Compendium of Single Event Transient (SET) and Total Ionizing Dose (TID) Test Results for Commonly Used Voltage Comparators

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***Abstract* — This data compendium reports single event transient (SET) and total ionizing dose (TID) test results for commonly used commercial-off-the-shelf (COTS) and radiation hardened voltage comparators targeted for possible use in space-based missions. Interesting trends in the variability of the radiation performance of these devices due to differences in lot date codes, manufacturers, circuit design, and test conditions are analyzed herein.**

I. INTRODUCTION

NEXT to operational amplifiers, voltage comparators are one of the most commonly used analog discrete integrated circuits (ICs), deployed in large quantities in nearly every spacecraft subsystem. More specifically, these linear bipolar devices consist of a high-gain differential amplifier and are often critical to high precision, signal processing applications, including analog-to-digital conversion and mixed-signal circuit design.

A comparator accepts two analog signals and outputs a digital signal, indicating which input is higher. Essentially this function is 1-bit quantization. As the differential input voltage is changed, the output remains stable. In most cases, these discrete ICs are very simple in function, however, dedicated comparator chips offer several performance advantages over open-loop operational amplifiers (without negative feedback) used for the same purpose. Critical parameters for voltage comparator performance include input bias current, propagation delay, rise and fall time, input common mode voltage range, gain, current consumption, input offset voltage, and hysteresis.

As the demand for high performance electronics continues to grow, there has been enormous interest in using unhardened commercial-off-the-shelf (COTS) voltage comparators for a wide gamut of space projects, in some of the most stressing radiation environments. Commercial voltage comparators offer cutting-edge technology in terms of speed and unparalleled electrical performance, at a fraction of the cost of radiation hardened devices. However, as with any linear integrated circuit system, voltage comparators consist of analog components that are extremely sensitive to radiation effects. Existing work has shown the input and output stages of these ICs are often significantly impacted by radiation degradation, ultimately limiting their performance.

More specifically, over the years, it has been well documented that linear bipolar voltage comparators are most susceptible to enhanced low dose rate sensitivity (ELDRS) [1] and single event transients (SETs) [2]-[3]. ELDRS implies enhancement of current-gain degradation when an IC is exposed to low dose rate total ionizing dose (TID) [4]. The low dose rate sensitivity of these devices is strongly dependent on the manufacturing process and circuit design. SETs are also a major concern for comparators, and are the direct product of ion-induced electron-hole pairs which cause current spikes on the transistor terminals. In fact, comparators are often critical drivers for digital circuits so propagation of even a single, short duration transient could trigger significant excursions in the device output voltage, potentially causing a system level failure. Overall, voltage comparators show the most transient sensitivity as a function of circuit design conditions as compared to other common analog, linear devices [70].

Finally, it should be noted as NASA missions continue to venture into some of the most stressing radiation environments, while pushing the envelope in terms of performance demands, it is becoming absolutely critical to understand the radiation risks associated with using COTS versus radiation hardened electronics in space. For completeness, this compendium provides a comprehensive set of SET and TID data on commonly used commercial as well as radiation hardened voltage comparators, in order to facilitate identification of relevant radiation risk trade considerations when selecting spacecraft components.

Overall, this guide is intended to help spacecraft designers and users alike, identify general trends in the radiation performance of this common part type (over time) to properly evaluate suitability for use in various space radiation environments. This includes identifying worst case radiation

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degradation characteristics under variable usage conditions (i.e. supply voltage, differential input voltage, temperature, etc.) that are essential to understand in order to deploy adequate design mitigation strategies. Finally, an assessment of part-to-part, wafer-to-wafer, and lot date code variability in the radiation performance (as a function of circuit conditions) across these commonly used voltage comparators is also summarized herein.

II. DATA ORGANIZATION

The purpose of this compendium is to serve as a reference to highlight pertinent SET and TID data in order to document trends in the radiation sensitivity of a variety of the most commonly used voltage comparators for critical space flight applications. The intent is to define the worst case radiation response under various usage conditions for commercial and radiation hardened voltage comparators. However, as a result of the application specific nature of radiation test data, it is important for the reader to use this compendium as a general reference and to investigate, in more detail, the test conditions and facilities used for each individual piece part test (see references for more detailed information).

Due to rapid advancements and scaling of technology, radiation effects test results on commonly used voltage comparators are continually presented on a yearly basis. The radiation data summarized herein was acquired by several government and industry test organizations over the last 20 years.

In Section III, specific SET information is analyzed for commonly used devices, while TID data is discussed in Section IV. Tables II and III provide a high level summary of all the collected SET and TID radiation data as well as report references for several unique part numbers across various manufacturers and test conditions. The data tables are grouped by part function (single, dual, quad comparators) and, for the most part, are organized in chronological order by test date and sample lot date code. The tables contain only abbreviated information; it is highly recommended for the reader to review the referenced data source for a complete discussion of the radiation sensitivity and the impact of lot date code variability and test conditions in the results.

III. SINGLE EVENT TRANSIENT (SET) TEST RESULTS AND DISCUSSION

It has been a well-studied fact that voltage comparators are highly sensitive to heavy ions. In fact, for some of the softest parts, several single events can occur per year in a stressing radiation environment, such as geosynchronous orbit.

In particular, a heavy ion hit on the sensitive transistor of a high-speed comparator can result in an output transient pulse that is several volts in amplitude and a few microseconds in duration. It is concluded from general trends in collected SET data, the LET threshold and saturation cross-section are strongly dependent on the voltage difference between the two comparator inputs (“differential input voltage” or ΔVin) as well as the supply voltage conditions. The differential input voltage is also known as the “overdrive” condition which sets the comparator threshold. In most cases, when ΔVin is increased above 200 mV, high amplitude and long duration transients in linear bipolar comparators are suppressed. For small values of the differential input voltage (<1V), as ΔVin decreases, the device transient sensitivity increases [5]-[6]. In fact, the probability of a high amplitude transient on-orbit in a commercial LM139 device is about three orders of magnitude higher for low level signal detection applications: ΔVin <50 mV as compared to high level: ΔVin >1V [70]. For comparison, in the LM139, ΔVin=550 mV results in 1 upset/year versus ΔVin=1.5V which correlates to 0.1 upsets/year (or 1 upset every 10 years) [70]. It should be noted, BiCMOS comparators demonstrate less dependence on the differential input voltage conditions because of the CMOS circuitry in the latter stages of the device construction. Fortunately, a majority of space applications use values of ΔVin above 50 mV, and in some cases >1V [70].

Furthermore, it was also demonstrated the SET sensitivity can also be dependent on circuit loading (especially for the LM139, when the load resistance is reduced <1.5 kΩ) [8].

Finally, as a general guideline, proton-induced single event transient signatures are not a major concern for voltage comparators as long the differential input voltage is high, >30 mV [15]. When ΔVin is low, around 10 mV, a typical proton-induced transient width is ~200 ns with a very small proton saturation cross-section (~$3x10^{10}$ cm^2/device for ΔVin=12.5 mV) [15].

Interesting SET results for five commonly used voltage comparators will now be discussed in more detail. Table II summarizes additional SET data for several other devices.

1) LM139

The LM139 is one of the most commonly used voltage comparators, with a very long space flight heritage, spanning over 30 years. It is a high precision, rail-to-rail, quad differential voltage comparator with 4-channels, and an open-collector output connected to a pull-up resistor. This device consists of a differential input stage with two common-collector to common-emitter amplifiers and four lateral PNP bipolar junction transistors. As compared to more complex devices (i.e. LM111), the construction of this voltage comparator is considered somewhat simple due to the absence of an internal feedback loop at the open-collector output stage, which typically assures saturation of the output transistor [23].

Since its inception, the LM139 has been manufactured and sold by a number of different suppliers. Over the years, it has been extensively demonstrated the radiation performance of this device is subject to lot date code variability. In particular, SET testing has shown the LM139 transient response is heavily dependent on the product’s manufacturing origin and wafer fabrication process [7]-[10], making it an interesting part candidate for discussion.

The LM139 was first introduced to the market by National Semiconductor Corporation (NSC) in 1972. Prior to 2005, there were several single event effects and total ionizing dose studies on this device that used die manufactured prior to 1999 on the original UK 4” wafer fab line (from the Greenock, Scotland facility).

In 2000, the manufacturing line of the LM139 (as well as National’s other high volume, analog, linear bipolar products) was moved to the NSC Arlington, TX facility. It underwent a 22% die shrink and was subsequently produced on a 6” wafer [7]. Following this Class I process change, the radiation performance (including the SET susceptibility) was documented as marginal [11].

As a direct result, NSC moved the manufacturing process back to a radiation tolerant UK 6” wafer fab line (Scotland) and a number of improvements were made to the process flow and circuit design, which subsequently improved the radiation performance of this device [7]. Texas Instruments (formerly National) currently manufactures the most common radiation hardened version of this part, the LM139AxRLQMLV. Note, an alternate part number for this die is also the RM139.

Heavy ion SET testing was specifically performed on the radiation hardened LM139AxRLQMLV device in 2008 by National Semiconductor at the Texas A&M (TAM) Cyclotron [7]. The trigger threshold was set to ±15 mV and the output was monitored for negative and positive-going transients [7].

Overall, it was observed the SET response of the radiation hardened version of the LM139 is strongly dependent on the test conditions such as the ion beam penetration and beam angle [7]. Beam facilities with limited range (like Brookhaven National Laboratory) and incident beam angles >0° (used to achieve greater effective LETs) can result in underestimation of the SET saturation cross-section [7]. These results indicate the geometry of the device sensitive volume must be accurately modeled for rate prediction calculations.

Other device operating conditions such as differential input voltage and supply voltage also have a significant impact on the SET characteristics including amplitude, pulse width, and saturation cross-section. Results from the most recent heavy ion SET testing of the LM139AxRLQMLV are shown in Figure 1 and are summarized in [7]. The SET cross-section dependence on the differential input voltage is indicated at low LET. Figure 1 also shows that as the supply voltage (Vcc) increases, the saturation cross-section is consistently lower (across the entire LET range), exhibiting an inverse relationship between Vcc and SET susceptibility.

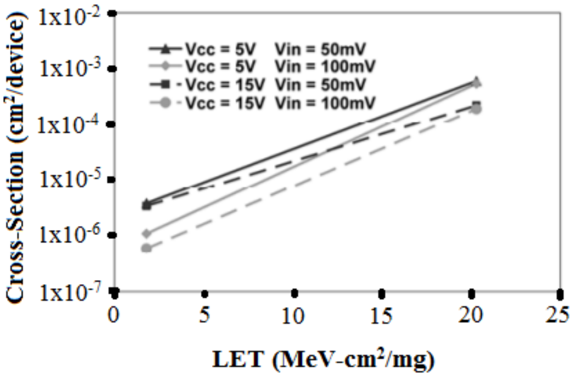


Fig. 1. LM139AxRLQMLV SET cross-section versus LET for various supply voltages and differential input voltages ΔVin (reported in [7]).

Figure 2 shows the same trend in the transient sensitivity as a function of various differential input voltages at a fixed supply voltage of Vcc=±5V. At high LET, the saturation cross-section dependence on ΔVin is negligible (also shown in Figure 1). For ΔVin <1V, the LM139 has the lowest LET threshold and one the highest saturation cross-section ~7x10^{-4} cm^2/device. For ΔVin =1V and 2V, the LET threshold is larger and the saturation cross-section is about an order of magnitude smaller.

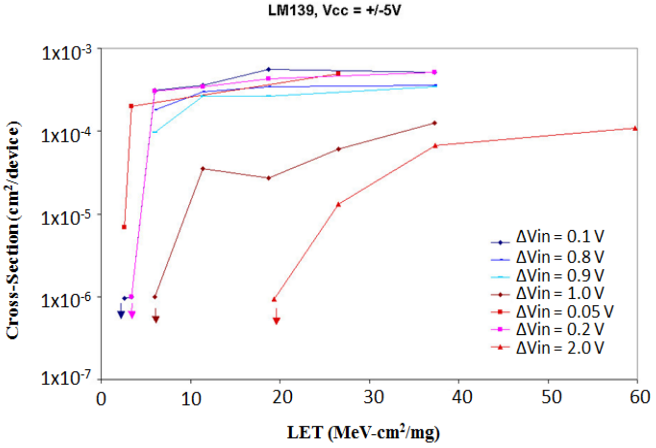


Fig. 2. LM139 SET cross-section as a function of LET for fixed supply voltage and varying differential input voltages (reported in [15]).

Other general notable observations on the transient signature characteristics for the radiation hardened version of the LM139 include: predominately negative-going SETs when the comparator output is high, fall times that match the part switching speed, *and a worst case, maximum pulse width of 3 μs* [7]. It was also observed, the transient amplitude is smaller when the comparator output state is low, as most of the transients never reach the power supply voltage rails [15].

As for the commercial version of the LM139, the transient sensitivity was also extensively characterized in the early 2000’s [8], [9], [12]. The lateral PNP input transistors were attributed as the cause of the SET sensitivity dependence on bias conditions [9]. It has been shown that transistors biased in the off-state (reverse biased) are most susceptible to transient effects [32]. More specifically, legacy testing (prior to the die shrink) showed the LET threshold and heavy ion saturation cross-section is also highly dependent on the input voltage differential (ΔVin) (similar to the radiation hardened version of the LM139), varying from an LET of 1-10 MeV-cm^2/mg and 1x10^{-5} to 3x10^{-4} cm^2/device (as first reported in [12]). The saturation cross-section is observed to be smaller and the part is less sensitive as ΔVin increases (for larger values of the differential input voltage, fewer transients reach their maximum amplitude). *Conversely, the commercial version of the LM139 device is most sensitive to single event transient effects (peak amplitude and duration) when ΔVin is small <500 mV.*

In general, it was observed for both the commercial and radiation hardened versions of this device, when the LET increases above 3 MeV-cm^2/mg, the transients reach their maximum saturation amplitude (rail-to-rail). At high LET, the transients hit the power supply voltage rails, where they settle for a short period of time and then decrease [15]. *The percentage of rail-to-rail transients is heavily dependent on the bias conditions. For ΔVin <0.7V, 90% of SETs were observed to saturate. At ΔVin=1V, less than 1% of the transients were rail-to-rail* [34].

The proton SET sensitivity of the commercial version of the LM139 was studied in 1998 with 200 MeV protons [10]. Noteworthy observations include transients that can reach rail-to-rail saturation amplitude with durations longer than 200 ns (max 1 µs). The proton threshold energy (E_o) was observed to be ~30 MeV for ΔVin=12.5 mV. The proton threshold increases for larger input voltage differentials [10].

It is also important to note, the SET recovery and the transient waveform shape, for both the commercial and radiation hardened versions of the LM139, is strongly dependent on the value of the output pull-up resistor [7]; however it does not impact the part SET sensitivity (LET threshold and saturation cross-section) [15]. Figure 3 shows typical transient waveform shapes (same input bias conditions and LET value) for different values of load resistance. There is a direct relationship between the load resistor value and the duration of the transient exponential decay [34].

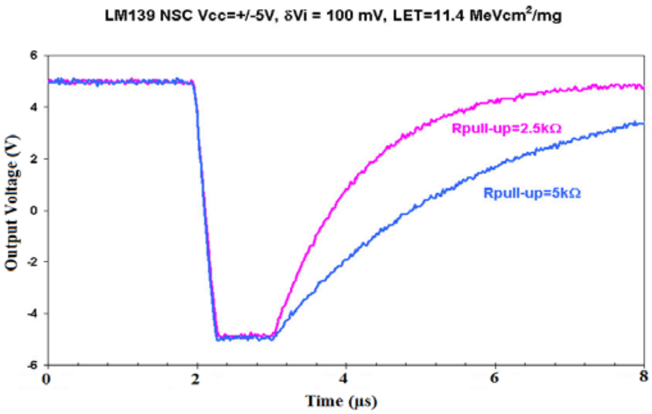


Fig. 3. Typical LM139 transient waveform shapes for two different pull-up resistor values (reported in [15]).

Finally, a study in 2009 showed the LM139 SET sensitivity is somewhat dependent on temperature (increase in amplitude and SET threshold at high temperature). As the device temperature is increased >100°C, the slew rate decreases (worst case up to 50%) and as a result, the recovery time from the transient increases [33].

Collectively the results documented over the years for both the commercial and radiation hardened versions of the LM139, emphasize the application specific nature of this device's single event transient performance.

2) IS-139ASRH

The Intersil IS-139ASRH is a single event radiation hardened quad voltage comparator. Functionally, it is equivalent to the industry standard, commercial version of the LM139. Unlike its commercial counterpart, however, the IS-139ASRH is constructed on Intersil's proprietary dielectrically isolated (DI), Rad Hard Silicon Gate (RSG) BiCMOS process which incorporates vertical NPN and PNP transistors (as opposed to lateral PNP transistors in the commercial version of the LM139). The IS-139 also includes a triple redundant comparator architecture, followed by a SET hardened (CMOS) majority voting logic block, on-chip filtering, and optimized device sizing for transient mitigation [16].

Transient testing was performed at TAM to an LET of 83.9 MeV-cm^2/mg (gold ions) under various differential input voltage or "overdrive" conditions. *As ΔVin was increased to 5.8 mV (and above), the comparator output transients were completely eliminated over a range of input capacitance, input resistance, and three different supply voltage conditions [16]*. Therefore, the worst-case transient LET threshold for the IS-139ASRH is several times larger than that for the LM139, indicating this device is substantially less sensitive than its commercial counterpart. Note, below this minimum 5.8 mV overdrive threshold, transients on the order of *2 µs* in duration were observed for the IS-139ASRH, which is consistent with prior conclusions of increased device transient sensitivity for very small differential input voltages [16]. Note, the maximum transient duration of the LM139 was 3 µs [7].

3) LM111

The Texas Instruments (formerly NSC) LM111 is a single, high speed, differential voltage comparator. The device has only one channel and an open-collector, open-drain output. It uses a PNP substrate transistor, connected as an emitter-follower at the input, and it has a somewhat more complicated layout as opposed to the LM139 [6]. The emitter-follower transistors then drive a differential NPN transistor in the second stage of the circuit [6].

The LM111 test samples were characterized for SET sensitivity at room temperature and at 76ºC using the 15 MeV/amu beam at the TAM Cyclotron. The SET measurements were performed by the Jet Propulsion Laboratory (JPL) in 2009 [45].

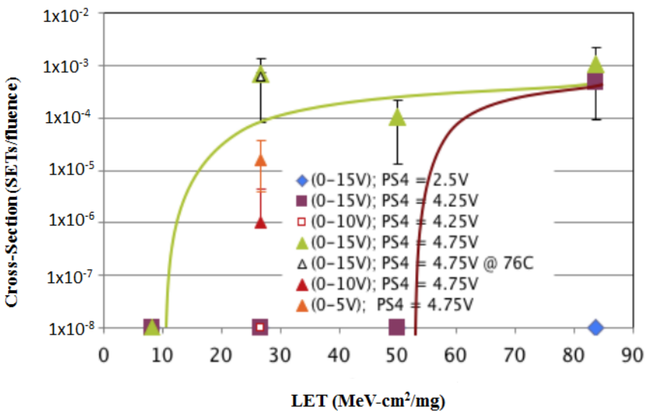


Fig. 4. LM111 SET cross-section versus LET for various supply voltages and differential input voltages (note colored curves are intended to be guides and are not Weibull fits to the data) (reported in [45]).

Figure 4 plots the average SET response for transients greater than -100 mV (negative-going transients) for different supply voltage (Vcc) and differential input voltages (ΔVin). Note, in this case ΔVin >2V (large values). Interestingly, the response curves show that as ΔVin increases (above 4V), the LET threshold decreases, indicating the worst case biasing condition is Vcc=15V and ΔVin=4.75V (high supply voltage and large differential input voltage). It is also important to note, the increase in temperature from ambient to 76ºC did not significantly impact the measured SET cross-section.

Additional testing of the LM111 showed predominately negative-going transients at the output. Similar to the LM139, the transient amplitude and duration were also strongly affected by values of ΔVin <1V and less impacted by larger values of the differential input voltage [6], [10], [41], [42]. For very small values of ΔVin (20 mV), the saturation cross-section was experimentally observed to be $8x10^{-6}$ cm^2/device (at Vcc=5V) [6]. The response is driven by the emitter current in the substrate PNP transistor. It was also demonstrated the LM111 shows a more gradual dependence on the differential input voltage, compared to the LM139, because of the emitter-follower configuration which does not have the sharp cutoff conditions of the differential transistor pair used in the 139 circuit [6]. In general, the LM111 maximum transient pulse amplitude was observed to be 6-12V and 0.4-1 µs in duration [10], [40], [41]. Interestingly, the worst case saturation cross-section (~$1x10^{-3}$ cm^2/device) and LET threshold (<3 MeV-cm^2/mg) was observed for the highest supply voltage, Vcc=15V [41].

4) *MAX997*

The Maxim Integrated MAX997 is a COTS, low power, ultra-high-speed voltage comparator with internal hysteresis. The MAX997 is optimized for single +3V or +5V applications. Common uses of this device range from GPS receivers to high-speed sampling circuits, line receivers as well as threshold detectors.

The SET measurements were performed by MEI Technologies and Goddard Space Flight Center (GSFC) at TAM with the 15 MeV/amu beam. The date code of the test samples was 0531. The test conditions include Vcc set to 4.3V (high bias) and 0V (low bias). Test temperatures included 21ºC (room temperature), 45ºC, 65ºC, and 85ºC [13].

Overall, there was no general temperature dependency on the SET pulse shape indicated by the results. It was noted, however, the pulses appeared to be longer in duration (≥20 ns) at the highest test temperature (+85ºC). The device LET threshold was reported to be <2.7 MeV-cm^2/mg with maximum pulse amplitudes of 4-5V and typical pulse widths ranging from ~10 to 20 ns (increasing with LET value, up to the maximum LET tested of 84.1 MeV-cm^2/mg).

Finally, the devices are more susceptible in the “high” bias condition of 4.3V (cross-section of ~$4x10^{-6}$ cm^2) as opposed to the “low” bias condition (cross-section of $1x10^{-6}$ cm^2), especially at low LETs [13]. This behavior is consistent with the observations documented for the LM111.

5) *RH1011M*

The RH1011 is a radiation hardened, general purpose comparator manufactured by Linear Technology on their in-house Class S process flow, using a 7 µm bipolar process. Although it is pin compatible with the commercial LM111, it offers significant design advantages including four times lower bias current, six times lower offset voltage, and five times higher voltage gain [44].

This device was tested in 2012 at the Lawrence Berkeley National Lab (LBNL) (at room and elevated temperature) as discussed in [17].

This device only demonstrated slight SET sensitivity under varying differential input voltage conditions. The measured SET cross-section was observed to be ~1.6% of the total area of the die and the results were not dependent on temperature [17]. The worst case transient pulse duration and amplitude occurred when ΔVin was close to the offset voltage or the inverting input bias was close to the hysteresis boundary voltages [17]. The widest SET pulse width was on the order of the RH1011 specified response time.

The report in [17] recommends designers perform a circuit simulation for this part by injecting transients as wide as the maximum response time, while varying the device bias during these injections The same trends apply, as previously noted for the other voltage comparators, for smaller differential input voltages, the larger the SET cross-section. With the appropriate capacitance filtering at the output, the transients were fully mitigated up to an LET of 114 MeV-cm^2/mg at room and elevated temperature of 100°C [17]. The selection of an appropriate parasitic capacitance is extremely critical to successful circuit mitigation design strategies, such as RC filtering.

IV. TOTAL IONIZING DOSE (TID) TEST RESULTS AND DISCUSSION

In terms of the low dose rate total ionizing dose (TID) response in voltage comparators, sensitive parameters that can experience significant degradation include input bias current ($+I_B$ and $-I_B$), response time, supply current (Icc), gain, input offset current (Ios), and input offset voltage (Vos). The low dose rate performance is also strongly dependent on manufacturing process as well as circuit design.

1) LM193

The LM193 is a low power, low offset, dual differential voltage comparator manufactured by Texas Instruments (formerly NSC). This device also underwent several die revisions over the years (including a die shrink) similar to the LM139 as discussed in Section III. Like the 139, the radiation performance of the LM193 is subject to date code variability. For lot date codes between 1999 and 2002, the LM193 TID performance was characterized as marginal [11]. Since then, there have been a number of process and layout changes which have significantly improved the part's radiation performance [11].

The "ELDRS immune" space grade version of this device is the LM193AxRLQMLV, manufactured on the NSC radiation tolerant UK 6" (Scotland) wafer fab line. Based on test data presented in [11], the LM193AxRLQMLV is rated to 100 krad(Si) for both high dose rate (HDR) and low dose rate (LDR) applications. Based on the test results, it was demonstrated the HDR (37 to 45 rad(Si)/s) test condition for these space grade devices is worst case (largest parametric drifts as a function of radiation exposure) as compared to LDR irradiation (0.01 rad(Si)/s) (as shown in Figure 5). As expected, the most radiation sensitive parameters included input bias current (Figure 5), input offset voltage, and response time [11]. The input offset current and supply current remained relatively stable throughout the test. Furthermore, the HDR unbiased test condition, with leads shorted during irradiation, was also the absolute worst case.

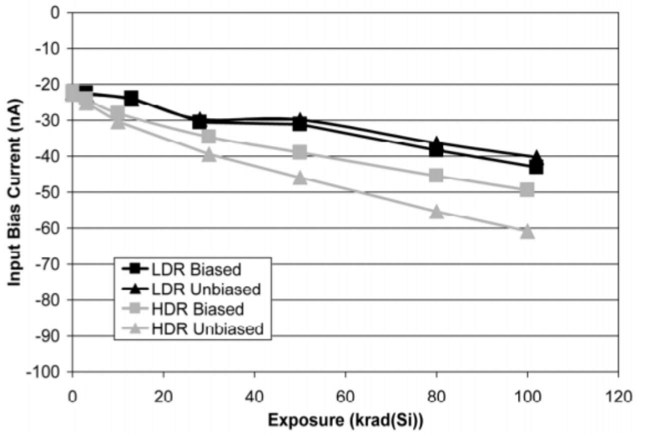


Fig. 5. LM193AxRLQMLV change in input bias current as a function of total dose for the low dose and high dose rate irradiations (Vcc=5V and Vcm=0V) (reported in [11]).

For comparison, HDR and LDR TID test results for the commercial version of the Texas Instruments/National Semiconductor LM193 is discussed herein, in order to highlight the enhanced low dose rate sensitivity of the COTS version of this device. TID testing was performed at the Jet Propulsion Laboratory (JPL) in Pasadena, CA. The parts were from lot date code 9950G. Test conditions included biased and unbiased irradiation at both high (50 rad(Si)/s) and low (0.01 rad(Si)/s) dose rates up to an accumulated dose of 200 krad(Si) (HDR) and 30 krad(Si) (LDR) respectively.

Overall, the LDR parts began to exceed the manufacturer spec limits between 3.6 and 6 krad(Si) (input bias current) while the HDR test samples remained within spec past 30 krad(Si). These results indicate the commercial version of the LM193 comparator is extremely sensitive to low dose rate effects, with the parametric degradation considerably more worst case as compared to the HDR irradiation (see Figure 6). Note, these results are in direct contrast to the trends in the TID test data for the radiation hardened version of the LM193.

For all test groups, the input bias current (I_B) demonstrated the most significant degradation as highlighted in Figures 6 (under various test conditions).

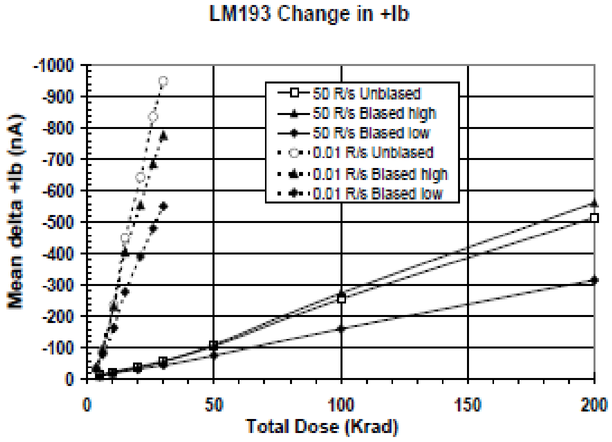


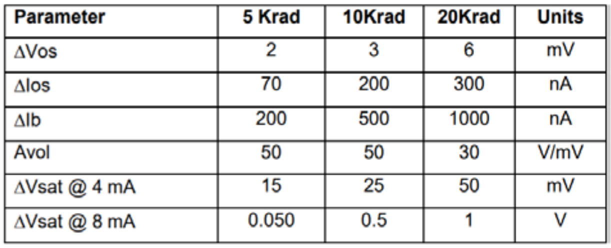
Fig. 6. Commercial LM193 change in input bias current ($+I_B$) as a function of total dose for low dose and high dose rate, biased and unbiased irradiations.

Most notably, the input bias current parametric degradation for the commercial LM193 showed considerable bias dependency in the results, while Vos (although it remained in spec to the highest levels tested) exhibited both bias and dose rate dependency. For Vos, the results at low dose rate were worse for the unbiased case, indicating the strong dependency on irradiation bias conditions. It is important to note in mixed signal applications, offset voltage errors can significantly affect the functionality of a circuit, especially when a large dynamic range is required [18].

Other notable observations during the LDR testing, included a significant decrease in the supply current, signifying the gain in the current sources degraded. Also, the devices were no longer able to sink current (in the 8 mA condition) above 20 krad(Si), indicating insufficient base drive to the output transistor. As expected, other sensitive parameters observed during this test were input offset current (Ios) and open loop gain (Avol).

In summary, the commercial version of the LM193 is considered usable only to ~15 to 20 krad(Si) in the ionizing space radiation environment, depending on the parametric tolerance of the circuit application. For design purposes, the commercial version of the LM193 is not recommended for applications exceeding 20 krad(Si). Based on the results of this JPL test, Table I provides general guidelines to summarize the LM193 statistical worst case radiation-induced degradation for critical parameters (across all test conditions).

TABLE I
SUMMARY OF LM193 STATISTICAL WORST CASE RADIATION-INDUCED DEGRADATION FOR CRITICAL PARAMETERS



Parameter	5 Krad	10Krad	20Krad	Units
ΔVos	2	3	6	mV
ΔIos	70	200	300	nA
ΔIb	200	500	1000	nA
Avol	50	50	30	V/mV
ΔVsat @ 4 mA	15	25	50	mV
ΔVsat @ 8 mA	0.050	0.5	1	V

3) RH119 / LM119

The Linear Technology RH119 is a dual comparator that features low input offset voltage and current and high voltage gain. The device is manufactured on a radiation hardened Class S production line and rated to 100 krad(Si) for high dose rate TID. The commercial counterpart to the RH119 is the LM119 (fabricated entirely with NPN transistors), which like the LM193, has been extensively characterized for ELDRS susceptibility in the past [14].

The TID testing on the RH119 was performed at the Jet Propulsion Laboratory (JPL) (log numbers 2162 and 2171). The parts were from lot date code 0429A. Test conditions included biased and unbiased irradiation at both high (25 rad(Si)/s) and low (0.005 rad(Si)/s) dose rates up to an accumulated dose of 15 krad(Si) for all test samples. Electrical characterization was performed at ambient room temperature.

Overall, no functional failures were observed in either the HDR or LDR testing up to and including 15 krad(Si) and all parameters remained within the manufacturer spec limits.

The only parametric measurements that showed very slight degradation were input bias current (I_B) and input offset current (Ios). For the Ios parameter, the changes were the most significant (although it did not exceed the spec limit) under bias during irradiation. Finally, the results indicated the RH119 did not demonstrate any ELDRS effects as there was no measurable difference between the amount of degradation for either the high or low dose rate testing.

For comparison, the Texas Instruments space grade equivalent of the RH119 is the LM119xRLQMLV (manufactured on the UK 6” wafer fab line). This device was tested at high and low dose rates and passed all parametric spec limits up to 100 krad(Si) as discussed in [14]. The input bias current parameter showed the most degradation. However, it should be noted, these LM119xRLQMLV devices also showed considerable variation in TID-induced parametric degradation across different wafer lots, indicating the importance of lot specific acceptance testing [14].

Finally, it should be noted, the commercial version of this device, the LM119, is very soft (<10 krad(Si)) with the biased condition demonstrating worst case performance. The most sensitive parameters included input offset current (Ios) and input bias current (I_B). However, it was documented the commercial version of the LM119 does remain functional up to 50 krad(Si) under HDR and LDR, biased and unbiased test conditions [55].

4) LM139

The history of the LM139 die revisions and process changes are discussed in Section III (1). The LM139 consists of four independent voltage comparators (quad) and is commonly used because it offers design engineers a wide supply voltage range to work with as well as low input offset voltage (2 mV typical), low input bias current (25 nA typical) and high precision. Over the years, it has been well documented, this device has been extensively characterized in the total ionizing dose environment, especially for its low dose rate sensitivity and significant enhancement in current-gain degradation [23]. As mentioned previously, the radiation performance of this device is subject to significant lot date code and part-to-part variability.

Based on collected LM139 total dose test data, from the last decade, the biased test condition has been demonstrated to be worst case with the most sensitive parameters including input bias current (I_B), input offset voltage (Vos), and sink current (Isink) [22].

Devices manufactured on the Arlington, TX 6” wafer fab line (fabricated in September 2000) showed marginal performance with parametric failures below 30 krad(Si) [21], including wide channel-to-channel variations in the TID response. Specifically, the input offset voltage measurement showed enhanced degradation in the delta radiation response of comparator 1 versus the other three comparators in the package [21]. Figure 7 shows a -15 mV shift in the input offset voltage at 30 krad(Si) for channel 1, while the other three channels shifted <5 mV up to 100 krad(Si). As discussed in [21], the metallization layout was analyzed to identify a susceptible region of the die where metal overlays the active area on one of the transistors in the comparator 1 current mirror. As a result, NSC made modifications to the metal mask to correct the issue for follow-on die revisions.

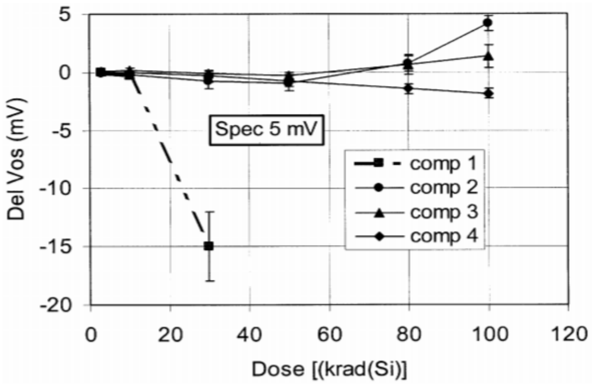


Fig. 7. LM139 delta input offset voltage (Vos) for Arlington, TX 6” wafer line (reported in [22]).

In 2008, the ELDRS free version of this device, the LM139AxRLQMLV, was characterized under biased and unbiased irradiation test conditions [11]. The test samples met all of the manufacturer specifications up to and including 100 krad(Si) for high and low dose rate exposures. Similar to the TID response of the radiation hardened LM193, the input offset voltage drift showed bias dependency. A negative drift was observed for biased parts while a positive delta was noted for unbiased parts [11]. Furthermore, the channel-to-channel variation in the parametric response was significantly reduced as compared to older versions of the LM139 die.

Additionally, the enhanced hydrogen sensitivity in the TID response of the radiation hardened version of the LM139 should also be noted. As discussed in [22], several test samples of the LM139 were irradiated at 10 rad(Si)/s for two values of H_2 soaking (prior to irradiation), 100% and 1%. The data is presented in Figure 8 which shows an order of magnitude increase in the delta input bias current as a function of dose when the LM139 package is exposed to various molecular hydrogen contents (as compared to the baseline NSC LM139 HDR and LDR test samples which were not exposed to hydrogen). Input offset voltage also increased as a result of hydrogen exposure.

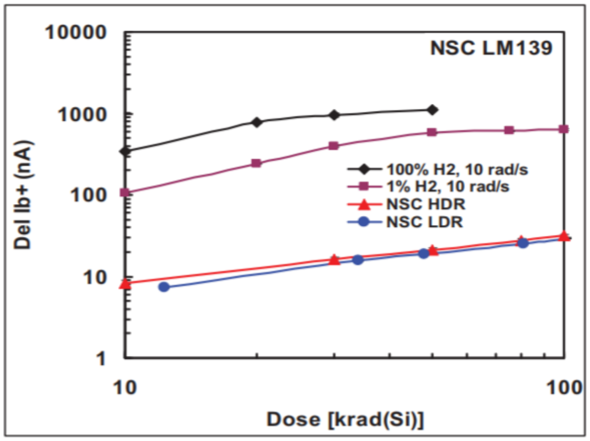


Fig. 8. ELDRS immune LM139 delta input bias current (I_B) for various hydrogen exposures and dose rates (reported in [22]).

Finally, a circuit analysis study of the TID induced degradation of a commercial version of the LM139 voltage comparator was performed in [23]. The application load resistance was set to 5 kΩ and voltage gain was analyzed as the main parameter of interest. It was determined the high impedance (common-collector), differential input stage of the device is responsible for most of the degradation, up to 20 krad(Si). Also at the input, the radiation-induced decrease in the supply current can be potentially attributed to degradation of the current sources [32]. This effect can impact both voltage gain and slew rate in the LM139 circuit. The output stage of the LM139 does not significantly degrade until much higher TID levels (due to the saturation operating mode of the open-collector output transistor), while the intermediate (common-emitter) amplifier stage did not show any measurable impact on the overall circuit degradation. It is also important to note, for small load resistances <5 kΩ, degradation of the output stage results in functional failure of the device [23].

Overall, it is important to emphasize the application specific and lot date code sensitivity of the LM139.

5) LM111

The LM111 is a commercial single high-speed voltage comparator that works over a wide range of supply voltages. It is also a very popular part choice with designers because it drives large loads over a wide output voltage range while featuring low input bias currents [20].

Like the LM139 and LM193, the LM111 was also moved from the UK fab to the Arlington, TX line, and then back to the UK 6” fab (for the production of the space grade version of this device). As a result, over the years, the LM111 has also demonstrated considerable part-to-part variability in the low dose rate response to the total ionizing dose environment. In general, it has been shown the radiation performance of this device is strongly dependent on a number of variables including manufacturer, wafer processing, operating conditions, temperature, thermal cycling, the type of irradiation (gamma versus electrons), and dose rate [14].

Specifically, degradation of the LM111 input bias current (I_B) has been analyzed extensively [19]. A study of the bimodal irradiation response observed for the input bias current of the National Semiconductor LM111 (from a single lot date code) was presented in 1999 [20]. As part of this investigation, the test devices (from the NSC UK 4” wafer line) were irradiated in a Co-60 gamma cell at high and low dose rates as well as elevated temperatures by NSWC Crane. As shown in Figure 9, nearly one in three devices from the same wafer lot (7D) demonstrated a significantly larger increase in I_B as a function of total dose [19].

At the time, the cause of this effect was attributed at the circuit level. Specifically, to the substrate PNP input transistors degrading differently due to increased base current in the die across the same wafer lot. It was also determined that the degradation of the lateral PNP current sources driving the inputs and the NPN differential amplifier compete with the input transistor degradation to produce this bimodal response [20].

Later studies identified other key factors which appear to cause the build-up of TID-induced oxide defects in the LM111, which include variations and stresses from the burn-in pre-irradiation thermal cycle process performed during part packaging (as discussed in [19]).

Overall it has been demonstrated the LM111 circuit is much more sensitive to small local fluctuations in defect accumulation as comparted to other commonly used voltage comparators available on the market today. Once again, this drives the importance for proper evaluation and consideration of this bimodal distribution during radiation lot acceptance testing. *It is recommended, at a minimum, larger sample sizes of this device be tested in order to maintain confidence in the data distribution* [20].

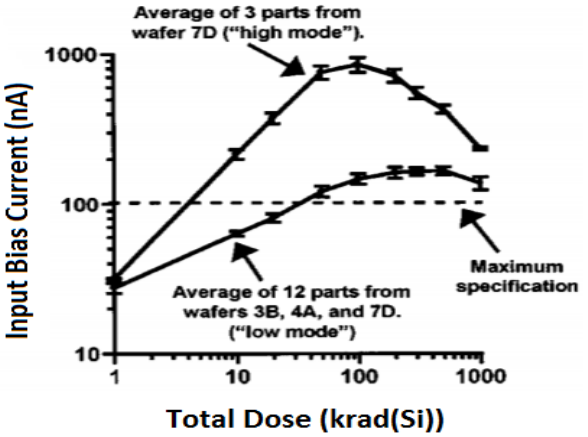


Fig. 9. LM111 input bias current response for room temperature high dose rate 50 rad(Si)/s irradiations. The results indicate a broad distribution in circuit response (reported in [19]).

V. SUMMARY

Analog voltage comparators are one of the most commonly used components, critical to electronic hardware design for space flight projects. As with most linear bipolar devices, it has been widely documented over the years, these part types are extremely sensitive to radiation effects, especially single event transients (SETs) and total ionizing dose (TID).

Every flight project has specific radiation and reliability requirements that each selected voltage comparator is expected to meet or exceed. This need accentuates the importance of having a complete set of radiation characterization data for these device types as a reference to help identify expected worst case performance characteristics or potential limitations (at the component, circuit, or even system level).

Based on published SET data, it has been extensively demonstrated a heavy ion hit on a sensitive transistor inside a voltage comparator can result in an output transient perturbation that is several volts in amplitude and a few microseconds in duration. Over the years, it has been documented that there is a strong correlation between SET sensitivity and the voltage difference applied at the positive and negative inputs of the device. In general, the lower the comparator input voltage differential (ΔVin), the higher the device sensitivity. One design strategy is to increase ΔVin above a minimum of 200 mV to ensure mitigation of transient effects (amplitude and duration). RC filtering is another viable solution provided a SPICE circuit analysis is performed to verify the proper parasitics are selected, especially load resistance.

Other key factors must also be considered when characterizing the SET sensitivity for a voltage comparator (depending on the part number) including the supply voltage, temperature, ion beam penetration range, and beam angle. Note, aside from the LM139, in general, there does not appear to be any significant temperature dependency observed in the SET response of the tested comparators. However, the LM139 results do indicate the significant nature of characterizing the impact of elevated temperatures [33] and hydrogen sensitivity [22] on the SET response in analog devices. The temperature effects on transients are strongly dependent on the relative locations of sensitive transistors as well as the type of device and specific application [33].

For total ionizing dose, including ELDRS, typical sensitive parameters include input bias current ($+I_B$ and $-I_B$), response time, supply current (Icc), gain, input offset current (Ios), and input offset voltage (Vos). The space-grade QMLV versions for some of the Texas Instruments/National Semiconductor comparators appear to be ELDRS immune and qualified to 100 krad(Si) for both high and lose rate, biased and unbiased test conditions. Overall, the TID response appears to be strongly dependent on manufacturing process and circuit design/device construction.

In summary, the data contained herein is intended to serve as a reference for expected trends in the radiation response of commonly used analog voltage comparators and guide design risk mitigation strategies. *For specific applications, as with any bipolar linear device, it is recommended to still perform (application specific) radiation testing to evaluate the total ionizing dose, displacement damage (although not covered in this compendium), and single event transient response of flight parts. Critical parameters to characterize include input currents, input offset voltage, gain, and output currents, at a minimum. SET testing should also be performed in the worst case condition with at least a minimum input voltage differential of 10 mV.*

Finally, as emphasized in this paper, lot date code variability in the radiation response of the parts analyzed herein is a very important consideration for implementing appropriate radiation hardness assurance processes and design strategies. When using legacy voltage comparator data for any radiation hardness analyses, it is recommended to always check the lot date code of the planned flight parts beforehand in order to ensure an applicable assessment is being performed.

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Table II

SINGLE EVENT TRANSIENT (SET) TEST RESULTS SUMMARY

Part #	Part Descr.	Mfr.	Process Technology	Test Facility / Test Date	Lot Date Code	Sample Size	Supply Voltage	Effective LET$_{TH}$ (MeV-cm^2/mg)	Saturation Cross-Section (cm^2/dev)	Summary of Test Results	Data Ref.
AD9696	single	ADI	Commercial Bipolar	LBNL / 1997	9605	unknown	±15V	< 3	~2x10^{-5}	ΔVin = 50 mV, >100 mV transients. LET threshold showed minimal dependence on ΔVin, saturation cross-section larger for small ΔVin.	[15], [26]
AD790	single / dual	ADI	Complimentary Bipolar	BNL / 2002	unknown	unknown	+5V	~1 @ ΔVin = 20 mV ~3 @ ΔVin = 50 mV ~11 @ ΔVin = 1 V	~3x10^{-3} @ ΔVin = 20 mV ~5x10^{-5} @ ΔVin = 50 mV ~2x10^{-5} @ ΔVin = 1 V	Incorporates high-speed vertical PNP as well as standard NPN transistors. Single supply with active output. Low LET threshold for small ΔVin. Part sensitivity decreases for large ΔVin >100 mV. For ΔVin >200 mV, no high amplitude transients (ΔVin = 1V all transients <0.5V). Galactic Cosmic Ray (GCR) upset rate: 1 upset/year @ ΔVin = 48 mV and 0.1 upsets/year @ ΔVin = 230 mV.	[28], [70]
MAX997	single	Maxim	Commercial Bipolar	TAM / 2008	0531	2	4.3V / 0V	< 2.7	~4x10^{-6} (high) ~1x10^{-6} (low)	SET saturation cross-section increases for wide transients (>20 ns) at higher temp (85°C). Max pulse amplitudes 4-5V and pulse widths ~10-20 ns (increasing with LET value). Higher SET sensitivity for high bias (especially at low LETs).	[13], [30]
ISL28196	single	Intersil	BiCMOS	NRL / 2010	0724	5	+5V	–	–	Laser test from 25 to 75°C. Maximum amplitude exceeds 5V (saturated at supply limits) with FWHM ~10 us. SETs decreased magnitude with increasing temperature.	[50]
RH1011M	single	LTC	Radiation Hardened Bipolar, 7 µm, BIPS700	LBNL / 2012	1013A, 9721B	4	±12V	6	4x10^{-4}	Smaller ΔVin showed higher susceptibility to trigger voltage and SET cross-sections. For higher LET, less dependence on ΔVin. No temperature dependence.	[17]
AD8561AR	single	ADI	Commercial Bipolar	JSC URSC-ISDE / 2013	0775B	3	+7V	< 16	2x10^{-5} @ LET=40	Catastrophic failure not observed up to LET 40 (25°C and 7V supply).	[49]
LM111H	single	NSC / TI	Commercial Bipolar	LBNL / 1992	9151	unknown	+5V / ±15V	> 10 @ ΔVin = 25 mV	1x10^{-4} @ ΔVin = 25 mV	Transients always negative-going pulses. Saturation cross-section relatively independent of bias voltage. Max pulse 6.5V amplitude with 1 µs duration.	[10], [41], [42]
LM111	single	Motorola	Commercial Bipolar	IPN / 1994	unknown	unknown	±15V	~2	2x10^{-4}	ΔVin = 100 mV, >2.4V transients. Rate in geostationary orbit for transients greater than 2.4V: 0.01 event/device-day.	[15], [37]

Part #	Part Descr.	Mfr.	Process Technology	Test Facility / Test Date	Lot Date Code	Sample Size	Supply Voltage	Effective LET$_{TH}$ (MeV-cm^2/mg)	Saturation Cross-Section (cm^2/dev)	Summary of Test Results	Data Ref.
LM111	single	NSC / TI	Commercial Bipolar	BNL and TAM / 1996	unknown	unknown	±15V	<< 7	8.5x10^{-5} @ LET 7.3 and ΔVin = 25 mV	Ar (LET=7.3) run showed smaller amplitude of 2.5V and shorter duration of 0.1 µs than pulse taken at Xe. Low versus high output effects transient pulse amplitude and duration.	[10]
LM111	single	NSC / TI	Commercial Bipolar	LBNL / 1997	9619	unknown	+5V / +10V / +15V	< 3 @ ΔVin = 50 mV	~1x10^{-3} (15V) ~1x10^{-4} (10V) ~9x10^{-5} (5V)	Larger LET threshold as ΔVin increases. Device most SET sensitive for ΔVin = 50 mV, >100 mV transients.	[15], [26], [41]
LM111	single	NSC / TI	Commercial Bipolar	BNL and TAM / 1999 and 2001	unknown	unknown	±15V	no data @ ΔVin = 25 mV	8x10^{-6}	Transients strongly effected by ΔVin <1V. Showed gradual dependence on input voltage differential compared to PM139/LM139 because of emitter-follower configuration at input. For Xe, amplitude of pulse 12V with 0.4 µs max duration. Transients always negative-going. Angular SET dependence seen in data.	[6], [10], [40], [41]
LM111	single	NSC / TI	Commercial Bipolar	TAM / 2010	unknown	unknown	unknown	< 28	~2x10^{-3} @ LET 83	Worst case biasing condition Vcc=15V and ΔVin = 4.75V (high supply voltage and large differential input voltage). Increase in temperature from ambient to 76ºC did not significantly impact SET sat cross-section.	[45]
LM119	dual	NSC / TI	Commercial Bipolar	LBNL / 1997	9535	unknown	±15V	3 @ ΔVin = 50 mV	~2x10^{-4}	ΔVin does not impact part SET sensitivity, saturation cross-section or LETth (response due to high supply voltage).	[26], [41]
LM119	dual	NSC / TI	Commercial Bipolar	BNL / 2001 and 2002	unknown	unknown	5V / 10V / 15V	~2.5 @ ΔVin = 20 mV ~6 @ ΔVin = 50 mV	~1.2x10^{-3}	ΔVin = -5V, >300 mV transients. Saturation cross-section dependent on ΔVin and supply voltage (σ increases with Vcc) but not affected by output load conditions. Cross-section for positive ΔVin order of magnitude smaller than for negative ΔVin. Positive ΔVin resulted in lower LET threshold. Distribution of transients is bimodal when ΔVin is low. For ΔVin = 200 mV, most high amplitude transients (42 ns @ 50 mV) suppressed and cross-section reduced by order of magnitude; transient amplitude reduced to 25 ns, few ns duration. GCR upset rate: 1 upset/year @ ΔVin = 26 mV and 0.1 upsets/year @ ΔVin = 90 mV.	[15], [26], [39], [43], [70]
LM119	dual	NSC / TI	Commercial Bipolar	BNL / 2010	unknown	unknown	unknown	–	–	SET >200 mV @ LET 60 MeV-cm^2/mg.	[45]

Part #	Part Descr.	Mfr.	Process Technology	Test Facility / Test Date	Lot Date Code	Sample Size	Supply Voltage	Effective LET$_{TH}$ (MeV-cm^2/mg)	Saturation Cross-Section (cm^2/dev)	Summary of Test Results	Data Ref.
RH119	dual	LTC	Radiation Hardened Bipolar	HIF / 1999	9639A	unknown	+5V	< 5.8	~3.1x10^{-4} @ ΔVin = 830 mV ~2.5x10^{-4} @ ΔVin = 300 mV	ΔVin = 580 mV, >2V transients. Saturation cross-section has minimal dependence on differential input voltage ΔVin.	[15], [38]
LM193	dual	NSC / TI	Commercial Bipolar	TAM / 2002	0145	2	±12V	~2 (low) ~5 (high)	1x10^{-3} (low) 1x10^{-4} (high)	ΔVin = 100 mV, >500 mV transients.	[15], [24]
LM193AJ-QMLV	dual	NSC / TI	Radiation Hardened Bipolar	NRL / 2007	0525A	1	+10V / 0V	–	–	Pulsed laser test at NRL (at 67 MeV-cm^2/mg), small values of ΔVin resulted in largest SET amplitude and pulse width (for ΔVin = 50 mV, 4V transients and for ΔVin = 1V, 1V transients). For output high (10 V) all SETs negative-going, for output low (0V) all SETs positive-going.	[25]
LM139	quad	NSC / TI	Commercial Bipolar (UK 4”)	LBNL / 1997	9318	unknown	+3V / +5V	< 5 @ ΔVin < 200 mV	~7x10^{-4}	SET sensitivity (transient amplitude and duration) dependent on applied bias (attributed to lateral PNP transistors in first stage of amplifier). Threshold LET values increases for larger ΔVin.	[9], [26]
LM139	quad	NSC / TI	Commercial Bipolar (UK 4”)	BNL, TAMU, UCL / 1996 and 1998	1901F (prior to 2000)	unknown	+5V / ±15V	~2 @ ΔVin = 25 mV (can vary with ΔVin from 1 to 10)	~5x10^{-4} (@ LET 20)	ΔVin = 100 mV, >500 mV transients (max 10V amplitude and 2 µs duration). Saturation cross-section and LETth dependent on ΔVin (smaller ΔVin, higher SET sensitivity). For ΔVin >350 mV, SET amplitude and pulse width smaller than LM139AJRLQMLV (die shrink parts). For small ΔVin ≤50 mV, same performance as LM139AJRLQMLV. For very large input voltage ΔVin >2V, no transients observed. Proton SET sensitivity: duration 1 µs, amplitudes can go rail-to-rail, proton threshold energy ~30 MeV for ΔVin = 12.5 mV (increases for larger ΔVin).	[7], [10], [12], [15], [27]
LM139	quad	NSC / TI	Commercial Bipolar (UK 4”)	BNL / 1999	JM38510/ 11201BCA	4	±7V	20 @ ΔVin = 2V	2x10^{-4} (high output) 1x10^{-4} (low output)	For ΔVin ≥2V, LM139 less SET sensitive. Worst case transient observed: peak amplitude of 1.1V with a FWHM width of 2.2 µs. GCR upset rate: 0.55 upsets/year @ ΔVin = 1V and 1.5 upsets/year @ ΔVin = 100 mV.	[12], [35], [70]
HS139	quad	Harris / Intersil	Commercial Bipolar	BNL / 1999	Prior to 2000	unknown	unknown	~8-10	3x10^{-4}	Legacy Harris non-radiation hardened version of quad voltage comparator. Only slight dependence on applied bias observed.	[12]

Part #	Part Descr.	Mfr.	Process Technology	Test Facility / Test Date	Lot Date Code	Sample Size	Supply Voltage	Effective LET_{TH} (MeV-cm^2/mg)	Saturation Cross-Section (cm^2/dev)	Summary of Test Results	Data Ref.
HS139RH	quad	Harris / Intersil	Radiation Hardened Silicon Gate (RSG) BiCMOS	LBNL / 1999	Prior to 2000	unknown	+5V / +10V / +13V	~10	~1x10^{-4} to 1x10^{-3}	Unlike LM139, HS139RH did not demonstrate strong systematic dependence on ∆Vin. LETth decreases slightly with applied bias voltage. Saturation cross-section larger than LM139 but LETth much smaller, especially for small ∆Vin. For ∆Vin <1V, HS139RH less SET sensitive. Second stage of difference amplifier most sensitive region of device.	[9]
LM139J	quad	NSC / TI	Commercial Bipolar (UK 4”)	TAM / 2007	0535	2	+5V / 0V	< 5	~9x10^{-4}	Devices SET tested after TID exposure to 68 krad(Si). Results indicated no dependence on transient amplitude and duration as function of neither TID nor bias voltage (up to tested TID level). Transient durations impacted by value of output pull-up transistor. At high LET, saturation σ shows minimal dependence on ∆Vin. At low LET, saturation σ decreases as ∆Vin increases.	[29], [31]
LM139J	quad	NSC / TI	Commercial Bipolar (UK 4”)	NRL / 2007	EH324AB	1	+5V / 0V	< 1 @ ∆Vin = 25 mV	~9x10^{-2}	Devices SET tested after TID exposure to 100 krad(Si). Results indicated strong dependence on transient amplitude and duration as function of TID and bias voltage. Decrease in parasitic output signal due to degradation of current sources (impacts device function: voltage gain and slew rate).	[29], [32]
LM139J	quad	NSC / TI	Commercial Bipolar	NRL / 2009	0535F	1	+5V / 0V	–	–	SET sensitivity dependent on temperature. As temp increases up to 120°C, transient amplitude increases and device slew rate decreases (up to 50%). Recovery time from transient increases at elevated temps. Effect is application dependent.	[33]
LM139J	quad	NSC / TI	Commercial Bipolar	IUCF / 2012	1132AC	1	+5V	–	–	This device did not demonstrate an increased proton sensitivity as compared to the radiation hardened part: RM139AJRQMLV.	[51]
LM139AJR LQMLV	quad	NSC / TI	Radiation Hardened Bipolar (UK 6”)	LBNL / 2008	After 2000	3	+5V / +15V	2.5	8.9x10^{-6}	Ion beam angle, trigger voltage, input voltage (at low LET) (larger input voltage, SET pulse width decreases), supply voltage (larger saturation cross-section for lower Vcc), and load resistance impact transient duration and amplitude. For high output, negative SETs observed and fall times match switching speed of part. Max transient duration 3 µs. For large ∆Vin >2V, no transients observed. SET recovery dependent on value of output pull-up resistor.	[7]
RM139AJR QMLV	quad	NSC / TI	Radiation Hardened Bipolar (UK 6”)	JPL / 2009	0527	3 (100% H$_2$) 6 (1% H$_2$)	+5V	10	–	Enhanced hydrogen sensitivity. Order of magnitude increase in input bias current and input offset voltage degradation for parts soaked in 100% and 1% molecular hydrogen; delta degradation increases with increasing dose.	[22]

Part #	Part Descr.	Mfr.	Process Technology	Test Facility / Test Date	Lot Date Code	Sample Size	Supply Voltage	Effective LET$_{TH}$ (MeV-cm^2/mg)	Saturation Cross-Section (cm^2/dev)	Summary of Test Results	Data Ref.
RM139AJR QMLV	quad	NSC / TI	Radiation Hardened Bipolar (UK 6")	IUCF / 2012	JM0794062	3	+5V	–	–	Parts tested with 200 MeV protons at normal incidence, no transients detected under various load and input differential voltage conditions (including 50 and 98 mV) up to ~1x10^{10} p/cm^2 fluence. For higher proton fluence ~1x10^{11} p/cm^2, an SET was measured to be 0.1 µs in duration. Proton saturation cross-section 3.22x10^{-12} cm^2/device.	[51]
IS-139ASRH	quad	Intersil	Radiation Hardened Silicon Gate (RSG) BiCMOS	TAM / 2000	unknown	3	+9V / +15V / +30 V	–	–	For ∆Vin ≥5.8 mV (small ∆Vin) transients eliminated over range of input capacitance, resistance, and three different supply voltages. Worst-case transient LETth several times larger than that for LM139. Below min overdrive threshold of 5.8 mV, transients on order of 2 µs in duration observed.	[16]
PM139	quad	ADI	Commercial Bipolar (3003Y 1987)	BNL, UCL / 1999	9524A	unknown	5V / 10V	~4 (can vary with ∆Vin from 3 to 13)	~6x10^{-4}	∆Vin <200 mV, >500 mV transients (max 10V amplitude. and 2 µs duration – nearly all transients saturated). LETth and saturation cross-section depends strongly on ∆Vin for small values. Results do not depend on output load resistance when ∆Vin <200 mV. LETth increases steadily as ∆Vin increases. For ∆Vin >1V, most transients not saturated, LETth no longer depends on input voltage conditions and LETth increases as load resistance decreases, saturation σ is about 4x lower for large ∆Vin.	[6], [15], [27]
LM339	quad	ST	Commercial Bipolar	unknown	unknown	unknown	unknown	< 2	~1.2x10^{-3}	∆Vin = 30 mV, >2V transients.	[15], [36]
CMP401	quad	ADI	BiCMOS	BNL / 2002	unknown	unknown	unknown	< 3 @ ∆Vin = 50 mV	1x10^{-4}	Low LET threshold for small ∆Vin. Part sensitivity decreases for large ∆Vin >100 mV.	[28]
RHD5912	quad	Aeroflex	Radiation Hardened BiCMOS	LBNL / 2013	unknown	unknown	+3.3V / +5V	< 10	4x10^{-5}	Similar in performance and spec to LM139 but much improved SET sensitivity. Transient response time 1 µs followed by 50 µs recovery (duration depends on output pull-up resistor and output capacitance). LETth for transients exceeding trigger levels increases with decreasing supply voltage (from reduction in gain and increase in propagation delay). 5V performance results in lower SET error rate.	[48]
CMP401	quad	ADI	Complimentary BiCMOS	BNL / 2002	unknown	unknown	+5V	~3 @ ∆Vin = 50 mV	~1x10^{-4} @ ∆Vin = 20 mV ~3x10^{-5} @ ∆Vin = 1 V	Saturation cross-section showed minimal dependence on ∆Vin because of active CMOS output stage. Also less dependence on low and high input voltage conditions. GCR upset rate: 1 upset/year @ ∆Vin = 80 mV and 0.1 upsets/year @ ∆Vin = 360 mV.	[70]

Part #	Part Descr.	Mfr.	Process Technology	Test Facility / Test Date	Lot Date Code	Sample Size	Supply Voltage	Effective LET$_{TH}$ (MeV-cm^2/mg)	Saturation Cross-Section (cm^2/dev)	Summary of Test Results	Data Ref.
LP365	quad	NSC / TI	Commercial Bipolar	BNL / 1999	unknown	unknown	unknown	< 4 @ ΔVin = 10 mV	1x10^{-3} @ ΔVin = 10 mV (worst case)	ΔVin = 10 mV, >500 mV transients, LETth and saturation cross-section highly dependent on ΔVin. For ΔVin >200 mV, LETth >10 MeV-cm^2/mg and saturation cross-section 1x10^{-4} cm^2/device. Transient amplitudes reach saturation when threshold LET depends on input voltage differential for ΔVin <200 mV. Same behavior as PM139.	[6]

***Legend:**

Manufacturers:
ADI – Analog Devices Incorporated
LTC – Linear Technology Corporation
NSC –National Semiconductor Corporation
ST – ST Microelectronics
TI – Texas Instruments

Radiation Test Facilities:
BNL – Tandem Van de Graff, Brookhaven National Laboratories, Long Island, NY
HIF – Heavy Ion Facility at the Université Catholique de Louvain, Belgium
IPN – Institute Physique Nuclaire, University of Orsay, France
IUCF – Indiana University Cyclotron Facility Bloomington, IN
JSC URSC-ISDE – Russian Federal Space Agency Moscow, Russia
LBNL – 88-inch Cyclotron Lawrence Berkeley National Laboratory, Berkeley, CA
NRL – Naval Research Laboratory, Washington, DC
TAM – Texas A&M University Cyclotron Institute College Station, TX
UCL – Cyclotron de Louvain-la-Neuve Universite Catholique de Louvain, Belgium

Table III
Total Ionizing Dose (TID) Test Results Summary

Part #	Descr.	Mfr.	Process Technology	Test Facility / Test Date	Lot Date Code	Sample Size	Supply Voltage	Dose Rate (rad(Si)/s)	Parametric Deg. Level (krad(Si))	Summary of Test Results	Data Ref.
MAX913	single	Maxim	Commercial Bipolar	GSFC / 1998	9704	5 (biased)	5V	0.035-0.174	> 100	No measurable radiation induced parametric degradation up to and including 100 krad(Si).	[12]
MAX909ESA	single	Maxim	Com Bipolar 3	unknown	unknown	unknown	unknown	50-300	25	All parameters meet spec limit to final irradiation level of 25 krad(Si).	[67]
CMP01	single	ADI	Complimentary BiCMOS	GSFC / 1998	9729	8 (biased)	5V / 15V	0.33	> 200 (Vcc = 5V) > 60 (Vcc = 15V)	No radiation sensitive parameters up to 200 krad(Si) for Vcc=5V. For Vcc=15V all parts met spec up to and including 60 krad(Si), sensitive parameters: input bias current (I_B), CMRR, input offset current (Ios) which recovered after 240 hour anneal @ 25°C.	[12]
AD790	single / dual	ADI	Complimentary BiCMOS	ONERA-DESP / 1999	unknown	unknown	unknown	unknown	20	No measurable radiation induced parametric degradation up to and including 20 krad(Si).	[69]
AD8465	single	ADI	Bipolar XFCB2	GSFC / 2011	1046	unknown	unknown	17	> 80	All parameters meet spec limits up to and including final dose step of 80 krad(Si) – not application specific testing.	[46]
LM111	single	NSC / TI	Commercial Bipolar	SALK / 1998	9646	4 (biased)	unknown	0.05	6.5	Pre-rad Vos (mV) measured to be: 0.739, after 35 krad(Si): 1.652, and after 80 krad(Si): 2.519. Pre-rad Ios (nA) measured to be: 0.59, after 35 krad(Si): 28.62, and after 80 krad(Si): 62.26.	[47]
LM111 / LM311	single	various	Commercial Bipolar	NAVSEA / 2000	HH94AD HH89AB	25 (LM311) 35 (LM111)	unknown	0.008 / 50	various	Irradiated LM311 and LM111 samples from 5 different manufacturers (Texas Instruments, National Semiconductor, STI, Philips, On-Semi/Motorola). Input bias current (most sensitive parameter) varies by factor of 100 across manufacturer. ELDRS observed in Phillips, Motorola and NSC parts.	[65]
LM111	single	NSC / TI	Commercial Bipolar	CRANE / 2000	B61AD	unknown	unknown	0.01	6.5	At low dose rate input bias current failures at 6.5 krad(Si). Delta shift measured to be 100 nA at 6.5 krad(Si).	[63]
LM111	single	NSC / TI	Commercial Bipolar	CRANE / 2000	B61AD	unknown	unknown	50	50	No measurable radiation induced parametric degradation up to 50 krad(Si) at high dose rate.	[63]
LM111	single	NSC / TI	Commercial Bipolar	GSFC / 2005	0126A	unknown	unknown	0.02	> 40	No measurable radiation induced parametric degradation up to and including 40 krad(Si).	[54]
LM111	single	NSC / TI	Commercial Bipolar	JPL / 2010	0528	4 (biased) 4 (unbiased)	±15V	0.01 < 50k 0.04 > 50k	5	For both biased and unbiased tests, variations of input offset current exceeded spec between 5 and 10 krad(Si) and input bias current exceeded spec at or before 5 krad(Si). By 30 krad(Si), input bias current degraded most severely, with some mean values more than an order of magnitude beyond spec.	[58]

Part #	Descr.	Mfr.	Process Technology	Test Facility / Test Date	Lot Date Code	Sample Size	Supply Voltage	Dose Rate (rad(Si)/s)	Parametric Deg. Level (krad(Si))	Summary of Test Results	Data Ref.
RH1011MW	single	LTC	Radiation Hardened Bipolar	RAD / 2008	0919A	5 (biased) 5 (unbiased)	12V	0.01	50	All parts met spec to 50 krad(Si) at low dose rate with minimal degradation to any measured parameter. Input offset current showed severe degradation during anneal.	[68]
MAX962ESA	dual	Maxim	Commercial Bipolar	APL / 1999	9627	unknown	unknown	4.52	> 30	No measurable radiation induced parametric degradation up to and including 30 krad(Si).	[12]
MAX972ESA	dual	Maxim	Commercial Bipolar	APL / 1999	9821	unknown	unknown	4.52	< 5	Parts tested to 5 krad(Si). All functionality failed at 5 krad(Si) with no recovery after anneal (168 hrs @ 100°C). Most sensitive parameters: positive current and input offset voltage.	[12]
MAX997	dual	Maxim	Commercial Bipolar	GSFC / 2007	531	unknown	unknown	20	> 30	All parameters passed within spec up to and including 30 krad(Si). Input offset voltage was not measured.	[66]
MAX9202	dual	Maxim	Commercial Bipolar	GSFC / 2011	1041	unknown	unknown	10	>2 0	Low measurement fidelity on input offset voltage but all other parameters pass up to and including final dose step of 20 krad(Si). Not application specific usage conditions.	[46]
MAX973ESA	dual	Maxim	3 µm BiCMOS	unknown	unknown	unknown	unknown	50-300	5	Vos and Icc went out of spec at 5 krad(Si).	[67]
LM119	dual	NSC / TI	Commercial Bipolar	GSFC / 2005	0423B	unknown	unknown	0.02	5	All parts passed all tests up to and including 5 krad(Si). Input bias current exceeded spec limit after 10 krad(Si).	[54]
LM119	dual	NSC / TI	Commercial Bipolar	RAD / 2008	0806	5 (biased) 5 (unbiased)	unknown	0.01 / 50	< 10	Input offset current (Ios), input offset voltage, input bias current (I_B), power supply current, output voltage high and low were measured parameters up to 50 krad(Si). Ios for all biased samples exceeded spec at first endpoint 10 krad(Si). Unbiased parts showed no degradation in Ios up to and including 50 krad(Si). Significant I_B degradation measured for all samples, biased and unbiased. All other parameters remained within spec. All parts remained functional up to 50 krad(Si).	[55]
RH119W	dual	LTC	Radiation Hardened Bipolar	JPL / 2007	0429A	5 (biased) 4 (unbiased)	±10V	0.005 / 25	> 15	No parametric failures up to and including 15 krad(Si). Input offset current showed largest amount of degradation but remained within spec up to and including 15 krad(Si). Generally biased test condition worst case for most parameters. No low dose rate sensitivity observed.	[57]
LM193	dual	NSC / TI	Commercial Bipolar	JPL / 2001	9950G / 0551	3 (biased) 3 (unbiased)	15V	0.01 / 50	3.6	Significant low dose rate sensitivity. Input bias current degraded the most, followed by input offset current (Ios), and then input offset voltage (Vos). Change in input bias current was faster for low dose rate samples and exceeded spec between 3.6 and 6 krad(Si) test levels. Unbiased worst case at LDR and biased worst case at HDR. Functional failures observed starting at 15 krad(Si).	[57], [62]

Part #	Descr.	Mfr.	Process Technology	Test Facility / Test Date	Lot Date Code	Sample Size	Supply Voltage	Dose Rate (rad(Si)/s)	Parametric Deg. Level (krad(Si))	Summary of Test Results	Data Ref.
LM193	dual	NSC / TI	Commercial Bipolar	GSFC / 2002	Flight Lot	unknown	unknown	0.06 to 0.40	< 7	Input bias current went out of spec at 7 krad(Si); Vio went out of spec at 15 krad(Si); functional after 65 krad(Si).	[61]
LM193	dual	NSC / TI	Commercial Bipolar	GSFC / 2008	0525A	unknown	unknown	0.01	5-7	Vbias went out of spec at 7 krad(Si); offset current went out of spec at 7 krad(Si); offset voltage went out of spec at 10 krad(Si).	[56]
LM193Ax RLQMLV	dual	NSC / TI	Radiation Hardened Bipolar	WSMR / 2007	JM06BT043	10 (biased) 10 (unbiased)	5V / 30V	0.01 / 45	100	All legs passed TID testing to a radiation level of 100 krad(Si) with all parameters within spec limits. No low dose rate sensitivity. High dose rate parts showed more drift than low dose rate.	[11]
MAX505A EAG	quad	Maxim	CMOS	unknown	unknown	unknown	unknown	50-300	25	All parameters meet spec limit to final level of 25 krad(Si).	[67]
LM339	quad	NSC / TI	Commercial Bipolar	ASTRIUM / 2000	9830	unknown	unknown	0.0083	5-10	Most sensitive parameter is input bias current. At 5 krad(Si), I_B delta measured to be 50 nA, by 50 krad(Si) delta was 770 nA.	[63]
LM339D	quad	NSC / TI	Commercial Bipolar	PSI / 2012	unknown	unknown	unknown	7.5	< 10	Input bias current (I_B) went out of spec at 15 krad(Si) and voltage gain went out of spec between 10 and 20 krad(Si). Response time also increased.	[53]
LM139	quad	NSC / TI	Commercial Bipolar	NAVSEA / 2002	M38510 / 11201BDA	6 (biased) 2 (unbiased)	unknown	0.295	< 5	Output saturation voltage (Vol) out of spec and significantly degraded at 5 krad(Si) for unbiased parts (worst case). All biased devices failed to operate between 10 and 20 krad(Si) as Vol went out of spec. All devices (biased and unbiased) showed power supply current degradation after 5 krad(Si).	[61]
LM139	quad	NSC / TI	Radiation Hardened Bipolar	GSFC / 2005	0302	unknown	unknown	0.02	> 40	No measurable radiation induced parametric degradation up to and including 40 krad(Si).	[54]
LM139A	quad	NSC / TI	Radiation Hardened Bipolar	BALL / 2013	B7A1119A	unknown	unknown	0.01	> 30	No measurable radiation induced parametric degradation up to and including 30 krad(Si).	[60]
RM139AJ RQMLV	quad	NSC / TI	Radiation Hardened Bipolar	JPL / 2001	HID0205A	3 (biased) 4 (unbiased)	unknown	0.01	> 100	Input bias current and input offset voltage degradation at 5 krad(Si) for low dose rate biased parts. A slight bias dependency was only observed for high dose rate parts (unbiased performed better than biased). Unbiased parts passed spec limits up to 200 krad(Si). Other test parameters: supply current, saturation voltage, output sink current stayed within or near spec limits up to 200 krad(Si).	[62]
LM139Ax RLQMLV	quad	NSC / TI	Radiation Hardened Bipolar	WSMR / 2007	JM051X21	10 (biased) 10 (unbiased)	5V / 30V	0.01 / 45	100	All legs passed TID testing to 100 krad(Si) with all parameters within spec limits. No low dose rate sensitivity. High dose rate parts showed more drift than low dose rate.	[11]
LM139AW RQMLV	quad	NSC / TI	Radiation Hardened Bipolar	GSFC / 2012	JM046X13; A009 and A095	unknown	unknown	0.0005	> 30	All parameters meet spec limits up to and including 30 krad(Si) at low dose rate.	[52], [59]

Part #	Descr.	Mfr.	Process Technology	Test Facility / Test Date	Lot Date Code	Sample Size	Supply Voltage	Dose Rate (rad(Si)/s)	Parametric Deg. Level (krad(Si))	Summary of Test Results	Data Ref.
PM139	quad	ADI	Commercial Bipolar	GSFC / 1998	9720A	8 (biased)	15V	0.33	> 200	No measurable radiation induced parametric degradation up to and including 200 krad(Si).	[12]
PM139A	quad	ADI	Commercial Bipolar	JPL / 2009	0046A	unknown	unknown	0.01	> 50	No measurable radiation induced parametric degradation up to and including 50 krad(Si).	[57]
HS9-139RH	quad	Intersil	Radiation Hardened Silicon Gate (RSG) BiCMOS	Intersil / 2006	unknown	18	±15V	0.01 / 0.1 / 50	100	Most sensitive parameter is input bias current. Input offset current, output drive current, power supply current, open loop gain showed little change. Input offset voltage average value remained nearly constant, but range of this parameter increased (although no parts failed the 8 mV post-rad limit).	[64]
RHD5912	quad	Aeroflex	BiCMOS (rad hard by design 5 µm)	RAD / 2013	unknown	5 (biased) 5 (unbiased)	5V	91.27	> 1000	No parameters exceed spec limits up to 1 Mrad(Si). Input offset voltage showed most change as function of TID. Output voltage low measured under various load conditions. Other parameters of interest that showed minimal degradation: quiescent supply current, input offset current, input bias current, CMRR, PSRR, gain, output leakage current, short circuit output current, input voltage, and input current.	[48]

***Legend:**

Manufacturers:
ADI – Analog Devices Incorporated
LTC – Linear Technology Corporation
NSC –National Semiconductor Corporation
TI – Texas Instruments

Radiation Test Facilities:
APL – Applied Physics Laboratory Laurel, MD
ASTRIUM – EADS Astrium Paris, FR
BALL – Ball Aerospace & Technologies Boulder, CO
CRANE / NAVSEA – Naval Sea Systems Command Crane, IN
DTRA – Defense Threat Reduction Agency Fort Belvoir, VA
GSFC – Goddard Space Flight Center Greenbelt, MD
JPL – Jet Propulsion Laboratory Pasadena, CA
NSC – National Semiconductor Corporation South Portland, ME
PSI – Paul Scherrer Institute Villigen, Switzerland
RAD – Radiation Assured Devices Colorado Springs, CO
SALK – Salk Institute La Jolla, CA
WSMR – White Sands Missile Range New Mexico