Single-Event Transients in Voltage Regulators

A. H. Johnston, *Fellow, IEEE*, T. F. Miyahira, F. Irom, and J. S. Laird

***Abstract*—Single-event transients are investigated for two voltage regulator circuits that are widely used in space. A circuit-level model is developed that can be used to determine how transients are affected by different circuit application conditions. Internal protection circuits—which are affected by load as well as internal thermal effects—can also be triggered from heavy ions, causing dropouts or shutdown ranging from milliseconds to seconds. Although conventional output transients can be reduced by adding load capacitance, that approach is ineffective for dropouts from protection circuitry.**

***Index Terms*—Radiation testing, single-event transient, voltage regulator.**

I. Introduction

DEALING with single-event transients (SETs) has proven to be a complex problem. Transients in linear devices are strongly affected by circuit application conditions, making it difficult to extend tests with a specific circuit configuration to other applications [1]–[9]. This paper discusses SETs in linear voltage regulators, using two widely used devices as test vehicles. These regulators can be used over a very wide range of input voltages, with input/output voltage differences up to 40 V. The wide range of supply voltages and variation in output loading conditions are critical parameters in determining SETs for these devices, but increase the complexity of radiation testing and data evaluation.

In studying SETs, the first step is to establish the criteria for the amplitude and duration of output voltage response. For voltage regulators, transients with small amplitude or short duration are often of secondary importance, but may induce unacceptable noise for critical circuits. Transients with large amplitude can produce voltage conditions that may damage other circuits, or produce noise-like effects that disrupt normal circuit functions. We have to keep in mind that the SETs from these regulators can take place even with a relatively large capacitor present at the device output. The low output impedance and high current compliance of the regulator basically overcome the expected filtering effect of bypass capacitors—up to the value of capacitance used during SET measurements—producing transients in a network that is often assumed to be immune from such effects when a first-order analysis is done by circuit designers.

Manuscript received July 14, 2006; revised September 6, 2006 This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration (NASA).

The authors are with the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA (e-mail: allan.h.johnston@jpl.nasa.gov; tetsuo.f.miyahira@jpl.nasa.gov; farokh.irom@jpl.nasa.gov; jamie.laird@jpl.nasa.gov).

Digital Object Identifier 10.1109/TNS.2006.886215

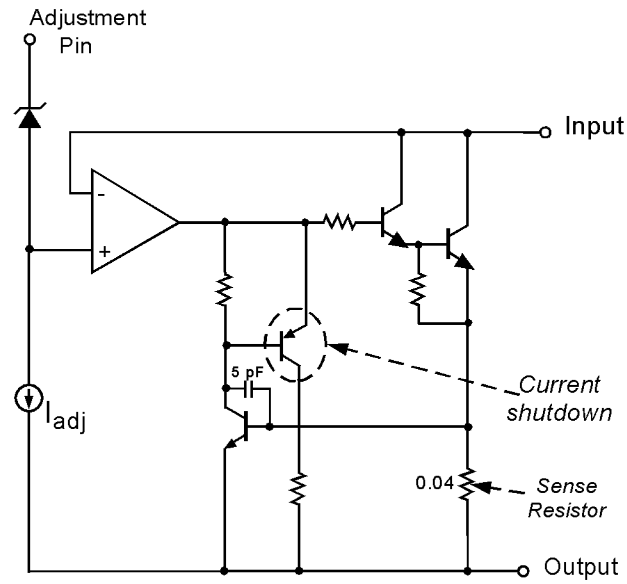

Fig. 1. Simplified diagram of the LM137 voltage regulator.

This paper evaluates SETs in two regulator circuits that can be used over a wide range of voltage and load conditions. Circuit-level models are developed that can be used to extend test results to a wider range of application conditions.

II. Devices Selected for Testing

A. Basic Properties

Two voltage regulators were selected for testing, the LM117 a positive voltage regulator, and the LM137, a negative voltage regulator with similar properties. Both regulators can deliver currents up to approximately 1 A (in the TO-39 package versions used in the study), with output voltages from 1.25 to 40 V. This allows a great deal of design flexibility, but it makes it far more difficult to establish conditions for radiation testing that can be applied to the wide range of possible application conditions.

The circuit design of the two regulators is very similar. They contain an internal bandgap reference voltage and use a floating current source that allows the output voltage to be adjusted—relative to the bandgap reference—with an external resistor network. Internal current limiting and temperature sensing circuits are included to improve reliability [10], [11].

An example of the basic circuit configuration is shown in the simplified diagram of Fig. 1 for the LM137 negative voltage regulator. An internal bandgap reference in series with the adjustment pin and an external resistor network (not shown) determines the output voltage. The circuit has an internal current limiter that will shut down the regulator if the current through

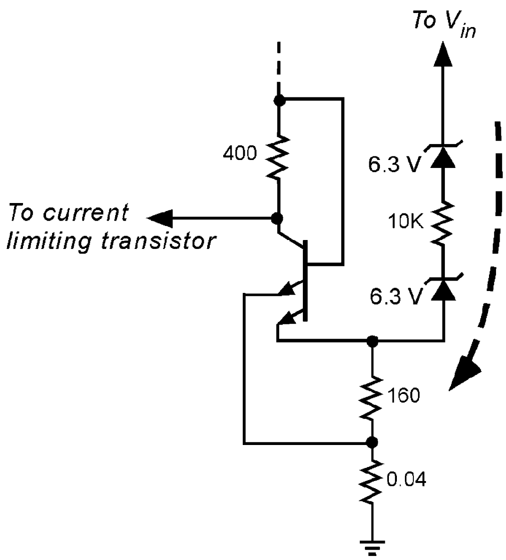

Fig. 2. Details of current shutdown circuit for the two regulators.

the 0.04 ohm resistor exceeds approximately 1 A. Although initial sensing of a high current condition is done with an npn transistor, turn on of the lateral pnp transistor ultimately produces the shutdown condition.

Although large output capacitances are often used for voltage regulators, the LM117 does not require a capacitor at the output. A 1 μF capacitor is recommended at the output of the LM137 to increase stability and improve transient response, but lower values can be used, particularly for low load currents. A wide range of capacitor values, load currents and input/output voltage are used in applications of these devices, all of which affect the SET response. One of the motivations for this paper is a specific application in flight hardware where the load capacitance of the LM117 was only 0.1 μF.

B. Current and Thermal Protection

The current protection circuit is more involved than shown in the simplified diagram of Fig. 1. An additional transistor is interposed between the sense resistor and the npn transistor to reduce the temperature sensitivity of the current limit value. In order to increase application flexibility the current limit is automatically reduced when the input-output voltage exceeds approximately 13 V by a zener diode network, shown in Fig. 2 [11]. Current through the zener diodes switches out part of the multi-emitter transistor, reducing the current threshold from approximately 1.2 A at low voltage to about 300 mA for high values of input-output voltage.

This has important consequences for radiation testing because current shutdown can also be triggered by heavy ions. The sensitivity of the circuit to shutdown is substantially different when the device is tested with high power supply voltages, where the current limit is reduced through the automatic compensation provided by the zener diode/multi-emitter network. Radiation tests must be done over a range of input/output voltage conditions in order to determine the sensitivity of the shutdown circuit to heavy ions.

TABLE I
PROPERTIES OF IONS USED FOR TESTING

Ion	Energy (MeV)	LET (MeV-cm^2/mg)	Ion Range (μm)
^{18}F	141	3.7	122
^{28}Si	186	7.9	76.3
^{35}Cl	210	11.4	63.5
^{48}Ti	194	19.8	40.1
^{58}Ni	265	26.6	42.2
^{129}Xe	1934	44.3	156
^{127}I	322	59.7	31.2
^{197}Au	2977	80.1	157

III. EXPERIMENTAL PROCEDURE

Heavy-ion tests were done at Brookhaven National Laboratory (in vacuum), and at Texas A&M (in air). The ions used for testing are listed in Table I. The package lids were removed before testing. All tests were done using normal incidence. Additional diagnostic tests were done using ^{252}Cf fission fragments (also in vacuum).

Most tests were done with an output voltage of 5 V (or -5 V for the LM137) using appropriate resistor combinations at the adjustment pin. The output load current was 20 mA, which was well above the minimum start-up current required, but low enough to avoid overheating the device during the tests when the devices are in vacuum. Reed relays at the output were used to change the capacitive load. Four different capacitance values were used: 0.1, 0.32, 1.1 and 4.7 μF. A Tektronix TDS784 oscilloscope was used to measure the waveforms, storing them on an external computer for later analysis. The oscilloscope trigger was set for a differential voltage of 0.2 V, capturing all waveforms that exceeded that value during each run. The output voltage that will affect other devices is application dependent, and is usually much larger than the 0.2 V threshold condition. The set of waveforms could be analyzed afterwards for specific values of output voltage and time duration that are critical for specific applications, which is usually determined by a worst-case analysis.

IV. TEST RESULTS

A. Output Transients

LM117 Positive Regulator: Positive- and negative-going transients can occur in the LM117. Negative-going transients (with the exception of those caused by shutdown and thermal protection) have very short duration, typically <0.5 μs, and are quickly corrected by the emitter-follower output circuit. Therefore the main emphasis of this paper is on positive-going transients that not only persist for longer times, but can potentially destroy other circuits if they are too large.

SETs from the LM117 depended strongly on capacitive loading. Transients with output amplitude less than approximately 0.3 V are within the active operating range of the control amplifier, and persist for time intervals that are of the same

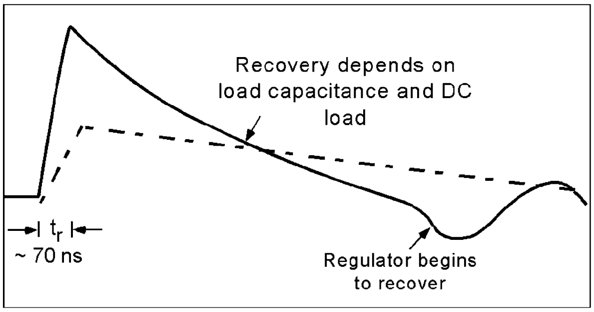

Fig. 3. Generalized waveform of positive-going transients for two different capacitive load conditions. Recovery does not begin until the waveform is close to the initial voltage value.

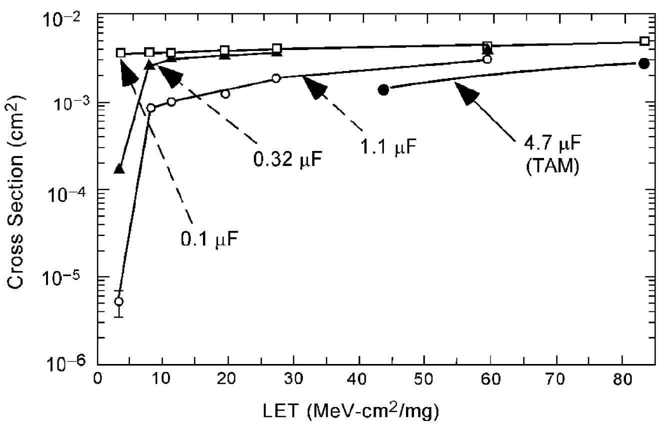

Fig. 4. Cross section for SETs in the LM117 voltage regulator for various values of load capacitance.

order as the normal electrical transient response ($\sim$0.5 μs). Transients with higher amplitude go beyond the linear control range, resulting in an extended time response because the output stage is asymmetric, designed to source current, not to absorb it. The general nature of those positive-going transients is shown in the diagram of Fig. 3. The dashed line corresponds to a load capacitor that is twice that of the waveform in the solid line. An impulse-like positive response occurs for approximately 70 ns that is higher for the condition of reduced load capacitance.

Recovery of the output waveform depends on the load current and output capacitance, with nearly constant slope that continues until the output voltage is within the linear range of the control amplifier. At that point the voltage starts to recover with a damped oscillatory behavior that persists for several microseconds. The oscillatory period is somewhat longer with higher load capacitance. The amplitude is lower when tests are done with a higher load capacitance, but the time interval for the initial "charging period" is the same. The main effect of higher load capacitance is to extend the linear recovery period, as shown.

A triggering threshold of 0.2 V was used to capture transients during various test sequences. Fig. 4 shows the dependence of the cross section on LET for transients above 200 mV. No transients were observed during the tests at Brookhaven—which has ions with much shorter range—with the highest value of load capacitance (4.7 μF), but transients were observed for the 4.7 μF condition during tests at Texas A&M, which has ions with much longer range.

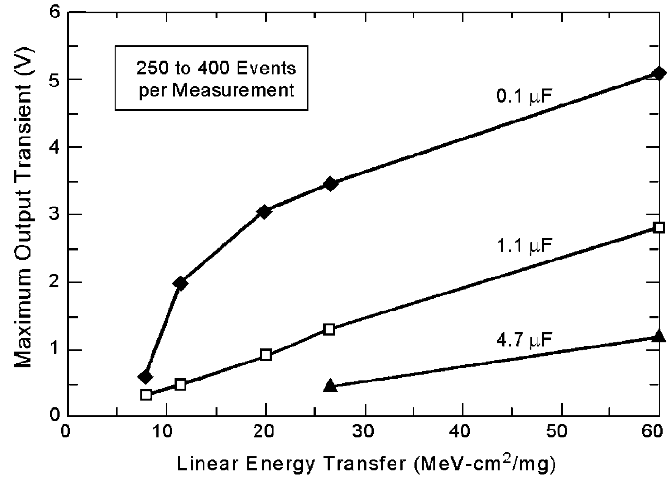

Fig. 5. Maximum value of output transient observed for experimental runs where several hundred events are captured.

The maximum value of the transient voltage increased with LET; transients $>$1.3 V occurred even with a load capacitance of 1.1 μF for LET values of 26.6 MeV - cm^2/mg and above. The maximum peak transient voltage that was observed during a test sequence where $\sim$250 to 400 total events were observed is shown in Fig. 5. This is a useful way to compare experimental results because often the main concern is whether the transient voltage will exceed maximum allowable voltage ranges for circuits that are powered by the voltage regulator. The maximum amplitude is lower for high values of load capacitance, as shown. The difference between the input and output voltage was 15 V for these measurements. The threshold LET was very low, well below the approximate 15 MeV-cm^2/mg value where upsets from protons are expected. Although we did not include proton tests in our study, upset from high-energy protons is likely to be important for these devices, particularly when they are used with low output load capacitance.

LM137 Negative Voltage Regulator: Although the LM137 is a negative-voltage regulator, it uses a Darlington npn output stage that is very similar to that of the LM117 with the input and output terminals interchanged. Negative-going transients were observed for the LM137 that closely parallel the positive transients from the LM117. The LM137 is less stable than the LM117, and the damped oscillatory behavior during the recovery period persisted for about twice as long for the LM137 compared to the LM117.

The SET cross section for a load capacitance of 0.32 μF is shown in Fig. 6, comparing results for two different threshold conditions. The cross section is about a factor of five lower for transients $>$ 0.5 V compared to the lower threshold voltage condition (0.2 V) that was used during the individual runs. The saturation cross section and threshold LET of the LM137 are very similar to that of the LM117 (Fig. 4), even though circuit design details are somewhat different for the two devices.

B. SEU Effects in Protection Circuits

Although the protection circuits in the two regulators are very similar, most of the experimental work on SEU effects was done on the LM137, using a laboratory ^{252}Cf fission source. After

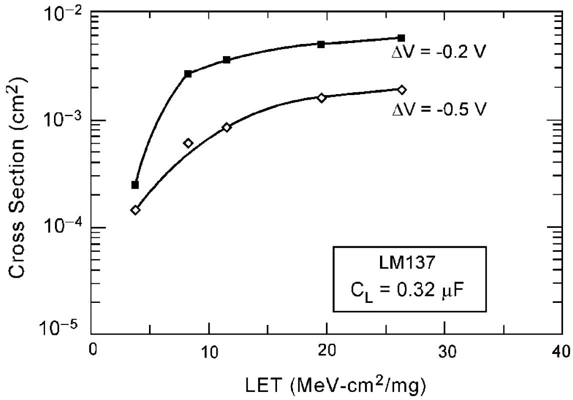

Fig. 6. SET cross section for the LM137 negative regulator for two different threshold conditions.

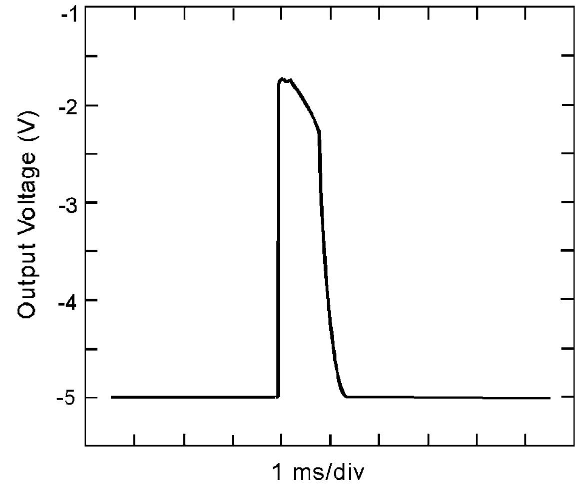

Fig. 7. Output voltage of the LM137 when the internal current protection circuit is triggered by californium ions.

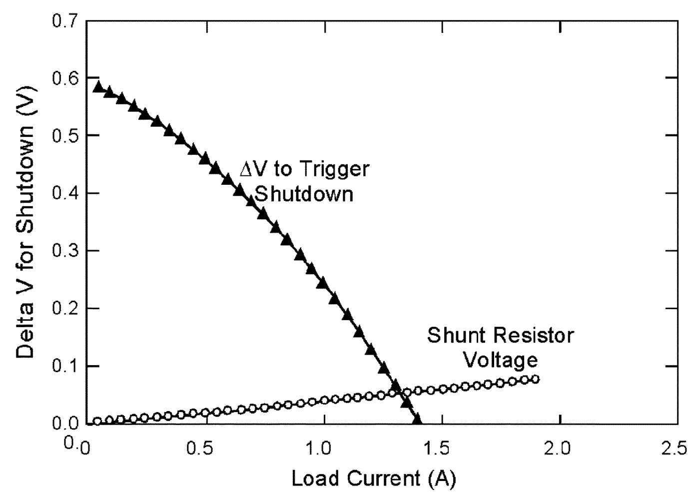

Fig. 8. SPICE analysis showing how the base-emitter voltage of the npn transistor in the current limit circuit of the LM137 is affected by output current.

correction for passive over-layers, the range of the fission fragments is approximately 10 μm for "heavy" fragments and 12.5 μm for "light" fragments. The depth of the n-isolation wells in these circuits is approximately 12 μm. One way to assign an effective LET for ^{252}Cf ions is to integrate over the ion range, yielding an effective LET of 21 MeV-cm$^2/\mathrm{mg}$ for heavy fragments and 24.5 MeV-cm$^2/\mathrm{mg}$ for the light group. This is applicable to npn and lateral pnp transistors where charge collection in the substrate is cut off by the buried layer, but not for substrate transistors where charge collection can extend beyond the isolation well into the substrate. Fortunately, substrate transistors are not directly involved in the current shutdown circuitry (see Figs. 1 and 2), and we expect that the tests with ^{252}Cf are a reasonable simulation of heavy ion effects once the correction is made for ion range.

Current Protection: Tests of the current overload protection circuit were done under various load conditions, using a thermoelectric cooler to limit the temperature rise in the device when it was operated at high load current. The LM137 regulator was in a vacuum chamber for those experiments. Device temperature was monitored with a thermocouple. When the load current was increased to approximately 550 mA the ^{252}Cf fragments could trigger the current protection circuit. A typical waveform is shown in Fig. 7. A dropout occurs at the output with widths from about 0.5 to 1.4 ms when the current protection circuit is tripped.

The current protection SEU mode does not depend on output capacitance. The cross section, measured with ^{252}Cf, was 6×10^{-5} cm^2. The area of the collector of the npn transistor in the current limit circuit is 1.2×10^{-4} cm^2, consistent with the mechanism where that transistor is turned on by the ion. A rough estimate of the event rate for galactic cosmic rays in space can be made by assuming that the LET threshold is 10 MeV-cm$^2/\mathrm{mg}$, and that the saturation cross section is the same as the cross section measured with ^{252}Cf. The resulting estimate is an upset probability of 0.5% per year (at solar maximum).

It was only possible to trigger current limiting when the regulator was driving a relatively high load current. Thus, this mechanism is unlikely to be important at moderate loads, even though it is important for applications with high loads. A SPICE analysis of the circuit was done to calculate the effect of different load currents on the threshold conditions for this mechanism. Those results are shown in Fig. 8, assuming an internal shunt resistor of 0.04 ohms. The ordinate shows how the base-emitter voltage of the npn transistor in the current limit stage (see Fig. 2) is affected by load current.

Thermal Protection: A clever circuit technique is used in both regulators that will shut down the regulator if a sudden thermal overload occurs. This is incorporated into the current protection circuit by locating the two transistors in the current protection circuit in different locations on the die. One transistor is close to the large-area output transistor, where most of the power is dissipated, and the other is at the opposite edge of the die. A large difference in localized temperature will activate the shutdown circuit within a few milliseconds [11].

Thermal shutdown could also be triggered by heavy ions. Tests of the thermal protection circuit were done by allowing the device to heat up to temperatures above $100°C$, and irradiating it with ^{252}Cf. When the ions were not present the device operated normally. Thermal shutdown caused the device to turn off for much longer periods—on the order of seconds—compared to

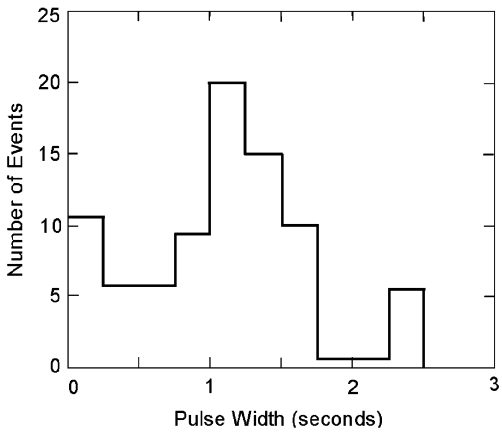

Fig. 9. Histogram of the dropout period for the second response mode of the LM137 voltage regulator.

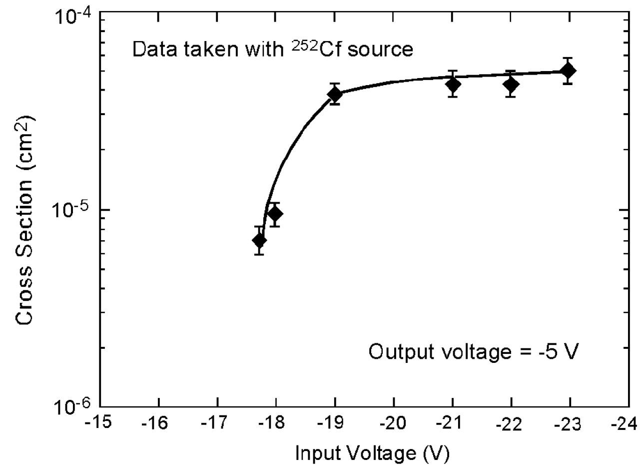

Fig. 10. Cross section for the shutdown mode of the LM137 vs. input voltage. The output voltage was -5 V.

the dropouts that could be triggered from current limiting when the device operated at lower temperature. Fig. 9 shows a histogram of the "off" duration for several events that occurred. Some were of shorter duration, but the majority persisted for one second or longer.

When the shutdown mode occurred, no short-duration transient was present at the output, implying that the output transistor current did not change during the process of triggering the shutdown mode. This verifies that shut down is caused by a transient in an internal transistor in the shutdown circuitry, not by a larger than expected transient (or current) at the output. Once shutdown took place, the output voltage decayed exponentially with a time constant equal to the load resistance and the output capacitance.

Thermal shutdown was investigated to a more limited extent during tests with heavy ions. The cross section for the shutdown response mode was 1.1×10^{-4} cm^2. The threshold LET for the shutdown mode was between 3.7 and 7.9 MeV - cm$^2/\mathrm{mg}$. The shutdown mode occurred when the 4.7 μF capacitor was in place at the output, as well as for tests with lower capacitance values. Thus, adding additional filter capacitors at the output will not prevent this mode from occurring (unless extremely large capacitors are used).

SEU triggering of the thermal shutdown mode could be suppressed by reducing the input voltage, i.e., lowering the differential voltage between the input and output. Fig. 10 shows the dependence of the cross section for thermal shutdown on input voltage in subsequent tests done with ^{252}Cf (the cross section with ^{252}Cf is about a factor of two lower than the cross section observed for shutdown during tests at BNL, probably due to the lower range of ^{252}Cf fission fragments). There is a sharp decrease at -17.7 V, indicating that the shutdown mode will not occur if the differential voltage between input and output is below 12 V.

As shown in earlier in Fig. 2, two 6.3-V zener diodes are present in the current limit circuit path between the input and output voltage in the LM137, which are used to lower the internal current limit trip condition when the input/output differential voltage exceeds 12.6 V. This changes the internal conditions for current limiting, increasing the sensitivity of the thermal shutdown circuitry to heavy ions, and providing an explanation for the experimental results obtained with ^{252}Cf.

Thermal shutdown was not investigated for the LM117, only for the LM137. The internal circuitry of the two circuits is similar, but there are differences. For example the internal sense resistor is about twice as large for the LM117 compared to the LM137.

V. Discussion

The wide range of possible application conditions makes it particularly difficult to deal with SETs in these types of voltage regulators, which are intended for use over a wide range of conditions. The SET response depends on several factors, including input/output voltage, load capacitance, load current, and operating temperature. Sorting out the effect of these variables and their possible interdependencies is a complex problem.

First, consider the dependence on voltage and capacitance. If the load capacitance is high—several microfarads or more—then the maximum output may be limited by the charge on the capacitor at the *input* to the device, as depicted in the simple diagram of Fig. 11. The limiting condition is that of shorting the input and output when the output stage turns on. If the two capacitors are equal, the maximum transient output is limited to $1/2$ the difference of the input and output voltages (other cases can be treated by simple circuit analysis). This elementary consideration causes the maximum output transient voltage to depend on input voltage. It also provides a way to bound the transient voltage by inspection that is particularly useful for applications with large output capacitance, although it assumes that there is sufficient resistance (or inductance) in the raw power source to make charge at the input the limiting factor for short-duration transients.

There are other reasons for the transient output voltage to depend on the difference between input and output voltage. Charge generation and collection also depend on voltage conditions, increasing with voltage. Although those effects can be investigated with circuit analysis programs such as SPICE, the modeling accuracy is limited, and does not incorporate the voltage

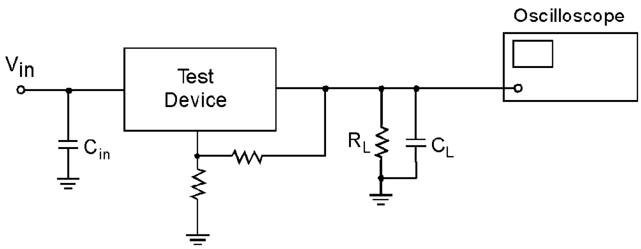

Fig. 11. Circuit model of a voltage regulator used for elementary analysis of the voltage dependence.

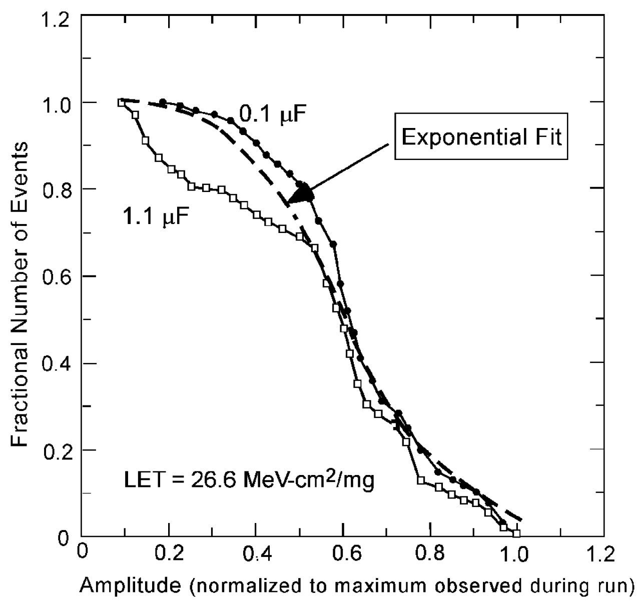

Fig. 12. Normalized distribution of transients for two different experimental runs with different load capacitance.

dependence of charge collection in the internal transistor structures.

Another important consideration is that many of the transients have amplitudes that are low enough so that they are unimportant in most applications. It is useful to develop a method that can be used to estimate the approximate fraction of the transients that have large amplitudes. One way to do this is by fitting distribution functions to the observed results. Fig. 12 shows the relative amplitude of transients for two different experimental runs of the LM117. The LET was 26.6 MeV - cm^2/mg. Each run corresponded to a different load capacitor. The figure normalizes the number of events as well as the peak amplitude that was observed during the run. The exponential fit that was applied to both data sets fits the results reasonably well for events with high amplitude, which are the main concern. This approach allows the effect of different load capacitors to be determined for different circuit conditions, provided the peak amplitude—as shown previously in Fig. 5—is known experimentally. It is more convenient and intuitive compared to detailed statistical analyses or histograms.

As discussed earlier, the internal protection circuits that are provided in these regulators can be triggered by heavy ions under certain conditions. For applications with load currents that are less than $1/2$ the maximum rated current, neither mechanism is likely to occur provided that the internal chip temperature is low enough to avoid triggering the internal thermal protection mode. However, long dropout periods can occur when either mode is triggered, which are clearly of concern for most applications. The LM117 and LM137 devices that were tested in this paper were in TO-39 packages, with internal current limiting at approximately 200 mA (for the condition where the input/output voltage difference is above 17 V).

Devices in power packages can provide currents up to 2.2 A, and will likely exhibit transients with higher output amplitude compared to devices in the smaller package because they can provide higher peak current. The current limit is determined by internal resistors in the specific die, not by external circuitry. Thus, the results in this study are only applicable to devices with the smaller package type. There are also different design variations, including "HV" devices that are rated for 65 V maximum input voltage compared to the 45 V maximum rating of the devices that were studied here. Different results should be expected for those devices because lower doping levels are required.

Transients from voltage regulators can affect other circuits in a variety of ways, increasing the difficulty of characterizing and defining transient events. Although we have emphasized transients with high amplitude, voltage regulators are often used for local regulation on circuit cards where transients of smaller amplitude can interfere with normal operation, or induce noise that is much greater than expected. The threshold LET for low-amplitude transients is very low, making it likely that protons can induce low amplitude transients in addition to heavy ions.

The work in this paper shows how different circuit and application conditions can affect SETs in voltage regulators. Load capacitance is one of the most important parameters, but other factors—including the actual chip temperature—can also be important. The circuit protection mechanisms are difficult to evaluate, requiring extensive testing, but may be critically important in system applications.

As discussed in [10] and [11], the circuit designs used in these regulators are complex, using sophisticated design techniques that rely on close matching of various internal transistors. However, there are obvious ways to reduce their susceptibility to SETs that do not require a deep understanding of the detailed circuit design. It should be possible to limit the maximum transient amplitude by adding a circuit that will clamp the voltage between the output of the amplifier and the input to the Darlington output stage (see Fig. 1), reducing the output voltage transient to $\sim$1 V. The duration of the transients could be reduced by slight changes in the output design, including using a lower value for the emitter degeneration resistor that would increase the current in the first stage of the Darlington transistor combination.

Various modifications could be used for the current limit and shutdown modes, including increasing the area of the sensitive transistors, and reducing the value of the internal transistors in that particular part of the circuit. Both approaches would increase the threshold LET, decreasing the event rate.

Although these techniques could be effective in reducing the sensitivity of these circuits to SETs, a detailed analysis would be needed in order to make sure that circuit stability and safe operating conditions within acceptable limits.

VI. Conclusion

This paper has examined single-event transients in voltage regulators. SETs in these devices are strongly affected by output load conditions, particularly load capacitance. A simple model was developed that allows characterization data to be extended to a broader range of application conditions, including a characterization method that evaluates the dependence of maximum output amplitude on capacitance and LET.

Input and output voltage conditions also affect SETs in voltage regulators, as well as the DC load. Internal circuits that provide current limiting and thermal overload protection can also be triggered by heavy ions. When those modes are activated, dropouts can occur that range from 1 ms to approximately one second in duration. The dropouts will occur even with large values of output capacitance, and are generally more difficult to deal with compared to short-duration output transients.

The sensitivity of protection circuits to SEU effects depends on the specific application conditions, and increase when high load currents are used. The cross section is comparable with the collector area of the individual transistors in the overload circuits, consistent with turn-on of those transistors from heavy ions.

References

[1] R. Koga, S. D. Pinkerton, S. D. Moss, D. C. Mayer, S. D. LaLumendiere, S. F. Hansel, K. B. Crawford, and S. D. Crain, "Observation of single event upsets in analog microcircuits," *IEEE Trans. Nucl. Sci.*, vol. 40, no. 6, pp. 1838–1844, Dec. 1993.

[2] R. Koga, S. H. Penzin, K. B. Crawford, S. D. Crain, S. D. Moss, S. D. Pinkerton, S. LaLumendiere, and M. C. Maher, "Single event upset (SEU) sensitivity dependence of linear integrated circuits (ICs) on bias conditions," *IEEE Trans. Nucl. Sci.*, vol. 44, no. 6, pp. 2325–2332, Dec. 1997.

[3] R. Ecoffet, S. Duzellier, P. Tastet, C. Aicardi, and M. Labrunee, "Observation of heavy ion induced transients in linear circuits," in *Proc. IEEE NSREC '94 Data Workshop*, 1994, pp. 72–77.

[4] R. L. Pease, A. L. Sternberg, L. W. Massengill, R. D. Schrimpf, S. Buchner, M. Savage, J. Titus, and T. Turflinger, "Critical charge for single-event transients (SETs) in bipolar linear circuits," *IEEE Trans. Nucl. Sci.*, vol. 48, no. 6, pp. 1966–1972, Dec. 2001.

[5] P. Adell, R. D. Schrimpf, H. J. Barnaby, R. Marenc, C. Chatry, P. Calvel, C. Barillot, and O. Mion, "Analysis of single event transients in analog circuits," *IEEE Trans. Nucl. Sci.*, vol. 47, no. 6, pp. 2616–2623, Dec. 2000.

[6] S. Buchner and D. McMorrow, "Single event transients in linear integrated circuits," in *Proc. Nuclear and Space Radiation Effects Conf. Short Course*, 2005, pt. 4.

[7] A. H. Johnston, G. M. Swift, T. F. Miyahira, and L. D. Edmonds, "A Model for Single Event Transients in Comparators," *IEEE Trans. Nucl. Sci.*, vol. 47, no. 6, pp. 2624–2633, Dec. 2000.

[8] S. Buchner, D. McMorrow, A. L. Sternberg, L. W. Massengill, R. L. Pease, and M. Maher, "Single event transient (SET) characterization of a LM119 voltage comparator: An approach to SET model validation using a pulsed laser," in *Proc. RADECS '01*, 2001, pp. 431–437.

[9] R. Pease, A. L. Sternberg, Y. Boulghassoul, L. W. Massengill, S. Buchner, D. McMorrow, D. S. Walsh, G. L. Hash, S. D. LaLumendiere, and S. C. Moss, "Comparison of SETs in bipolar linear circuits generated with an ion microbeam, laser light and circuit simulation," *IEEE Trans. Nucl. Sci.*, vol. 49, no. 6, pp. 3163–3170, Dec. 2002.

[10] R. J. Widlar, "New developments in IC voltage regulators," *IEEE J. Solid-State Circuits*, vol. 6, no. 1, pp. 2–7, 1971.

[11] R. C. Dobkin, "5 A regulator with thermal gradient controlled current limit," in *Proc. IEEE Int. Solid State Circuit Conf.*, 1979, pp. 228–229.