SINGLE EVENT EFFECTS ON COMMERCIAL SRAMS AND POWER MOSFETS: FINAL RESULTS OF THE CRUX FLIGHT EXPERIMENT ON APEX[1]

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Abstract

The CRUX experiment on the APEX satellite monitored single event effects on 1 Mbit and 256 Kbit SRAMs and 100 volt and 200 volt power MOSFETs. The single event upsets (SEUs) on the SRAMs were mapped in geographic and geomagnetic coordinates. Other single event effects (SEEs) were observed, including multiple bits upsets (MBUs) and single hard errors ("stuck bits"). Sensitivity to programmed logic state was also analyzed. The relatively large sample sizes for most part types and almost two year flight time in a hostile radiation environment provided a data set adequate for investigation of the range in device response within the flight lots. Single event burn-out (SEB) conditions were observed on the power MOSFETs. The rates on the 200 volt devices were much higher than on the 100 volt and occurred primarily in regions of space dominated by trapped protons.

I. INTRODUCTION

The Air Force APEX (Advanced Photovoltaic and Electronics Experiment) satellite flew from August 1994 to May 1996. The satellite was in an elliptical orbit of 362 by 2,544 kilometers at a 70 degree angle of inclination. The CRUX (Cosmic Ray Upset Experiment) on APEX was designed to flight test commercial SRAMs and power MOSFETs in order to validate models that predict the SEE behavior of these devices. Tables 1 and 2 list the part types flown. A major contributor to the capability of the CRUX experiment was the presence on APEX of the Cosmic Ray Environment and Dosimetry Experiment (CREDO). [1] CREDO measured the total doses accumulated in flight at ten different sites within the CRUX and CREDO boxes and the environment in terms of LET of encountered particles.

II. SUMMARY OF PREVIOUS RESULTS

Three previously published papers reported the preliminary results of the CRUX experiment on the Air Force APEX satellite. [2,3,4] References 2 and 3 presented the results for the SRAMs based on 176 days of experimental data taken from the first 262 days of the mission. (The spacecraft was in safehold for 90 days.) Some of the conclusions from those two papers are reviewed here.

The first paper focused on correlating the occurrence of single event upsets (SEUs) with the measured environment. It was shown that, during quiet magnetospheric and solar conditions, the trapped protons dominated the upset rates on

Table 1
SRAM Devices on CRUX

Part Type	Manufacturer	Technology	Chip Size	# of Devices	Total Bits
MT5C1008CW25	MICRON	NMOS/CMOS	128K x 8	23	24,117,248
88130L45PC	EDI	NMOS/CMOS	128K x 8	9	9,437,184
ZQ0405 4628128	HITACHI/ELMO	NMOS/CMOS	128K x 8	16	16,777,216
MT5C2568CW-25	MICRON	CMOS	32K x 8	40	10,485,760
8832C12C1	EDI	CMOS	32K x 8	18	4,718,592
71256L100DB	IDT	NMOS/CMOS	32K x 8	19	4,980,736

[1] This work was supported by the USAF/Space Division, DSWA, and NASA/HQ.

these commercial memories. This was verified with measurements from the CREDO instrument. Preliminary upset rates were plotted on world maps for various altitudes. The maps clearly showed the influence of the trapped proton belts, including the South Atlantic Anomaly (SAA), on upset rates. Rates were predicted using standard models and generic part test data. Comparisons between these predicted rates and flight SEU rates showed that use of non-flight lot ("generic") ground test data to predict part performance can result in large errors, up to two orders of magnitude, in rate predictions.

The second paper presented the statistics of device variation within a part type. The large number of devices flown of each part type provided a unique statistical basis to quantify the degree of variation in device single event effect performance. The EDI 256K and MICRON 1M showed very large device to device variations. The CRUX data also verified cyclotron tests showing that some devices have extreme differences in upset sensitivity depending on their programmed logic state. In the case of the MICRON 1 Mbit part, the ratio was 98:2 of upsets when programmed to the "1" state versus the "0" state. Multiple bit upsets (MBUs) and stuck bit errors were also observed on the SRAMs, however, just 176 days of flight data did not provide adequate statistics to draw firm conclusions on these phenomena.

The third paper reported on the first observations of proton induced single event burn-outs (SEB) in space. Only 3 SEBs were observed on the 100 volt power MOSFETs. 205 SEBs were observed on the 200 volt devices and occurred primarily in trapped proton regions. It was confirmed that the rate of SEBs increases with increasing drain-to-source voltage and that there are thresholds below which SEBs do not occur. The results demonstrated the need for proper derating of power MOSFETs. The 200 volt power MOSFETs from the CRUX flight lot were accelerator tested with protons. Predictive SEB rates calculated with ground test data showed excellent agreement with flight rates[5].

Table 2
Power MOSFET Devices on CRUX

Part Type	Manufacturer	Technology	Maximum Voltage_{D-S}	# of Devices
2N6796	Harris	N-channel	100	12
2N6796	IR	N-channel	100	12
2N6798	Harris	N-channel	200	12
2N6798	IR	N-channel	200	12

III. THE FINAL CRUX DATA SET

Figure 1 is a plot of the perigee variation of the CRUX orbit as a function of mission time in days. The vertical line at mission day 262 marks the end of the data coverage for the results reported in References 2 and 3. Data for the time period after mission day 262 have been added to the CRUX flight database, bringing the total coverage to 20 months. With the perigee and apogee precession, data coverage in a range of plus and minus 70 degrees latitude and 400 to 2500 km altitude were taken. The additional flight data have provided improved statistics on the observed single event effects rates, especially for multiple bit upsets and stuck bit errors.

IV. WORLD MAPS OF UPSET RATES

The five minute time resolution of the data resulted in reasonable resolution of the spatial location of the single event effects. The single event upset (SEU) data for each part type were binned in latitude (Δ2°), longitude (Δ2°), and altitude (Δ100 km). Average SEU rates based on the amount of time spent in each bin and the number of bits were calculated and plotted on world maps. These maps are shown in Figures 2-5 for altitude bins 700, 1300, 1800, and 2500 km for the MICRON 256K devices. The effect that increasing the altitude has on the SEU rates is clear from the figures. The upset rates at all altitudes show extremely high correlation with proton flux contour maps of standard proton models and with fluences measured by CREDO. At 1300 km, the upset rates are eight to eleven times higher than at 700 km and twenty to thirty times higher at 1800 km. As altitude increases, the physical area of the trapped proton radiation belts increases as does the intensity of the high energy proton fluences. The SEU rate would be expected to peak at approximately 3000 km which is near the location of the peak of the high energy proton fluences. Because the altitude of the peak of the proton populations varies with energy, the location of the peak of the SEU rate should vary with the upset threshold of the device.

The upset rates on the HITACHI/ELMO 1M and the MICRON 1M devices for the 2500 km altitude bin are shown in Figures 6 and 7. These figures show the dependence of the SEU rates on the part type, with the MICRON 256K devices showing the highest upset rate. The rates for all of the devices are discussed in Section V. Also note in Figure 6 the relatively low rate of upsets on the HITACHI/ELMO 1M device in the high latitude regions. This implies that the HITACHI/ELMO devices are relatively hard to SEUs induced by heavy ions from galactic cosmic rays and solar particle events.

V. COMPARISON OF PART TYPES FOR UPSET RATES

Daily SEU rates were also calculated as a function of dipole shell parameter-L* (ΔL=0.1) based on the time spent in each bin and the number of bits for each part type. The results are plotted in Figure 8. The figure shows further evidence of the importance of trapped protons on the SEU rates of these devices. From the figure note that the peak rate occurs at approximately L = 1.4. This coincides with the location of the peak of the high energy trapped protons. Also, the peaks drop off sharply as L increases. Not shown on this plot are rates at L > 3 where the levels of SEUs remain very low even out to

* The magnetic dipole shells are labeled by the distance in earth radii along the magnetic equator from the center of the earth to the crossing of the magnetic field line.

high L values which are regions of high heavy ion exposure from galactic cosmic rays and solar particle events. Only 2% of upsets occurred at high L values even though 38% of flight time was spent there.

Figure 8 is also useful for comparing SEU rates on the six part types in the experiment. The MICRON 256K and IDT 256K devices had the highest SEU rates, with the MICRON 256K devices being a factor of five times more sensitive than the 1M devices and the IDT 256K devices a factor of two and a half times more sensitive. The observations are consistent with those of Underwood. [6] The lowest SEU rate was observed on the EDI 256K part type.

A comparison of the daily rates calculated for the entire mission with those given in previous publications (References 2 and 3) shows that the rates increased by a factor of two for each part type. It was speculated that this could be due to degradation caused by total ionizing dose; however, data do not support this theory. First, the increased rate is consistently a factor of two for all part types. If dose degradation were the cause of the increase, the increases in the rates probably would not be the same across all parts types. Second, dose level estimates based on predictions and dosimeter measurements in the CRUX box are only 7 to 10 krads depending on the location in the box. It is improbable that this dose level was high enough to cause the level of degradation required to significantly affect SEU rates.

A closer look at the environment exposure offers a plausible explanation for the increase. An analysis of the orbit showed that the average fluence level for the time period that the first analysis covered was about 30% lower than the level for the entire mission due to differences in the orbit precession. As the latitude of perigee reaches the magnetic equator the satellite spends more time in high intensity regions of the proton belts. Figure 1 shows that, during the first perigee precession through the magnetic equator, the satellite was in safehold so no data were collected during the times of highest exposure. Another factor contributing to higher exposure is the fact that APEX flew in the minimum phase of the solar cycle during the time when the proton levels were increasing. It is estimated that this increase amounts to approximately 40% from 1994 to 1996 depending on the location in space.

VI. Multiple Bit Upsets

The analysis of the first 176 days of data showed that thirty-four MBUs occurred on the HITACHI/ELMO 1M parts and one MBU occurred on the MICRON 256 Kbit parts. The other four part types did not exhibit MBUs during that time. By the end of the mission, MBUs had occurred on all of the part types. Underwood reported in Reference 6 that a disproportionate number of MBUs occurred in high L regions when compared to single bit upsets, impling that heavy ions are more likely to induce MBUs. To determine if the CRUX parts showed the same response, the MBUs on all part types for the entire mission were plotted as a function of time and dipole L parameter as shown in Figure 9. We have already seen from plots of the world maps that the HITACHI/ELMO 1M devices were relatively hard to SEUs in high latitude regions. The figure shows that, while some MBUs on the HITACHI/ELMO 1M devices occurred in high L regions, many more occurred at L < 2. However, for the other part types, MBUs were observed primarily in high L regions where heavy ions predominate. The figure also shows that the number of MBUs increased with time. The probable explanation is that heavy ion levels were increasing over the CRUX mission due to solar cycle changes.

MBU rates for the devices are shown in Table 4. Note that the HITACHI/ELMO 1M devices had a much higher MBU rate than the other devices.

The CRUX experiment flew, for the most part, during very quiet solar conditions, however, a few small solar particle events did occur. The “Xs” on the x-axis of Figure 9 mark the times of the solar events. On mission day 444 (October 1995), an increase in the incidence of MBUs appears to coincide with this event. However, definitive conclusions cannot be drawn with respect to solar particle events and MBUs because the figure also shows that there is not always a direct correlation between increases in the number of MBUs and solar events.

VII. Stuck Bit Errors

Stuck bit errors on the SRAMs were also observed and reported in References 2 and 3. By the end of the mission stuck bit errors had occurred on all part types. Stuck bit error rates are shown in Table 4. The highest rates occurred on the EDI 1M and IDT 256K devices. These errors were also plotted in Figure 16 as a function of time and dipole shell parameter. On the IDT 256K devices, 50% of the stuck bit errors occurred in heavy ions regions as opposed to 2% of the SEUS. The stuck bit error counts on the other part types were too low to make similar observations.

The times of the small solar events are indicated with “Xs” on the x-axis of Figure 10. Note the solar event on mission day 444. It is not obvious from the figure, but stuck bit errors on ten devices (MICRON 1M, EDI 1M, MICRON 256K, and IDT 256K) were detected at the time of the event (represented by one data point on the plot). Although the errors were at a low L value, they occurred outside of the South Atlantic Anomaly, suggesting that high energy heavy ions from the solar event penetrated the magnetosphere down to very low L values.

Table 4

MBU and Stuck Bit Rates on CRUX SRAMs

Part Type	MBUs/bit-20 months	Stuck Bits/bit-20 months
MICRON 1M	1.2×10^{-7}	1.7×10^{-7}
EDI 1M	2.1×10^{-7}	6.1×10^{-6}
HITACHI/ELMO 1M	8.9×10^{-6}	1.8×10^{-7}
MICRON 256K	2.6×1^{-6}	1.0×10^{-6}
EDI 256K	1.7×10^{-6}	6.4×10^{-7}
IDT 256K	8.0×10^{-7}	6.2×10^{-6}

VIII. SENSITIVITY TO PROGRAMMED LOGIC STATE

Experimenters reported the effect of programmed logic state on upset rates in ground tests. [7] They observed that the ratio of upsets on the MICRON 1M when the memory cells were programmed to “1s” compared to programming to “0s” was 98:2. The same ratio was observed on the MICRON 1M devices in the CRUX experiment. Table 5 gives the percentage of “1 to 0” SEUs compared to the number of “0 to 1” SEUs for all of the part types for the entire mission. These ratios did not change significantly from those calculated for the first 176 days of the mission. (See Reference 3)

Table 5

Part Sensitivity to Programmed Logic State

Part Type	% of 1s to 0s Upsets	% of 0s to 1s Upsets
MICRON 1M	98	2
EDI 1M	54	46
HITACHI/ELMO	72	28
MICRON 256K	80	20
EDI 256K	68	32
IDT 256K	82	18

IX. VARIATION IN NUMBER OF UPSETS PER DEVICE

The variation in the number of SEUs from device to device for each of the six part types was evaluated. To estimate the variation of the device under test (DUT) response within the CRUX box enclosure, the number of SEUs on each DUT was calculated. To determine the range of the response of the DUTs, the ratios of the maximum to minimum number of SEUs on the DUTs and the percent standard deviation/mean were calculated. These results are shown in Table 6. The parameters indicate that the MICRON 1M and EDI 256K devices had a wide range in the number of SEUs on different DUTs, whereas, the range of performance for the other part types was much smaller. In fact, the SEU rates on all of the HITACHI/ELMO 1M, IDT 256K, and EDI 1M DUTs were within ± 20% of the mean. For the MICRON 256K DUTs the variation was within ± 30% of the mean. However, the range of the SEU rates on the MICRON 1M and the EDI 256K was up to ± 200% higher than the mean.

The distribution of the DUT response was determined and compared to a normal distribution via the Shapiro-Wilkes “W” parameter. The results are given in Table 6. The distribution of the DUT SEU behavior for all of the part types except the EDI 256K are reasonable fits to the normal distribution. The MICRON 256K devices show the best fit, probably due to the large number of DUTs (40). The distribution of SEU rates on the EDI devices is not a good fit to the normal distribution. Figures 11 and 12 compare the distributions of the EDI 256K and the MICRON 256K DUTs to a normal curve. It is clear from Figure 11 that the EDI 256K devices appear to have a trimodel distribution with two groups of outliers consisting of two DUTs each. Although the sample size is small, the data strongly suggest that the EDI 256K devices probably did not come from the same mask set.

The two most important factors that account for differences in DUT performance are the difference in exposure on each DUT in the box due to shielding differences and sample variation within a flight lot. In order to distinguish the former from the latter, a 3-D model of the APEX spacecraft and the CRUX box was developed, and the relative exposure of each DUT to the environment was estimated based on trapped protons. (Protons were responsible for 98% of the upsets.) Linear regression fits between the number of upsets and the proton fluence levels on each DUT were calculated. The regression coefficients (r) and the probability, P(r,N), of r being from an uncorrelated population are given in Table 6. The data results show that the number of SEUs on the MICRON 256K and IDT 256K devices are strongly correlated with the level of proton exposure on the DUTs. The EDI 1M and the HITACHI/ELMO 1M devices show moderate correlation. However, the MICRON 1M and the EDI 256K devices show no correlation between the number of SEUs and the proton exposure. This is another indicator that there were large sample variations in the CRUX flight lot for these two part types. The regression fits for the EDI 256K and the MICRON 256K devices are shown in Figure 13 and 14. Note that, in spite of the correlation between upset rates and DUT exposure, the MICRON 256K data points show some scatter about the fit implying a moderate amount of variation in the flight lot.

Table 6
Variation in Number of Upsets per DUT

Part Type	Total # of Upsets	Max:Min	% std.dev./average	Fit to Normal	r	P(r,N)
MICRON 1M	146,270	10:1	52	.941	-.08	.70
EDI 1M	74,154	7:5	11	.940	.35	.35
HITACHI/ELMO 1M	83,049	7:5	9	.964	.35	.18
MICRON 256K	370,632	9:5	12	.981	.61	<.001
EDI 256K	11,065	9:1	81	.772	-.39	.107
IDT 256K	79,513	3:2	12	.937	.67	<.001

X. SINGLE EVENT BURNOUT CONDITIONS ON POWER MOSFETS

The results on the power MOSFETs reported in Reference 4 covered the time period from the beginning of the mission (August 1994) through December 1995. The final five months of data were added to the data set and are included in the final analysis.

A. Results for the 100 Volt Power MOSFETs

Table 7 shows that only seven SEBs occurred on the twenty-four 100 volt power MOSFETs during the entire mission. Five of the SEBs occurred at high latitudes and the other two occurred outside of the South Atantic Anomaly. This would imply that the SEBs were induced by heavy ions. It is important to note that one of the SEBs occurred at a drain-to-source voltage of 55 V which is very close to one-half of the maximum rated voltage and which agrees with past ground tests with heavy ions.

Table 7
SEBs on 100 Volt Power MOSFET DUTs

V_{D-S}	L-Shell	Lon. (deg)	Lat. (deg)	Alt. (km)
68	3.4	66	61	431
83	8.5	-177	-63	2,513
68	9.6	-48	61	2,520
89	1.3	161	15	2,267
55	8.9	-164	70	2,057
80	8.7	-172	-67	1,020
80	1.4	-123	-4	2,228

B. Results for the 200 Volt Power MOSFETs

Many more SEBs were detected on the 200 volt power MOSFETs than on the 100 volt. Only seven of the SEBs occurred at L values greater than 3. About 350 SEBs were detected at lower L values in regions dominated by trapped protons. Table 8 gives the SEBs on the 200 volt devices for L > 3.

All SEBs on the 200 volt devices are plotted on a world map (altitude range=1500-1999 km) in Figure 15 with intensity contours of protons with energies greater than 50 MeV and L=3 dipole shell contour. The figure shows that most of the SEBs occurred at low L values in trapped proton regions. Previous work (Reference 4) also correlated the occurrence of SEBs with the detection of high energy protons by the CREDO instrument. The ability of protons to produce SEBs was also shown in the laboratory by Oberg *et al.* (Reference 5). Oberg calculated rate predictions based on the ground tests that showed close agreement with the observed flight rates.

The dependence of SEBs on drain-to-source voltage was calculated for the 200 volt devices. The results are plotted in Figure 16. As expected from ground tests, the rate of occurrence of SEBs increases with increasing drain-to-source voltage.

Table 8
SEBs on 200 Volt Power MOSFET DUTs at L > 3

V_{D-S}	L-Shell	Lon. (deg)	Lat. (deg)	Alt. (km)
178	4.4	-93	-69	2,518
154	5.8	-7	62	1,983
130	3.6	10	58	1,228
130	7.0	-74	55	1,285
148	5.9	-141	-69	1,040
172	17.1	-41	68	2,527
196	6.4	133	70	2,487

XI. SUMMARY

Single event upset rates on the commercial SRAMs and single event burnout rates on the 200 volt power MOSFETs were strongly dependent on proton fluence levels. The MICRON 1M and EDI 256K devices had large ranges in the sensitivity to SEUs from device to device within a type, and the variation could not be attributed to differences in shielding alone. The number of upsets on HITACHI/ELMO 1M, EDI 1M, MICRON 256K, and IDT 256K devices differed from the mean by ± 20-30% and the MICRON 1M and EDI 256K by ± 200%. The SEU and MBU rates increased with mission time corresponding to the solar cycle increase in proton and heavy ion levels. A small solar event in October 1995 may have caused stuck bit errors on 10 DUTs of different part types.

Although all the vendors had agreed to supply devices from the same mask set (to assure lot homogeneity), the data tell us that this did not happen for all part types. A major ramification of this is that even if a supposedly homogeneous lot is ground tested using typically one to three samples, the error rate prediction could be off by a factor of up to ten.

Most SEBs on the 100 volt power MOSFETs occurred in high latitude regions. One of the SEBs occurred at a drain-to-source voltage of 55 V which is close to the 50% derating value. SEBs on the 200 volt power MOSFETs did not occur below 130 V. The voltage threshold was higher for SEBs in the proton regions. The SEB rate was strongly dependent on voltage threshold.

ACKNOWLEDGEMENTS

Recognition is gratefully acknowledged for the support of a number of organizations and individuals. We are indebted to the US Air Force/Space Division for the flight opportunity on APEX. Thanks are due to NASA/HQ and Defense Special Weapons Agency for their financial support for CRUX. Especially, we wish to thank many persons on the CRUX team for encouragement, guidance, long hours, and diligence. Without their enthusiasm, this effort would not have been possible. These include George Kramer, Steve Brown, Tom Budney, Tim Gruner, Miriam Wennersten, Christina Seidleck, Rick Schnurr, Keith Chamberlin, Tom Quinn, James Campa, Charles Clagett, Tom Correll, Lamar Dougherty, Herbert Foster, Richard Hoffman, and Angelo Russo.

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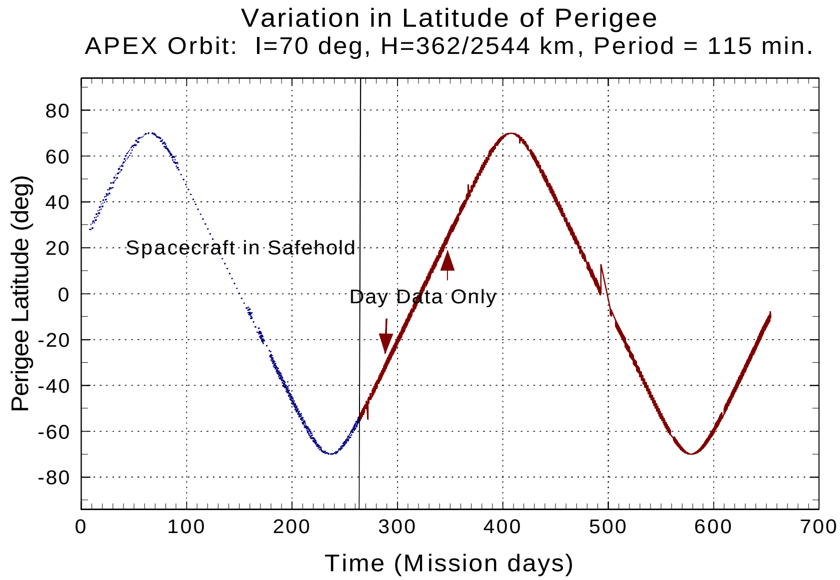

Figure 1: Latitude of perigee of the CRUX orbit as a function of mission time. The maximum daily exposure to trapped protons occurs when perigee is at the magnetic equator.

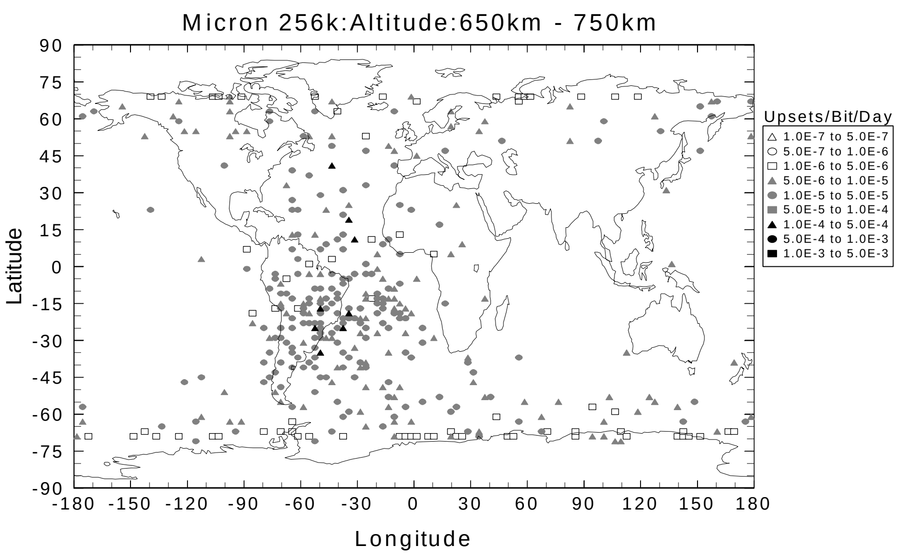

Figure 2: Upset Rates on the MICRON 256K. Most upsets occurred in the South Atlantic Anomaly.

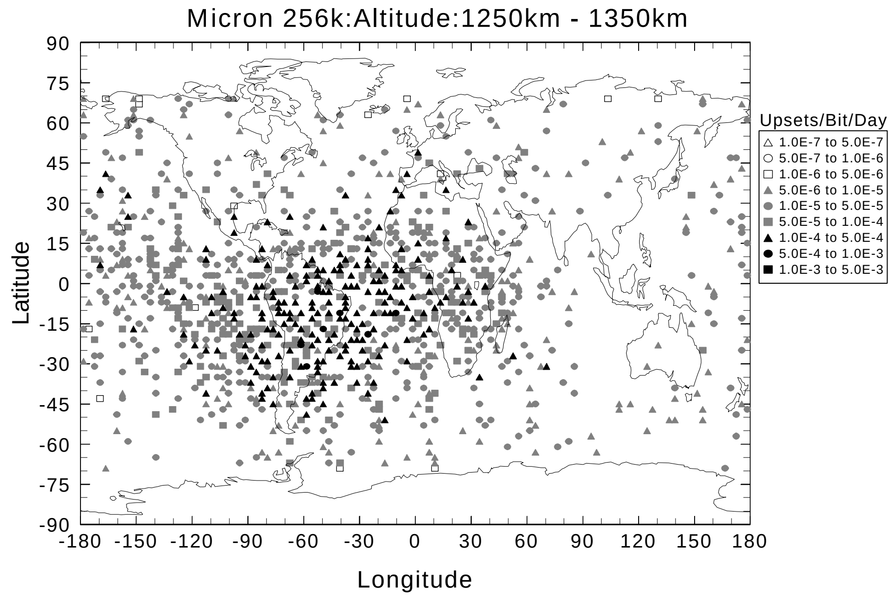

Figure 3: Upset Rates on the MICRON 256K. Note the increase in the size of the South Atlantic Anomaly. As a result of the higher proton fluences, the upset rates have increased.

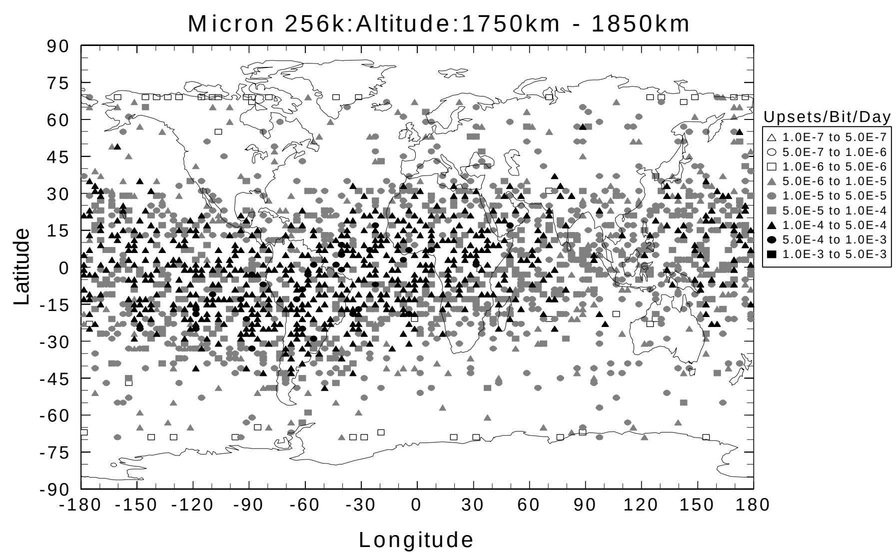

Figure 4: Upset Rates on the MICRON 256K. At this altitude it is possible to see the belt structure of the proton trapping regions. Upsets occur in a wide region at a higher rate.

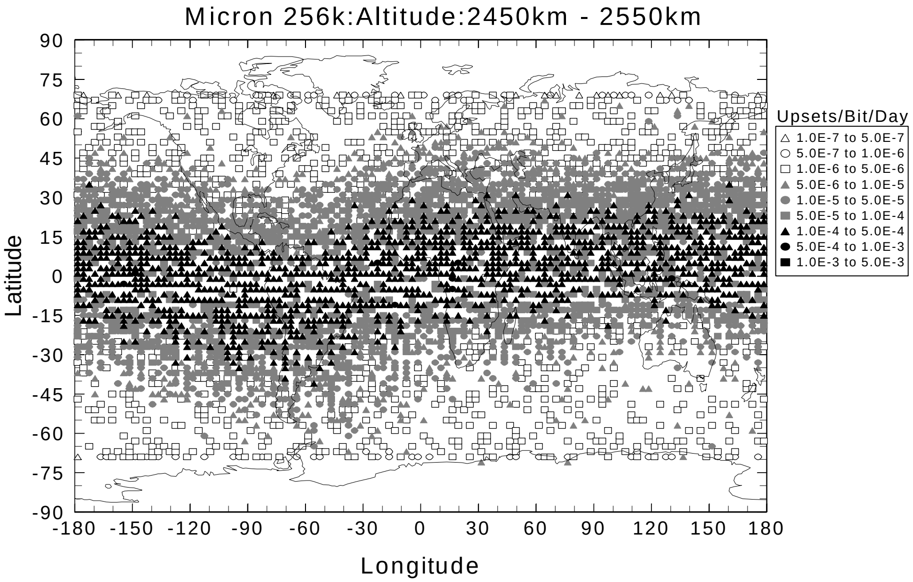

Figure 5: Upset Rates on the MICRON 256K. At 2500 km the high energy trapped protons have increased to levels near the peak of the population.

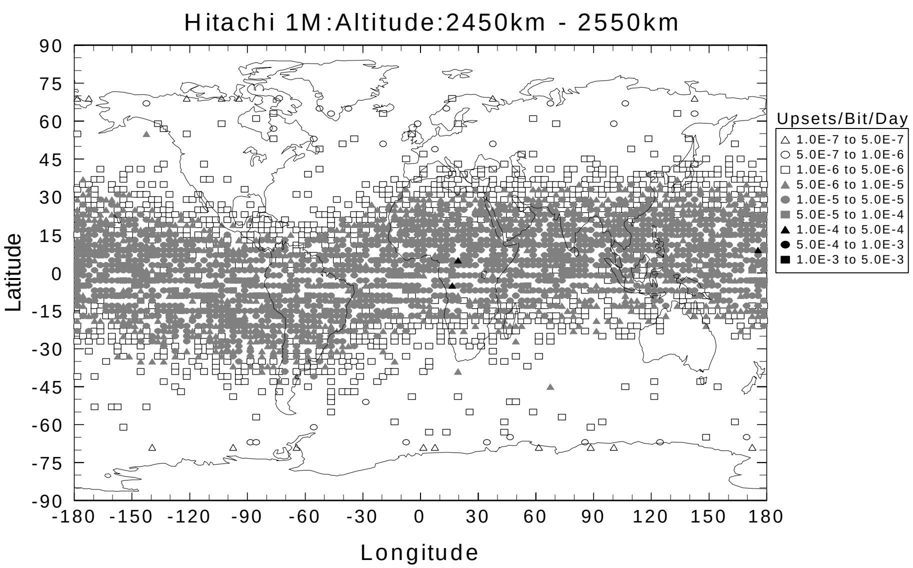

Figure 6: Upset Rates on the HITACHI/ELMO 1M. The rates are lower than those for the MICRON 256K. Note low rate at high latitudes (greatest exposure to heavy ions).

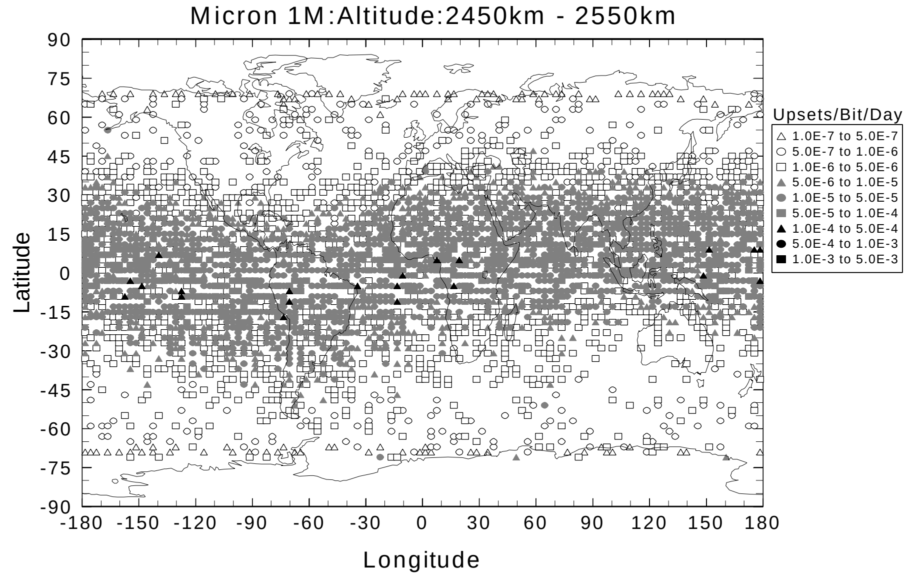

Figure 7: Upset Rates on the MICRON 1M. The rates are lower than the rates on the MICRON 256K.

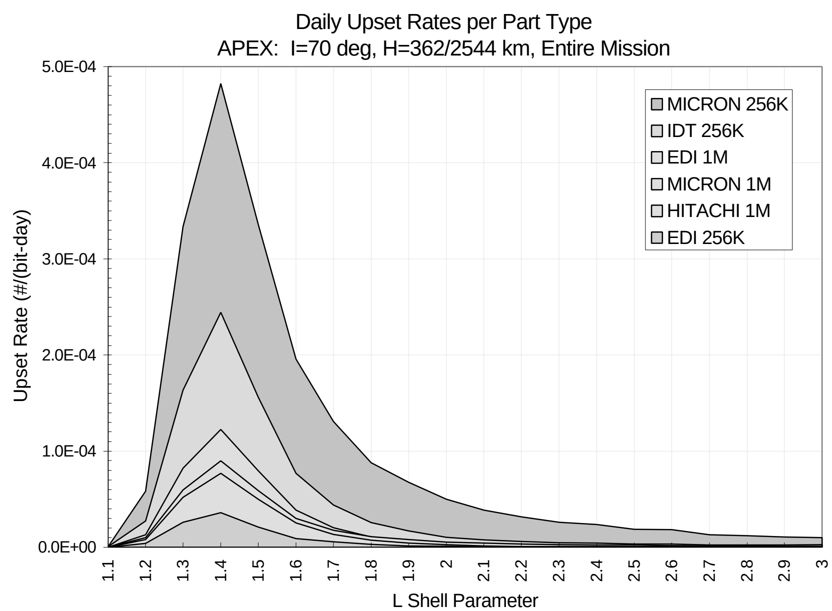

Figure 8: A comparison of the upset rates on all six part types flown on CRUX. The rates are lower on the 1M devices than on the MICRON 256 K and IDT 256K.

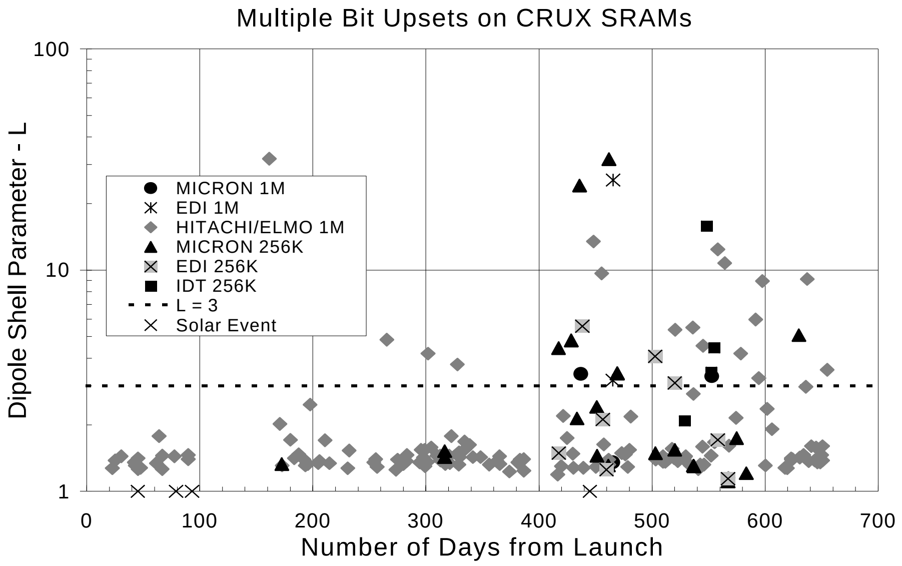

Figure 9: The dependence of multiple bit upsets on dipole shell parameter. Note the increase in MBUs at high Ls at the end of the mission.

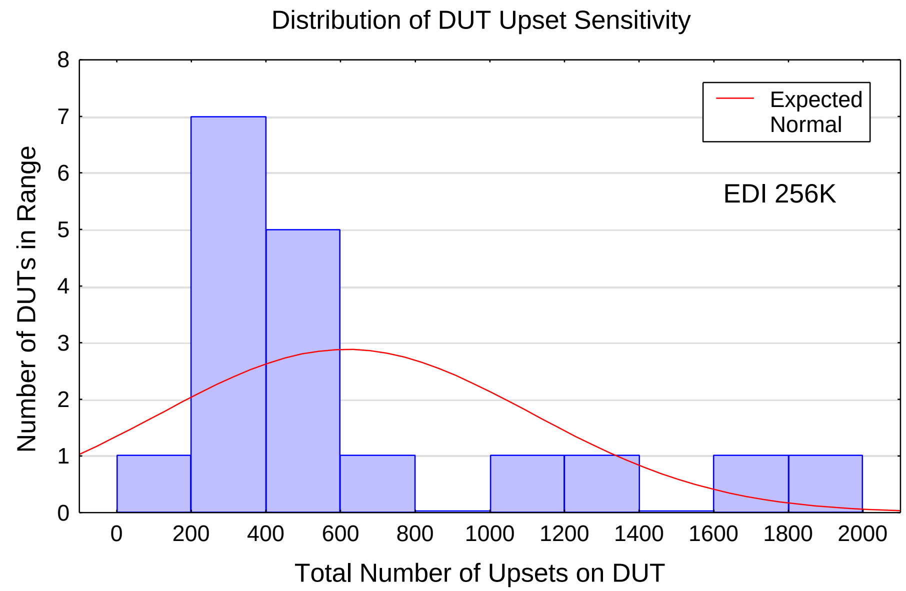

Figure 11: The distribution of the DUT sensitivity compared to a normal distribution. For the EDI 256K the distribution appears trimodal.

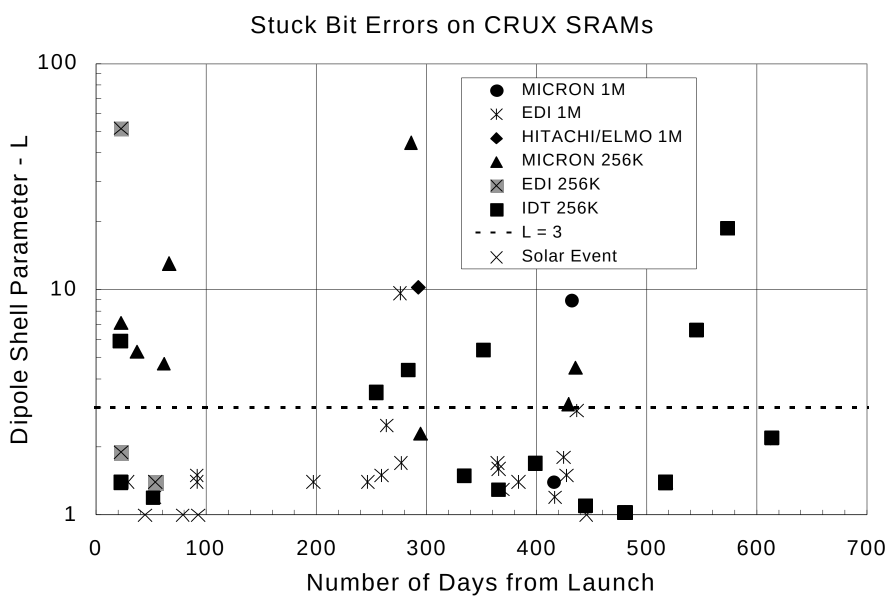

Figure 10: The dependence of stuck bit errors on dipole shell parameter. Errors occurred on 10 DUTs at mission day 444 which was the date of an October solar event.

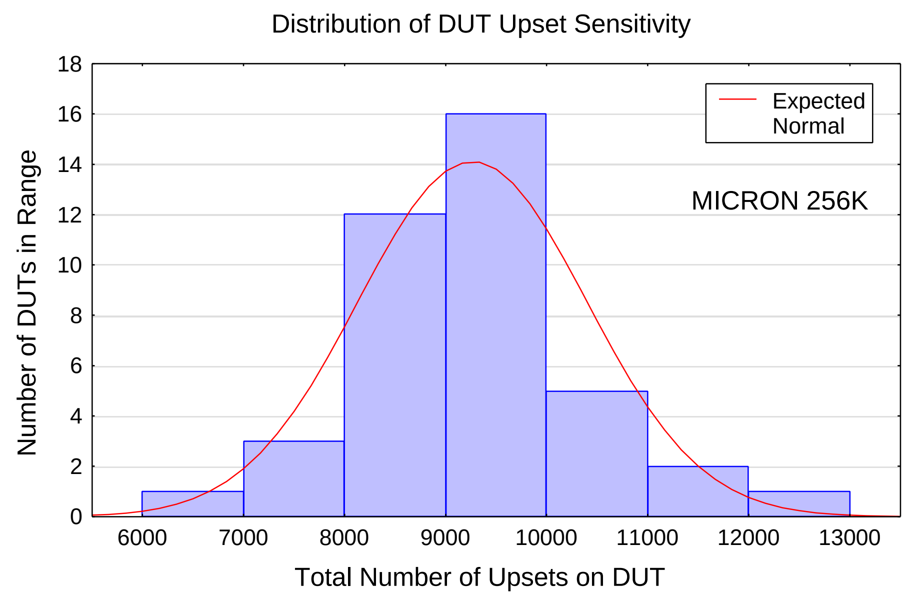

Figure 12: The distribution of the DUT sensitivity compared to a normal distribution. For the MICRON 256K.

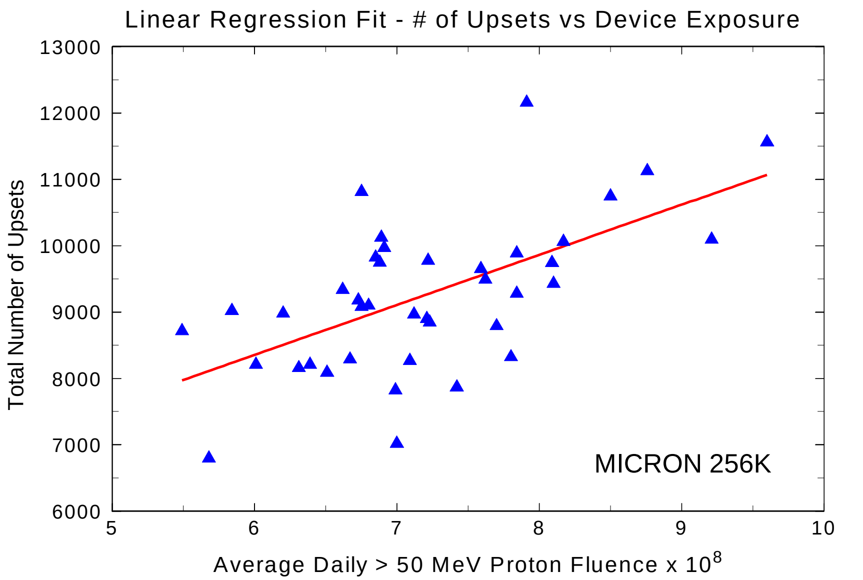

Figure 13: The positive correlation between DUT exposure (proton fluence) and the number of upsets is shown. One cause for the scatter around the fit is device to device variation.

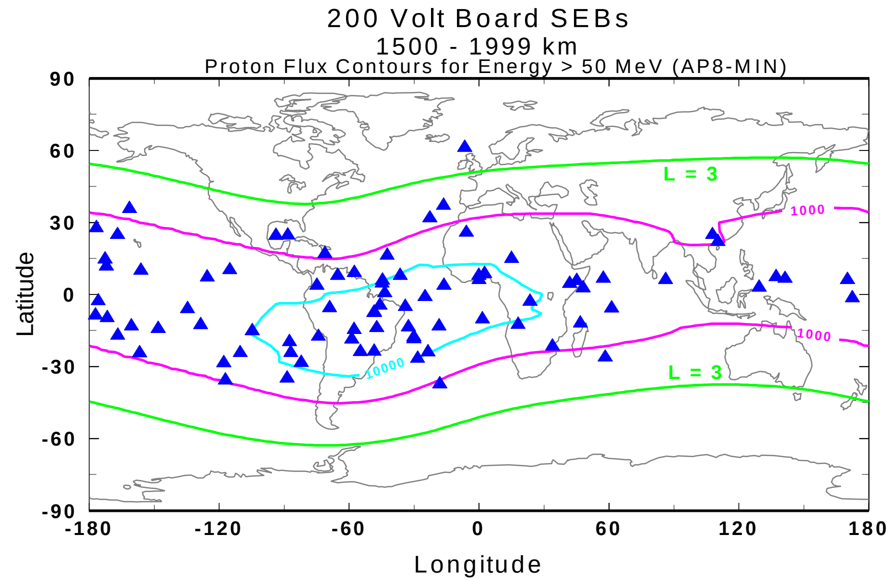

Figure 15: The location of SEBs on the 200 volt power MOSFETs. The proton contours at 1000 p/cm2/s mark the boundary of most of the SEBs. The rates are dominated by events in the proton trapping regions.

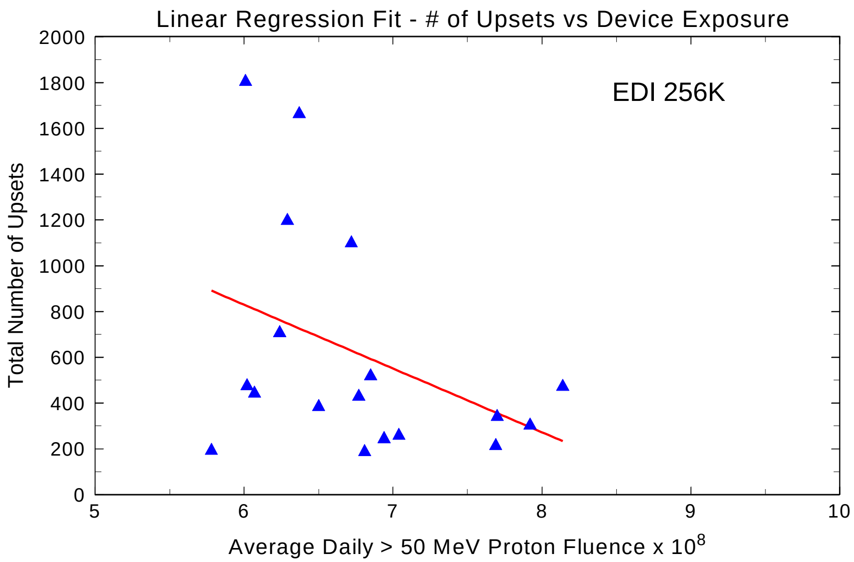

Figure 14: The lack of correlation between DUT exposure (proton fluence level) and the number of upsets is shown. This is an indication of the large DUT to DUT variation.

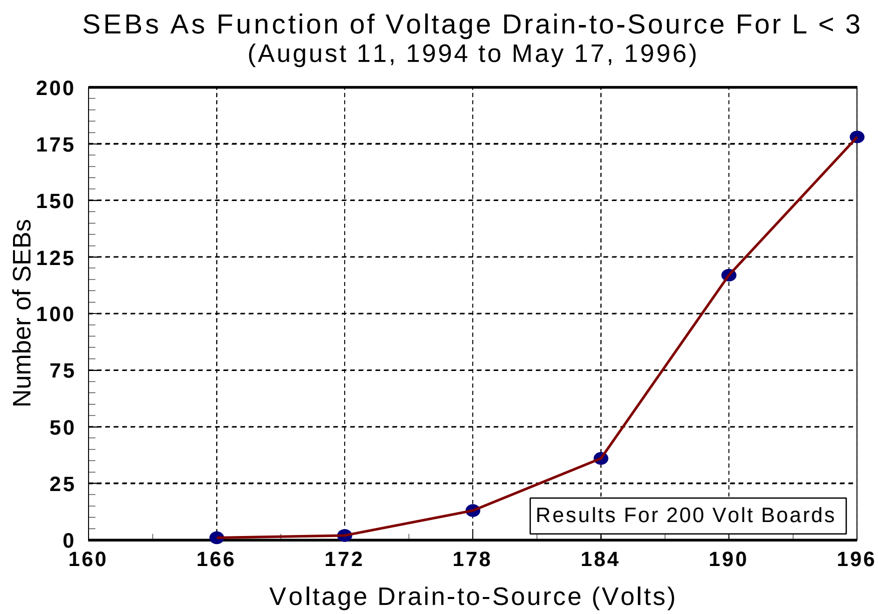

Figure 16: The number of SEBs on the 200 volt power MOSFETs are given as a function of drain-to-source voltage.