Heavy-ion Test Report for the MSK5978RH Low Dropout Voltage Regulator

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Test date: September 9th, 2012
Test report final draft: December 7th, 2012

I. Introduction

The purpose of this test is to examine the heavy-ion-induced single event effects (SEE) susceptibility of the MSK5978RH low dropout voltage regulator from M. S. Kennedy Corporation. NASA GSFC has previously performed pulsed-laser testing on the MSK5978RH, with application specific circuit configurations. Here, we evaluate the comprehensive radiation response under a wide range of device loading conditions, with heavy-ion beam. The test will carried out at the Lawrence Berkeley National Laboratory Facility.

II. Device Description

The MSK5978RH is a radiation hardened low dropout voltage regulator. The device offers low dropout down to 250 mV. The device also features internal short circuit current and thermal limiting. The part was designed and packaged with the RH3080 die from Linear Technology, Inc. Table I displays the part and test information. Figure 1 shows the pin configurations for the device. Detailed device specification can be found in the datasheet [1].

<table>
<thead>
<tr>
<th>Generic Part Number</th>
<th>MSK5978RH (RH3080 die)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Package Marking</td>
<td>No markings</td>
</tr>
<tr>
<td>Manufacturer</td>
<td>M. S. Kennedy Corp.</td>
</tr>
<tr>
<td>Lot Date Code (LDC)</td>
<td>1217</td>
</tr>
<tr>
<td>Quantity tested</td>
<td>2</td>
</tr>
<tr>
<td>Part Function</td>
<td>Low dropout voltage regulator</td>
</tr>
<tr>
<td>Part Technology</td>
<td>Bipolar</td>
</tr>
<tr>
<td>Package Style</td>
<td>Hermetically sealed 10 pin ceramic flatpack</td>
</tr>
<tr>
<td>Test Equipment</td>
<td>Power supply, digital oscilloscope, electronic load, multimeter, and computer</td>
</tr>
</tbody>
</table>

Table I
Test and part information
III. Test Facility

The heavy-ion beam testing was carried out at the Lawrence Berkeley National Laboratory (LBNL) Berkeley Accelerator Space Effects (BASE) Facility. The facility utilizes an 88-inch Cyclotron to accelerate a cocktail of ions: 4.5, 10, 16, and 30 MeV/nucleon. The device under test was positioned inside a vacuum chamber.

**Facility:** Lawrence Berkeley National Laboratory  
**Cocktail:** 10 MeV/nuc  
**Flux:** $< 1 \times 10^5$ ions/(cm$^2$·s)  
**Fluence:** $\leq 1 \times 10^7$ ions/cm$^2$  
**Ions:** Shown in Table II

<table>
<thead>
<tr>
<th>Ion</th>
<th>LET (MeV·cm$^2$/mg)</th>
<th>Range in Si (µm)</th>
<th>Energy (MeV)</th>
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<tbody>
<tr>
<td>Ne</td>
<td>3.49</td>
<td>175</td>
<td>216</td>
</tr>
<tr>
<td>Ar</td>
<td>9.74</td>
<td>130</td>
<td>400</td>
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<tr>
<td>Kr</td>
<td>30.86</td>
<td>113</td>
<td>886</td>
</tr>
<tr>
<td>Xe</td>
<td>58.78</td>
<td>90</td>
<td>1232</td>
</tr>
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</table>

IV. Test Methods

Figure 2 shows the circuit schematic diagram for the application circuit. We evaluated two circuit configurations. Configuration A contains a relay that switches between the two output resistors for either 1.5 or 3.3 V output. Configuration B is fixed at 1.5 V output. The maximum output load is 0.7 A. M.S. Kennedy supplied evaluation boards for this test. Specifications of the evaluation board can be found in the linked document [2]. The input and output filtering elements are important for single event transient (SET) characterization. In particular, the output capacitor equivalent series
resistance (ESR) value is not only pertinent for output stability, but can also impact transient characteristics [3]. The capacitance and ESR values of the input and output capacitors are shown in Table II.

Figure 3 shows a photograph of the custom designed test board. The test board contains BNC connections for power, output, electronic load, and replay switch. The test cards are clamped to an aluminum plate, via thermally conductive films.

The irradiation chamber is in a vacuum environment. Therefore proper heat dissipation is pertinent. We performed bench testing to determine the relation between the junction temperature and input voltage, for different output loading conditions. As shown in Figure 4, we found that the test setup, without active cooling, offered a maximum power dissipation of approximately 2.7 W, before the device exceeded the maximum junction temperature rating (125°C) and triggered thermal shutdown.

The test board was mounted to a cooling plate inside the vacuum chamber. The cooling plate was actively cooled by cycling liquid coolant from outside the vacuum chamber. We originally planned to monitor the case temperature via a thermistor. However computer malfunction prevented us from recording the temperature during the test. Therefore we maintained the input and output conditions from known bench test results that kept the power dissipation below 2.7 W.

Figure 5 shows a schematic block diagram of the test setup. The power supply, electronic load, and oscilloscope will be remotely controlled via LabVIEW programs through a lab computer in the control room.

5978RH ADJ VOLTAGE REGULATOR
Table II
Input and output capacitor description

<table>
<thead>
<tr>
<th>Referenced element</th>
<th>Capacitance (µF)</th>
<th>ESR (mΩ)</th>
<th>Part Number</th>
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<tr>
<td>C2, C4</td>
<td>0.1</td>
<td>TBD</td>
<td>08051C104KAT</td>
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<tr>
<td>C5</td>
<td>220</td>
<td>49</td>
<td>TAZH227K010L</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(CWR29FC227K)</td>
</tr>
</tbody>
</table>

Figure 3. Photograph of the custom test board.
Figure 4. Device junction temperature vs. input voltage, for different output load currents.

Figure 5. Block diagram of the testing setup.

Test Conditions

Test Temperature: Cooling plate at 5°C
Operating Frequency: DC
Power Supply: \( V_{\text{in}} = 5 \) to 10 V
Output Voltage: \( V_{\text{out}} = 1.5 \) or 3.3 V
Output Load: \( I_{\text{out}} = 100 \) or 500 mA
Angles of Incidence: 0° (normal), 30°, and 45°
Parameters: 1) Input supply voltage
2) Output current
3) Output voltage
Beam Time: 8 hours (scheduled)
V. Results

We found that the parts were susceptible to heavy-ion-induced glitches and perturbations. We will identify these events as transients. The SETs had duration of approximately 2 µs. The maximum amplitude of the worst case SETs, estimated from the peaks of the largest positive- and negative-going pulses, was approximately 0.5 V and 0.4 V, for the 1.5 V and 3.3 V output modes. So the worst case transients varied from 1.2 V to 1.7 V for the 1.5 V output, and from 3.1 V to 3.5 V for the 3.3 V output.

Figure 6 shows the SET cross section vs. effective LET, for various circuit conditions. The 1.5 V output was more sensitive to SETs relative to the 3.3 V output. In fact, the SET cross section was approximately one order of magnitude higher for the 1.5 V than the 3.3 V output. And the LET threshold (LETₜₜ) was approximately 3.49 MeV·cm²/mg for the 1.5 V output, while the 3.3 V output were not sensitive to SETs below an LET of 30.86 MeV·cm²/mg.

We considered the fact that the oscilloscope trigger settings were slightly different for the two outputs. The trigger levels were set at 3.15 V to 3.45 V for the 3.3 V output, equivalent to approximately 9% of the output. While for the 1.5 V output, the trigger levels were set at 1.45 V to 1.55 V, equivalent to approximately 6.7% of the output. The small difference did not appear to cause inconsistency in the number of SET captures for the two output settings. Alternatively, we may choose identical values for the absolute trigger range for both outputs (Vout ± 150 mV). The rank plot in Figure 7 shows the SET amplitude vs. the percentage of the total number of captured SETs, from an irradiation run with 1.5 V output. The figure shows that about 70% of the SETs are captured with amplitude greater than 1.65 V or less than 1.35 V. The corresponding SET cross section is approximately $5.4 \times 10^{-4}$ cm² for the 1.5 V output, which is about 5× the cross section for the 3.3 V output. So in this case the output sensitivity is smaller.

We also found that the 0.1 A output load was more sensitive to SETs relative to the 0.5 A output load. The cross section was approximately 2× higher for the 0.1 A load than the 0.5 A load, for 1.5 V output. The 3.3 V output did not show any SET with 0.5 A output load. The SET sensitivity is weakly dependent on the input voltage.

The SET characteristics (amplitude and duration) did not vary significantly with output load or input voltage. Figures 8 – 14 show examples of SETs for varying output and input conditions. The magnitudes of the SETs were slightly reduced for lower LETs. For example, Figure 14 shows an SET at LET = 9.74 MeV·cm²/mg. The magnitude of the pulse amplitude was approximately 200 mV less than that from Xe at normal incidence with LET = 58.87 MeV·cm²/mg.

Beam shadowing may have influenced the results from angular irradiations. Consequently, we did not observe any SET for Xe at 45° with an effective LET of 83.25 MeV·cm²/mg. Furthermore, we observed that the cross section decreases slightly for angular irradiations at similar effective LETs as normal incident irradiations. Data points that illustrate the effect include: Kr 30°, Kr 60°, and Xe 30°, with corresponding effective LET values of 35.63, 43.64, and 67.98 MeV·cm²/mg.

We did not observe any destructive event or functional interrupt during the irradiation. A summary of the irradiation run information is attached [4].
Figure 6. SET cross section vs. effective LET for the MSK5978RH irradiated with 10 MeV/amu heavy-ions, for various circuit conditions. Data set from one part only.

Figure 7. Rank plot showing the SET amplitude vs. percentage of the total number of captured SETs from an irradiation run with Xe at normal incidence at LET = 58.87 MeV·cm²/mg, for $V_{in} = 5$ V, $V_{out} = 1.5$ V, and $I_{out} = 0.1$ A.
Figure 8. Output voltage vs. time during an SET for the MSK5978RH irradiated with Xe at normal incidence at LET = 58.87 MeV·cm²/mg, for $V_{in} = 5$ V, $V_{out} = 1.5$ V, and $I_{out} = 0.1$ A.

Figure 9. Output voltage vs. time during an SET for the MSK5978RH irradiated with Xe at normal incidence at LET = 58.87 MeV·cm²/mg, for $V_{in} = 5$ V, $V_{out} = 1.5$ V, and $I_{out} = 0.5$ A.
Figure 10. Output voltage vs. time during an SET for the MSK5978RH irradiated with Xe at normal incidence at LET = 58.87 MeV·cm²/mg, for $V_{in} = 10$ V, $V_{out} = 1.5$ V, and $I_{out} = 0.1$ A.

Figure 11. Output voltage vs. time during an SET for the MSK5978RH irradiated with Xe at normal incidence at LET = 58.87 MeV·cm²/mg, for $V_{in} = 5$ V, $V_{out} = 3.3$ V, and $I_{out} = 0.1$ A.
Figure 12. Output voltage vs. time during an SET for the MSK5978RH irradiated with Xe at normal incidence at LET = 58.87 MeV·cm²/mg, for $V_{in} = 10$ V, $V_{out} = 3.3$ V, and $I_{out} = 0.1$ A.

Figure 13. Output voltage vs. time during an SET for the MSK5978RH irradiated with Xe at normal incidence at LET = 9.74 MeV·cm²/mg, for $V_{in} = 5$ V, $V_{out} = 1.5$ V, and $I_{out} = 0.1$ A.
VI. Conclusion

We found that the MSK5978RH low dropout voltage regulator is susceptible to heavy-ion-induced SETs. The SETs show characteristics of output ripple. The output oscillations varied from 1.2 V to 1.7 V for the 1.5 V output, and from 3.1 V to 3.5 V for the 3.3 V output. The duration of the oscillations lasted approximately 2 µs. The SET cross section shows a relatively strong dependence on the output voltage. The SET cross section was approximately 1 order of magnitude higher for the 1.5 V output than for the 3.3 V output at LET = 58.87. We also observed a higher cross section for the lower output load. Appropriate output filtering for ripple rejection may be required for space applications.

We did not observe notable effects in the SET characteristics from increasing power dissipation. We calculated the die junction temperature from the case temperature for various loading conditions prior to irradiation to ensure adequate heat dissipation. Proper heat sinking is critical during SEE testing of linear and switching regulators [5].

We did not observe any destructive event or functional interrupts for irradiations with Xe at normal incidence with LET = 58.87 MeV·cm²/mg, and at 30° tilt angle with LET = 67.98 MeV·cm²/mg. We note that the angular irradiation, especially at 45° incident angle, may have experienced beam shadowing effects.

VII. References

[4] Irradiation run summary

MSK5978RH_LBNL_Sep_2012.xls