections of the RD QA Manual. Sections to be considered include:

   a. QAM 5.0, Instructions, Procedures, and Drawings
   b. QAM 8.0, Identification and Control of Items
   c. QAM 11.0, Test Control
   d. QAM 12.0, Control of Measuring and Test Equipment

2. Witness selected portions of the machining and testing of the samples. Ensure that the applicable QA controls are being used.

3. Prepare a draft audit report for management review in the format described in QAM 18.0 subsections 3.6 and 5.5.2. Findings and observations are to be described in sufficient detail to enable suitable evaluation and corrective action to be taken. A statement on the effectiveness of the RD audit program elements which were audited, as defined by QAM 18.0, should be included in the report summary.
## HFBR Fracture Toughness Testing

**Attachment 2**

**RD QA AUDIT CHECKLIST**

**AUDIT: 89-9**  **TOPIC:** HFBR Fracture Toughness Testing  
**PREPARED BY:** Richard de Rocher  
**DATE:** 6/16/89

<table>
<thead>
<tr>
<th>REFERENCE</th>
<th>CHARACTERISTIC</th>
<th>S/U/NA</th>
<th>RESULT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. QAM 11.0</td>
<td>Were the test requirements provided by the organization responsible for the design of the item to be tested?</td>
<td>S</td>
<td>A memo from P. Tichler to C. Czajkowski and M. Schuster dated March 10, 1989, provided the test requirements.</td>
</tr>
<tr>
<td>2. QAM 5.0</td>
<td>Was the machining of the tensile and charpy impact specimens performed in accordance with written procedures?</td>
<td>S</td>
<td>Extremely detailed procedures, &quot;Hot Cell HFBR Charpy Impact Machining Procedure&quot; and &quot;Hot Cell HFBR Tensile Sample Machining Procedure&quot; were used.</td>
</tr>
<tr>
<td>3.</td>
<td>Were the machining procedures approved prior to use?</td>
<td>S</td>
<td>Both procedures had been approved by C. Czajkowski and M. Schuster.</td>
</tr>
<tr>
<td>4.</td>
<td>Do the machining procedures provide all the information necessary to perform the work?</td>
<td>S</td>
<td>Satisfactory test specimens were obtained.</td>
</tr>
</tbody>
</table>
5. QAM 8.0

What actions were taken to identify the specimens so that traceability to their location on the control rod follower was maintained?

Specimens were kept in individual marked envelopes during the testing. In addition, nine lead "pigs" were available to provide segregation.

6. QAM 5.0

Was the tensile and charpy testing performed in accordance with written procedures?

Yes, "Hot Cell HFBR Heating and Impact Testing Procedure" and "MTS Tensile Test Procedure" were used.

7.

Were the testing procedures approved prior to use?

Both procedures had been approved by C. Czajkowski and M. Schuster.

8. QAM 11.0

Do the testing procedures provide all the information necessary to perform the testing?

Yes, although the material characteristics made it necessary to make minor modifications to the test set-up, the test results were consistent and believable.
<table>
<thead>
<tr>
<th>REFERENCE</th>
<th>CHARACTERISTIC</th>
<th>S/U/NA</th>
<th>RESULT</th>
</tr>
</thead>
<tbody>
<tr>
<td>9. QAM 11.0</td>
<td>Do the test records, as a minimum, identify the items listed below?</td>
<td>S</td>
<td>Impact, tensile and dimensional test records included all the necessary information.</td>
</tr>
<tr>
<td></td>
<td>a. item tested</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>b. date of test</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>c. tester or data recorder</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>d. type of observation</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>e. results</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10. QAM 12.0</td>
<td>Is the measuring and test equipment used in the machining and testing calibrated?</td>
<td>S</td>
<td>Gage blocks were used to verify that the micrometer and caliper readings were accurate. An ice bath was used to calibrate the thermocouple. The impact tester was calibrated in accordance with ASTM E23 and the TBS tensile tester was calibrated by the manufacturer.</td>
</tr>
<tr>
<td>11. QAM 11.0</td>
<td>Were the following prerequisites considered prior to performing the tests?</td>
<td>S</td>
<td>All of the prerequisites listed were considered prior to performing the tests.</td>
</tr>
<tr>
<td></td>
<td>a. calibrated instrumentation</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>b. appropriate equipment</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>c. trained personnel</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>d. condition of item to be tested</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>e. suitable environmental conditions</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>f. provisions for data acquisition</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## PERSONNEL CONTACTED

<table>
<thead>
<tr>
<th>NAME</th>
<th>TITLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>P. Tichler</td>
<td>Safety Evaluation Group Leader</td>
</tr>
<tr>
<td>C. Czajkowski</td>
<td>Research Engineer</td>
</tr>
<tr>
<td>M. Schuster</td>
<td>Research Engineer</td>
</tr>
<tr>
<td>T. Roberts</td>
<td>Senior Technician</td>
</tr>
<tr>
<td>L. Milian</td>
<td>Chemical Associate II</td>
</tr>
</tbody>
</table>
Initially, no impact specimen will be positioned in the support-holder. Secure 50 capacity circular weights to hammer.

2 Turn on variable autotransformer to setting 140 (this is on all the way) to raise the anvil/support/base temperature. This takes ~1.5 - 2.0 hours to stabilize.

3 Turn on heat gun to assist in heating the base.

4 Place insulating cover (aluminum box) over the specimen support area immediately after turning on both heat sources. Be sure that the thermocouple is positioned within the impact specimen area.

5 After ~2 hours a stable temperature (215° ± 5°F) should be achieved. Remove insulating box cover and place specimen in support/holder. The specimen should be centered between the supports with the notched side positioned away from the hammer strike. Make sure impact specimen sits perpendicular and flush against supports. 

Note: As per the stated test procedure, elevated impact testing is to be performed at 210°F. However, to achieve this temperature value the impact sample must be initially heated to 215°F. This 5°F temperature difference is compensation for the heat losses incurred during insulating box cover removal, plus the time it takes to trigger the pendulum arm release mechanism. Repeated tests have determined that this must be accomplished within 3.5 sec. since this is the measured time it takes the impact sample temperature to fall 5°F, from 215 to 210°F.
6 Following specimen positioning, cover with insulating box. Insure that the thermocouple is within 1/16" of impact specimen and that the thermocouple does not disturb specimen positioning (use mirror to verify).

7 Observe specimen temperature to verify that the original temperature (215 ± 2°F) is indicated and achieved within a one minute time period.

8 If all these criteria are met, immediately start timing the heating period of the specimen for exactly 15 minutes.

9 Note, that anytime after the initial 2 hour heat-up period that the variable autotransformer setting may be lowered to reduce the temperature of the system. It should not be lowered passed setting 115. Lowering the transformer allows the heat-gun air flow controller to be the fine temperature adjustment.

10 While the specimen is in the 15 minute heating mode turn the central hub of the indicating mechanism fully counterclockwise carefully against the stop.

11 Since the 50 in-lbf scale will be used initially make sure the proper indicating mechanism scale is set.

12 As the end of the 15 minute heating period approaches check frequently (at 13, 14 mins. etc.) to insure that the temperature reads 215 ± 1 °F. At 15 minutes quickly lift insulating box cover out of the way and release the impact hammer as quickly as feasible after insulating box removal. This is not to take more than 3.5 seconds (This is the time it takes the specimen temperature to decrease from 215 to 210°F).

13 After the specimen break, align the scribe lines on the indicating mechanisms and use a magnifying glass to read the energy.

14 Remove specimen from catcher and repeat the procedure from step number 5 until all elevated temperature impact tests are completed.

Room temperature impact tests will follow the exact procedure, but without the references to heating the impact specimens.