Degradation of Precision Reference Devices in Space Environments*

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Abstract

The degradation of precision reference devices is investigated to determine the relative importance of ionization and displacement damage. The results are compared with theoretical calculations of a basic bandgap reference circuit. Several of the device types were degraded severely at 20 krad(Si), with about the same degradation as that predicted for the basic bandgap reference circuit. One very high precision device with an internal heater performed far better than any of the other devices in the study.

I. INTRODUCTION

Precision references are key components in many spacecraft applications, particularly those involving analog-to-digital conversion or similar precision-measurement functions. The voltage drift tolerance of these devices ranges from intermediate precision (≈0.01%) to high precision (0.002%). Because of these very demanding requirements, voltage reference circuits can be affected by changes in internal device parameters that are considered to be second-order effects for more conventional circuits. For some devices, protons produce significantly more degradation than equivalent ionization levels with gamma irradiation because of displacement damage. In these cases typical radiation testing with gamma irradiation will underestimate the degradation in the actual space application. Figure 1 shows an example for the AD2710; in this case the degradation is about four times greater with protons than with gamma rays.

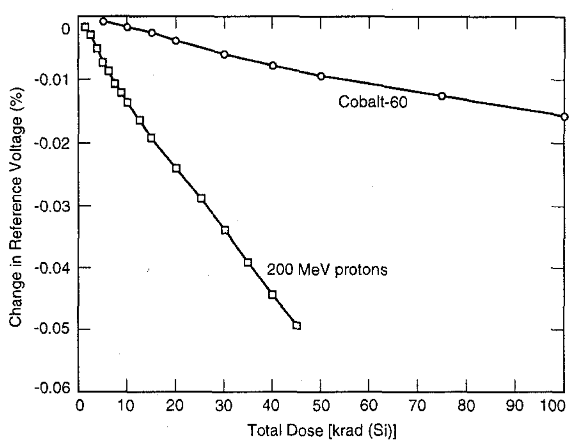

Figure 1. Comparison of the Effects of Proton and Gamma Radiation on Degradation of the AD2710 Precision Reference

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Radiation effects in bipolar linear devices can be very complicated because of the wide variety of internal structures that can be used in their design. Enhanced damage at low dose rate [1-5] — which affects only ionization damage, not displacement damage — adds an additional level of complexity to the evaluation of these devices. Tests with cobalt-60 irradiation at 0.005 rad(Si)/s were done for some of these devices and compared with tests at high dose rate to evaluate that aspect of device degradation. However, the key focus of the present work is that of understanding the underlying reasons for degradation of high-precision devices, not dose-rate effects.

Several different references were included in this work, including three high-precision devices with long-term stability below 0.003%, and one radiation-hardened device. All are fabricated with bipolar technology. Their characteristics are summarized in Table 1. The most critical parameter for these parts is usually long-term stability of the reference voltage, not initial accuracy. This is generally specified over a time period of 1000 hours. Although most applications can tolerate some degradation in stability, it becomes increasingly difficult to use them when the voltage shift due to radiation becomes significantly larger than the stability specification. For high-precision devices, the allowable voltage shift is very small, only a few hundred microvolts. One device, the RH1021, is fabricated with a process that is hardened to total dose, but not to displacement damage. The results in Section V will show that proton degradation was about the same for that device as for other devices, fabricated with unhardened processes.

The most unique device was the LTZ1000. It is much simpler in concept than any of the other devices, consisting of an internal subsurface zener reference, two matched npn transistors that are used to sense the internal chip temperature, and an internal heater that is used to raise the chip temperature to a fixed, constant value (this essentially eliminates the effect of temperature on voltage stability). The LTZ1000 requires external operational amplifiers for normal circuit operation, and does not contain any lateral or substrate pnp transistors. As shown in Table 1, the voltage tolerance and voltage drift specifications of the LTZ1000 were far better than any of the other devices.

II. EXPERIMENTAL PROCEDURE

Although other parameters may be important at higher radiation levels, the most critical electrical parameter for these devices is the output voltage. Electrical measurements were made with a Hewlett-Packard 3458A digital voltmeter. The

Table 1. Devices Included in the Voltage Reference Study

Device	Manuf.	Voltage (V)	Accuracy (%)	Stability (%)	Special Features
LTZ1000*	Linear Tech.	7.2	1	0.0002	Contains internal heater for temp. stability
LT1019A	Linear Tech.	10	0.05	0.002	
AD2710	ADI	10	0.01	0.0025	
REF02	ADI	2.5	0.3	0.01	
REF02	Linear Tech.	2.5	0.3	0.01	
AD674A	ADI	10	1	0.01	Internal reference in 14-bit A/D converter
RH1021	Linear Tech.	5	1	0.03	Guaranteed performance to 100 krad(Si)

*The LTZ1000 is not a stand-alone device, but requires two external op-amps. RH1056 op-amps were used to fabricate a working circuit with this device. Radiation tests were done in two ways: Irradiation of the complete circuits, and irradiation of only the LTZ1000 device.

short-term accuracy of this instrument is 0.6 ppm, about 1/3 of the stability specification of the LTZ1000. Although that limited the precision of the initial measurements, the output voltage exceeded the stability specification at relatively low radiation levels, so that measurement accuracy was not a significant factor in determining the radiation degradation.

Proton irradiations were done at the Indiana University cyclotron, using 200 MeV protons. The dose rate was about 20 rad(Si)/s. Total dose measurements were made at JPL, using two different cobalt-60 cells for high and low dose rate that have nearly identical physical geometry, but markedly different intensity. Devices were biased during irradiation. Bias was temporarily removed after each irradiation sequence so that the devices could be measured with the precision voltmeter under carefully controlled conditions. All of these devices are affected by temperature, and reproducible measurements require careful attention to measurement procedures. Electrical measurements were made after a five-minute warm-up period to allow thermal equilibrium to be established. A slightly longer warm-up period (10 minutes) was used for the LTZ1000 because of the internal heater, which requires a longer stabilization period. Control devices were measured at each interval to provide a secondary check on measurement precision.

III. Displacement Damage in Internal Transistors

Most of these circuits use a mix of high-performance npn transistors, for which these processes are optimized, and low-performance substrate and lateral pnp transistors. The pnp devices are usually used in subcircuits that can tolerate lower gain. Without test structures or processing information, it is not possible to directly determine the properties of internal transistors. However, the values shown in Table 2 are representative of transistors in linear integrated circuits that are designed to withstand total power supply voltage of 40 V or more, and are made with conventional processing techniques [6]. The change in gain at two different proton fluence levels are also shown in the table, assuming a proton energy of 200 MeV. Experimental results for npn and pnp transistors with neutron irradiation corroborate the assumptions in the table [7].

Although digital technologies are often changed to improve performance and density, linear circuit require close matching of emitter areas, high circuit voltage rating and high output current, and there is less advantage to be gained by process changes. The basic properties of these linear processes have changed very little over an extended time period. The base width of lateral pnp devices depends on interelement spacing (restricted by the voltage requirement), while the base width of substrate pnp devices depends on the base diffusion depth. Doping profile measurements and photomicrographs made on similar devices in our laboratory verify that the parameter values in Table 2 are applicable to current versions of linear devices that are made with conventional top-surface isolation.

Proton damage depends on energy [8]. We used 200 MeV protons for this study simply as a matter of convenience. The peak in the proton spectrum for most space systems is much lower, approximately 15 MeV; 15 MeV protons are about 2.8 times more effective at causing displacement damage in silicon devices as 200 MeV protons. Thus, the proton fluence values in this paper are ≈2.8 times higher than the comparable effective fluence of typical spacecraft.

Table 2 . Representative Displacement Damage Gain Degradation of Bipolar Transistors Used in Linear Circuits

Transistor Type	f_T (MHz)	Initial h_{FE}	h_{FE} after 1×10^{11} p/cm^2	h_{FE} after 1×10^{12} p/cm^2
Normal npn	250	300	270	206
Super-β npn	400	2000	1450	505
Substrate pnp	8	100	65	10 to 20
Lateral pnp	5	80	40	7 to 15

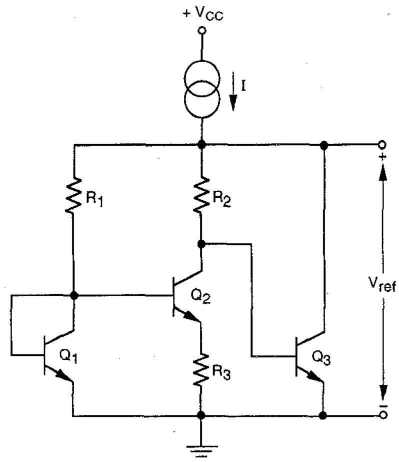

Figure 2. Basic Bandgap Reference Circuit Used for Benchmark Comparisons

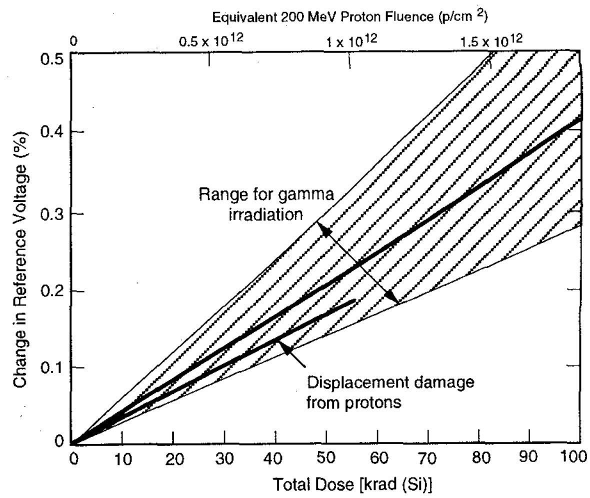

Figure 3. Calculated Degradation of Basic Bandgap Reference Circuit

IV. Basic Bandgap References

With the exception of the LTZ1000, the reference devices in this study all use variations of the basic bandgap reference to provide a stable internal voltage reference that is compensated for temperature effects. Although the actual circuits are far more complicated, it is still useful to examine degradation in a basic bandgap reference circuit to see how this fundamental building block is changed by radiation. A simple version of the bandgap reference circuit, which uses only npn transistors, is shown in Figure 2. The basic concept is that of compensating the base-emitter forward voltage V_{BE}, which has a negative temperature coefficient of approximately -2 mV/°C, with a corresponding positive gain term (proportional to absolute temperature) from the second stage. A first-order solution shows that zero temperature coefficient will result if the gain of the second term is 23, corresponding to an output voltage of 1.25 V [9]. More thorough analyses show that there is a second order quadratic term, which is corrected for in real reference circuits by adding additional circuitry [10].

These circuits must also accommodate the variation in transistor gain due to temperature, which is nominally ±50% from the room temperature value [11], except for the LTZ1000, which is designed to operate at a fixed temperature. The bandgap reference circuit relies on compensation of the competing temperature coefficients of forward voltage and the gain term, not feedback. This makes it inherently more sensitive to changes in internal component values than many other circuit parameters.

There is some latitude in the specific component values that are used in a bandgap reference circuit. Emitter area and resistance values both affect the performance. If the emitter areas of the transistors are widely different, high resistance values are required, decreasing the performance over temperature. The emitter area of Q2 was 1/5 that of Q1 and Q3, based on a sensitivity analysis of the temperature stability of the circuit with pre-irradiation gain values.

Total dose degradation of the basic bandgap reference circuit was calculated with the SPICE circuit analysis program, using total dose and neutron displacement data from operational amplifiers with npn input transistors [1-3, 7]. These results were shown in Figure 3. Gain degradation was the only factor considered; second-order effects such as the Early voltage, were not included. The total dose sensitivity is not necessarily the same for different processes, and a range of values was used to determine total dose response that correspond to different values of total dose damage for npn devices from the recent literature. This shows how total dose degradation in the basic reference would be expected to vary for different processes.

Displacement damage is less affected by processing, assuming devices with comparable base widths are used, and the simulation assumed that the npn transistors had a gain-bandwidth product of 250 MHz, at a current density 1/3 that of the current at which maximum gain occurs. The results of this analysis are shown in Figure 3, assuming that the damage is linear for both ionization and displacement damage. Note that even though this simple circuit does not use lateral or substrate pnp transistors, displacement damage still contributes a significant fraction of the net damage to this basic circuit in a proton environment. The change at 20 krad(Si) *[equivalent]* is about 0.07% for displacement effects, and between 0.04 and 0.12% for ionization effects, depending on the assumptions used for ionization dependence.

Circuit diagrams are only available for some of the device types in the study. The schematic of the REF02, shown in Figure 4, provides an example of the way in which bandgap references are used in real circuits. Transistors Q1 and Q2 are used to develop the forward voltage and compensating fractional voltage, but more complex circuitry using a differential amplifier is used to amplify the voltage difference between the two transistors. An additional resistor has been added to allow for external trimming of the temperature correction term. Additional gain stages are used to provide an output voltage of 5 V, but the manufacturer's schematic clearly shows the internal 1.23 V

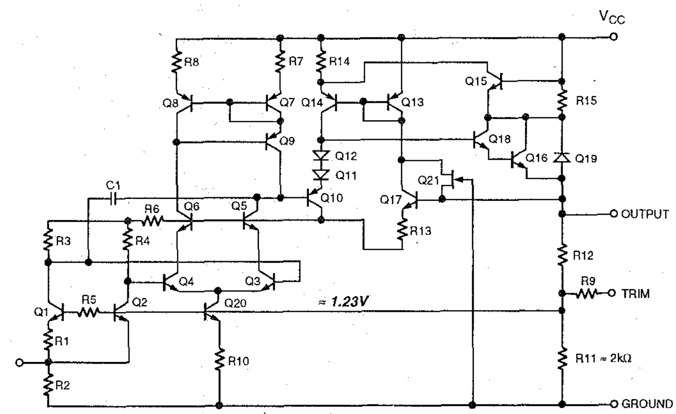

Figure 4. Schematic diagram of the Analog Devices REF-02

reference. This circuit is clearly far more complex than the basic bandgap reference, and contains some pnp transistors in other sections that could also contribute to degradation. Nevertheless, the results in the next section show that the estimates of degradation of the basic bandgap circuit are remarkably similar to the degradation of the more complex reference circuits.

V. Results and Discussion

Because calculations showed that the basic bandgap reference is significantly affected by displacement damage, proton tests were one of the key elements of the study. Proton damage experiments were done using 200 MeV protons at Indiana University. They were removed at selected intervals, measured with a high-precision voltmeter, and then subjected to additional irradiation. Ionization damage was determined by irradiating a different set of devices from the same date codes used for proton testing in a cobalt-60 facility using a dose rate of 50 rad(Si)/s. The test procedure was essentially the same as that used at the proton facility. In addition to tests at high dose rate, REF02 devices from both manufacturers were tested at 0.005 rad(Si)/s to determine how dose-rate effects would affect the references.

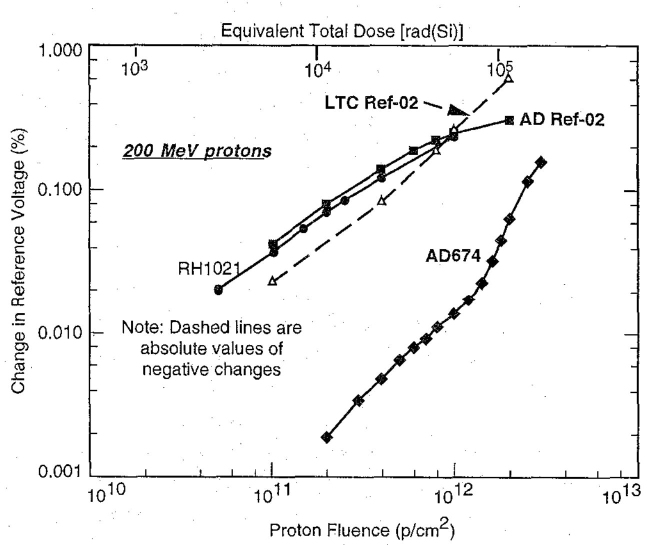

Figure 5. Proton Degradation of Moderate-Precision Reference Devices

A. Results with Protons

Figure 5 compares the change in reference voltage for the device types with intermediate precision when they were irradiated with protons. Some device types exhibited positive changes after irradiation, while others were negative (dashed lines are used for those that exhibited negative changes). However, the changes for different units of a specific device type and manufacturer were always in the same direction. Note that although the REF02 devices from two different vendors exhibited changes of nearly the same magnitude, they had opposite signs. The calculated degradation of the bandgap reference benchmark circuit is about 0.12% at a fluence of 4 x 10^{11} p/cm^2. The degradation of three of the intermediate-precision devices is very close to that calculated for the simple bandgap circuit. Note further that even though these devices are far more complex than the basic bandgap reference, and contain pnp as well as npn transistors, for all but the AD674A the degradation is nearly linear with increasing levels of radiation.

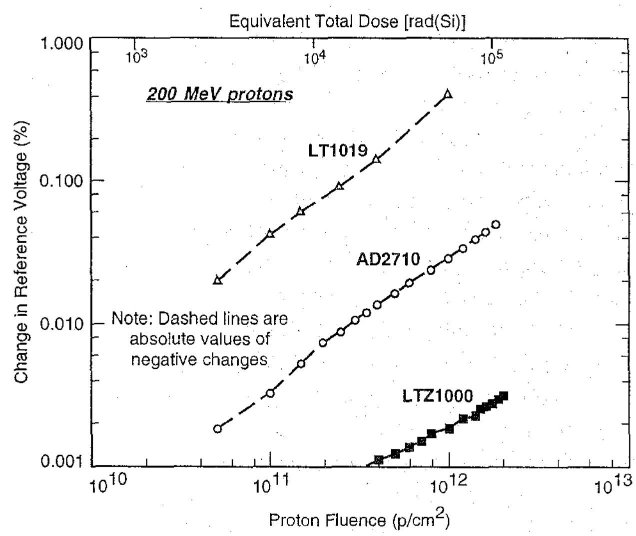

Figure 6. Proton Degradation of High Precision Reference Devices

The effects of proton irradiation on the three high-precision devices is shown in Figure 6. Although the degradation of all three device types was nearly linear, there were marked differences in the magnitude of the degradation. One of the high-precision devices, the LT1019, degraded rapidly at low radiation levels to the point where its performance was more nearly that of the group of moderate-precision devices. The AD2710 exhibited much less degradation.

The LTZ1000, with the internal heater, performed far better than that of the other two precision devices. However, as noted earlier, the LTZ1000 is not a stand-alone part, but requires two operational amplifiers and other external components in order to raise the internal chip temperature to a fixed value. It also is a very simple circuit with no internal pnp transistors, which relies on temperature control rather than compensation. Figure 7 compares the degradation of this part when it was irradiated separately with results when the entire circuit (using radiation-hardened RH1056 operational amplifiers) was irradiated with

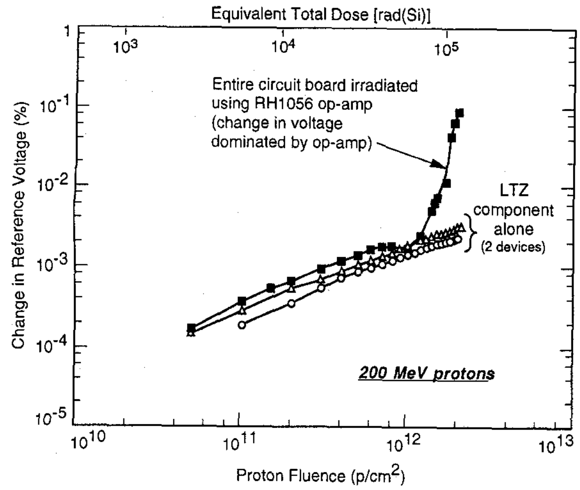

Figure 7. Degradation of LTZ1000 "Super-Zener" Device

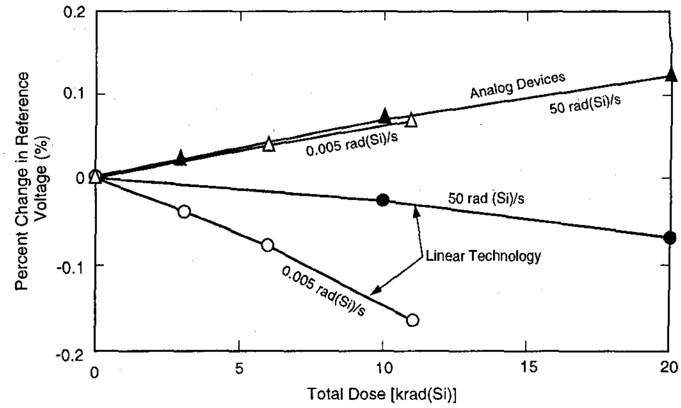

Figure 8. Comparison of total dose degradation at high and low dose rate for REF02

protons. The abrupt step at 1 x 10^{12} p/cm^2 when the entire circuit was irradiated is caused by degradation of the input offset voltage of the RH1056; this was verified by separate tests of the RH1056 in the same proton environment (note that the RH1056 is not hardened for displacement damage). If an op-amp with improved hardness were used, this step would not occur, and the reference would continue to operate with relatively small changes at much higher radiation levels.

B. Ionization Damage at High Dose Rate

Ionization damage of the intermediate-precision references was reasonably consistent with the calculations using the basic bandgap reference circuit. Most devices exhibited more damage when they were irradiated with protons compared to cobalt-60 irradiation that produced equivalent ionization damage, and in some cases the differences between proton and cobalt-60 results was quite large, possibly because they use lateral and substrate pnp transistors with much wider base width than the npn transistors used in the simple bandgap reference. The wider base width increases the sensitivity to displacement damage (see Table 2). An example of these results was shown earlier in Figure 1 for the AD2710, a high-precision device. The AD674A and RH1021 also exhibited substantially more damage when tested with protons than with gamma irradiation; the relative values are roughly the same as those estimated for the basic bandgap reference circuit. Table 3 compares the change in the reference voltage for several of the devices at high dose rate; the effect of protons is shown for comparison.

C. Low Dose Rate Results

Although dose-rate effects are not the focus of the present work, two device types were irradiated at 0.005 rad(Si)/s in order to determine how enhanced low dose rate (ELDR) effects could affect the results. Figure 8 shows the results of those tests, along with the results of the initial measurements on samples from the same lots at high dose rate. The REF02 from Analog Devices is more affected at high dose rate than the equivalent device from the same manufacturer, but there is essentially no dose-rate effect for the Analog Devices part. The Linear Technology REF02 is less affected by ionization damage at high dose rate, but the change in voltage is about four times greater at low dose rate.

The difference in the response of these devices may be due to either a fundamental difference in the ELDR sensitivity of the two manufacturers, or by differences in the internal circuit design. Several other parts produced by Analog Devices have exhibited very little dose-rate dependence, suggesting that the difference is most likely caused by differences in processing rather than circuit design.

Table 3. Relative Damage from Protons and Gamma Rays for Several Device Types

Device	Manuf.	% Change in V_{REF} at 20 krad(Si) Co-60	Protons	Ratio	Comments
LTZ1000	Linear Tech.	0.005	0.0065	1.3	"Super zener" with int. heater
LT1019A	Linear Tech.	-0.15	-0.165	1.1	
AD2710	ADI	-0.0035	-0.028	8.0	
REF02	ADI	0.12	0.13	1.1	
REF02	Linear Tech.	-0.06	-0.07	1.1	
AD674A	ADI	0.026	0.042	1.6	
RH1021	Linear Tech.	0.065	0.17	2.6	Hardened for ionization damage
Band-Gap Ref.	---	0.085	0.155	1.8	Theoretical circuit using only npn transistor

D. Overall Response of Circuit with Bandgap References

A number of issues affect the response of circuits that contain internal bandgap references. The most important factor is that the basic circuit relies on compensation of two competing effects, requiring relatively high gain to be effective. As noted in the analysis of the basic reference, even the relatively slight gain degradation that occurs for displacement damage in high frequency npn transistors at 1011 to 1012 p/cm2 (200 MeV) is sufficient to cause the output voltage to change beyond specification limits. The schematic diagrams provided by the manufacturers of several of these devices show that their internal design is remarkably similar to that of the basic bandgap reference considered in this study. Although the additional circuitry used to shift the output voltage and provide output drive capability may also affect the response, the radiation sensitivity of most of the reference devices was remarkably similar to that calculated for the basic reference circuit.

Displacement and ionization damage both affect the results. Although dose-rate effects may also be a factor, the basic reference relies on npn transistors which are less affected by ELDR than substrate and lateral pnp transistors [1,2]. This feature, along with the fact that the changes in output voltage caused by radiation are nearly linear with increased radiation level, make it unlikely that reference devices will exhibit the very large differences at low and high dose rate that are seen for other types of linear circuits.

The results show that there are inherent limitation in the basic bandgap reference circuit that affect the radiation response. The changes in output voltage that occur are small, but are sufficiently large to cause difficulty at relatively low radiation levels in applications that rely on stable voltage references. The LTZ1000, which uses temperature control instead of compensation, shows that it is possible to obtain far better performance in a radiation environment with alternative design approaches.

VI. Conclusions

These results for precision reference devices demonstrate that circuits with extremely high precision can be relatively sensitive at low radiation levels, even if they are fabricated with components that are relatively unaffected by radiation. The calculations for the basic bandgap reference show that second-order effects can become important for these classes of devices, including displacement damage, even for devices such as high f_T npn transistors that are normally not considered to be strongly affected by displacement effects. The results suggest that proton testing is required in cases where high precision is essential to circuit operation.

For devices with intermediate precision, the nearly linear behavior and magnitude of the change in voltage from radiation is about the same as that expected in a simple bandgap reference circuit for both ionization and displacement damage. This implies that their internal designs are not too dissimilar from the basic bandgap reference, and that similar assumptions about internal component matching are involved in the more elaborate designs used in practical circuits.

Two of the high-precision devices were much less affected by radiation. This is expected because such designs must incorporate additional corrections and compensation for internal component drift in order to meet the far more stringent temperature and stability requirements. The device with the internal heater that did not rely on compensation to reduce temperature sensitivity performed far better than any of the other device types, consistent with its design and the calculated sensitivity of the basic bandgap reference, which is used by all of the other device types.

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