Demonstration of Improved Fuse Clearing Energy when Augmented by Ultra-Fast eFUSE Protection

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https://ieeexplore.ieee.org/document/8932007
Introduction

Fuse Uses and Overview

• Fuses can protect devices from short circuits
• Fast-Acting Fuses have weak-spots designed to melt under excess energy
• Fast-acting fuses are characterized by:
  – Maximum Clearing Energy ($I^2t$)
  – Maximum Continuous Current
• Tested melting energies of fast-acting fuses
  – Steady State Current
  – Overloading Pulses
    • Tests with and without ultra-fast eFUSE protection
    • Waves of type A, B, C, and D

![Wave Shapes and Clearing Equations](https://www.Cobham.com/HiRel)

Fig. 1: Wave Shape and related Clearing Equation
Fuse Test Apparatus

Steady State and Unprotected Pulsed Test Cases

- Single-Ended Oscilloscope probes placed at Nodes 1, 2, and 3 on the Fuse Test Fixture Schematic
- Circuit achieved <40ns fall time from 36V-to-0V at Node 3
- Short Circuit Current Slew Rates measured at 1A/ns typical

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Circuit Segment</th>
<th>R</th>
<th>L</th>
<th>C</th>
<th>Resonant Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unprotected Fixture</td>
<td>1-2</td>
<td>1.46 mΩ</td>
<td>6.56 nH</td>
<td>70.95 pF</td>
<td>233.29 MHz</td>
</tr>
</tbody>
</table>

Table 1: Lumped R-L-C Values from Fig. 2

Fig. 2: Unprotected Fuse Test Fixture
Fuse Test Apparatus

Pulsed Test Cases Protected by the Smart Power Switch Controller (SPSC)

- Oscilloscope Probes:
  - Single-ended at Nodes 3, 6, and 7
  - Differential across Nodes 1 & 2
- When the SPSC detects a short-circuit condition it opens the circuit within approximately 250ns

Table 2: Lumped R-L-C Values from Fig. 3
Fuse Ratings

Time Current Curves

- Fuses imply indefinite operation at the rated current level, but in practice indefinite operation happens at <60% the rating
- Inflection point occurs when the $I^2t$ melting energy threshold becomes the domineering electrical stress factor to the fuse

Table 3: Fuses Evaluated from the PICO®II and MICRO™ families

<table>
<thead>
<tr>
<th>Family</th>
<th>Part#</th>
<th>Current Rating (A)</th>
<th>Nominal Cold Resistance (Ω)</th>
<th>Nominal Melting $I^2t$ (A² sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PICO®II</td>
<td>0251.062</td>
<td>0.062</td>
<td>7.000</td>
<td>1.13E-4</td>
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<tr>
<td>PICO®II</td>
<td>0251.125</td>
<td>0.125</td>
<td>1.700</td>
<td>1.74E-3</td>
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<tr>
<td>PICO®II</td>
<td>0251.200</td>
<td>0.200</td>
<td>0.895</td>
<td>4.8E-3</td>
</tr>
<tr>
<td>PICO®II</td>
<td>0251.250</td>
<td>0.250</td>
<td>0.665</td>
<td>1.16E-2</td>
</tr>
<tr>
<td>MICRO™</td>
<td>0273.015</td>
<td>0.015</td>
<td>44.0</td>
<td>1.23E-6</td>
</tr>
<tr>
<td>MICRO™</td>
<td>0273.050</td>
<td>0.050</td>
<td>3.52</td>
<td>6.66E-5</td>
</tr>
<tr>
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<td>0273.062</td>
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<td>2.55</td>
<td>1.15E-4</td>
</tr>
<tr>
<td>MICRO™</td>
<td>0273.100</td>
<td>0.100</td>
<td>1.38</td>
<td>3.85E-4</td>
</tr>
<tr>
<td>MICRO™</td>
<td>0273.200</td>
<td>0.200</td>
<td>2.30</td>
<td>4.09E-3</td>
</tr>
<tr>
<td>MICRO™</td>
<td>0273.250</td>
<td>0.250</td>
<td>1.75</td>
<td>6.40E-3</td>
</tr>
</tbody>
</table>
Fuse Test Scenarios – Scenario 1

- Test Scenario 1: Steady State $I^2t$ Melting Energy
  - Each fuse is placed in the unprotected test fixture
  - A 1Hz pulse is sent to ensure the fuse melts during a single pulse
  - Indirectly measured current by calculating the voltage drop divided by the cold resistance

(F6) V drop across fuse

(F8) V drop from VIN to fuse positive terminal

Voltage at Fuse Positive

Voltage at Fuse Negative

Voltage at VIN

Fig. 6: PICO®II 0251.062 Fuse that took 82.0692µs to open
Fuse Test Scenarios – Scenario 2

- **Test Scenario 2: Unprotected Pulsed Overcurrent Fuse Testing**
  - 1µs short-circuit faults were initiated at a 1kHz event rate, up to 1E6 pulses
  - Melting Energy determined by equations below:

- **Current Area (Amp-Seconds)**
  - \( I_{Area} (A \text{ sec}) = \frac{\text{Voltage Area (V sec)}}{\text{Resistance (Ω)}} \)

- **Current Per Pulse (Amps)**
  - \( I_{Per \text{ Pulse}} (A) = \frac{\text{Current Area (A sec)}}{\text{Pulse Duration (sec)}} \)

- **Melting Energy (Amp-Squared-Seconds)**
  - \( E_{Melting} (A^2 \text{ sec}) = I_{Per \text{ Pulse}}^2 \times \text{Duty Cycle} \times \# \text{ of Pulses} \)

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**Fig. 7: PICO®II 0251.062 Fuse without SPSC protection**
- (F6) V drop across fuse
- (F8) V drop from VIN to fuse positive terminal
- Voltage at Fuse Positive
- Voltage at Fuse Negative
- Voltage at VIN

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Fuse Test Scenarios – Scenario 3

• Test Scenario 3: SPSC Protected Pulsed Overcurrent Fuse Stressing
  – 1µs short-circuit faults were initiated at a 1kHz event rate, up to 1E6 pulses with the SPSC
  – The SPSC detects short-circuit conditions and shuts off the current flow to the load within 250ns typ.
  – Circuit parasitics take an additional 100-150ns to discharge energy

Fig. 8: PICO®II 0251.062 Fuse with SPSC protection
Fuse Test Results
Melting Energies for Specified vs Steady State Measurements

Fig. 9: PICO®II Melting Energy Measured vs. Specified

Fig. 10: MICRO™ Melting Energy Measured vs. Specified

Table 4: Specified vs. Empirical Melting Energies

<table>
<thead>
<tr>
<th>Part Number</th>
<th>Fuse Specification</th>
<th>Empirical Results</th>
<th>Multiples of Margin</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rating (mA)</td>
<td>Cold Res (Ω)</td>
<td>Melting (A²sec)</td>
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<tr>
<td>0251.062MXL</td>
<td>62</td>
<td>7</td>
<td>1.13E-04</td>
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<td>0251.125MXL</td>
<td>125</td>
<td>1.7</td>
<td>1.74E-03</td>
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<td>0251.200MXL</td>
<td>200</td>
<td>0.895</td>
<td>4.80E-03</td>
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<td>250</td>
<td>0.665</td>
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</tr>
<tr>
<td>0273.015V</td>
<td>15</td>
<td>44</td>
<td>1.23E-06</td>
</tr>
<tr>
<td>0273.050H</td>
<td>50</td>
<td>3.52</td>
<td>6.66E-05</td>
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<tr>
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<td>62</td>
<td>2.55</td>
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<td>200</td>
<td>2.3</td>
<td>4.09E-03</td>
</tr>
<tr>
<td>0273.250H</td>
<td>250</td>
<td>1.75</td>
<td>6.40E-03</td>
</tr>
</tbody>
</table>
# Fuse Test Results

Melting Energies for Steady State vs. Pulsed (Protected & Unprotected Overcurrent Faults)

![Fig. 11: PICO®II Fuse Stress Energies for All Test Conditions](image)

![Fig. 12: MICRO™ Fuse Stress Energies for All Test Conditions](image)

## Table 5: Fuse Stress Energy Summary for All Test Conditions

<table>
<thead>
<tr>
<th>PN</th>
<th>Fuse Specification</th>
<th>Empirical Results</th>
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<tr>
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<td>4.80E-03</td>
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<td>2.28E-01</td>
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<td>1.23E-06</td>
<td>3.31E-06</td>
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<td>6.66E-05</td>
<td>1.22E-03</td>
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<td>2.79E-03</td>
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<tr>
<td>0273.250H</td>
<td>250</td>
<td>6.40E-03</td>
<td>5.49E-03</td>
</tr>
</tbody>
</table>
The fuse resistance was measured during the fuse test runs after every 5E4 pulses.

The PICO®II fuses that weren’t protected experienced a fusing event before 1E6 pulses:
- Every fuse experienced an increase in resistance before the fusing event.

All PICO®II fuses survived when protected by the SPSC eFUSE controller:
- The 125mA and 200mA fuses exhibited a single resistance increase of 1.41% and 0.88% respectively.
Fuse Test Results - MICRO™ Family

Fuse Resistance Increase Between Protected and Unprotected Overcurrent Pulses

- The MICRO™ fuses **not protected** by the SPSC eFUSE all experienced a fusing event before 1E6 pulses
  - Every fuse experienced an increase in resistance before the fusing event
    - Except the 0273.200V and 0273.250H, which both fused faster than resistance could be measured
- The MICRO™ fuses **protected** by the SPSC eFUSE controller showed robust results (minus the 0273.015V which still experienced a fusing event)
  - All other fuses experienced no measurable resistance shift
Summary

- **PICO®II fuses** performed consistently between the specified and empirical data.
- **MICRO™ fuses** had mixed results, with the higher rated fuses (0273.200V and 0273.250H) performing worse.
- The total energy applied for the unprotected pulsed fuses to reach failure was significantly higher than the steady state melting energies.
- **Unprotected pulsed fuses** all experienced melting events before 1E6 pulses could be applied.
- **Protected pulsed fuses** all survived 1E6 pulses except for the 0273.015V.
  - The SPSC still played a significant role in extending the fuse lifetime of the 0273.015V.