Total Ionizing Dose Tolerance of Micro-SD Cards for Small Satellite Missions

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ABSTRACT

Tests have determined damage thresholds and failure rates as a function of total ionizing dose (TID) of beta radiation for various types of COTS micro-SD cards commonly used for memory storage in space applications. Radiation tolerance of high-density electronics are common critical failure modes for satellites, particularly for small satellites that often use lower shielding and less radiation-hardened COTS components. The tests evaluated SD-card formatting and read/write speeds at nine radiation intervals for up to ~1000 Gy TID, equivalent to ~15 times TID typically experienced annually on the unshielded exterior of satellites in Low Earth Orbit. A limited number of failures were observed beginning after ~400 Gy TID. Cards experiencing failures were subsequently tested at more rapid interval intervals, and typically recovered their initial read/write speeds after ≤24 hrs, except in more severe cases after >400 Gy TID. These results will facilitate satellite designers' selection of the appropriate quality and cost of the micro-SD cards for their particular mission, based on reliability and radiation tolerance.

INTRODUCTION

Micro-SD cards are an important component of most small satellites, used to store acquired data and retrieve other critical information from their high density memory.[1,2] Radiation tolerance of high-density electronics—such as micro-SD memory cards, computer microcontrollers, and CCD and CMOS optical sensors—are common critical failure modes for satellites, particularly for small satellites which often have reduced shielding due to mass constraints and often use less radiation-hardened commercial-off-the-shelf components (COTS) components due to cost and development time constraints. Hence, testing for potentially environmental-induced radiation damage SD cards and other electronics used in small satellites is critical to avoid possible deleterious or catastrophic effects over the duration of space mission.

This is increasingly more important as small satellite programs as CubeSats missions become more commonplace, mission lifetimes are extended, and orbital environments expand to more harsh environments. Also, mission objectives are becoming more ambitious, make more diverse and sensitive measurements, minimize shielding to reduce mass, and utilize more compact and sensitive electronics (often including untested COTS components). At present, CubeSats are most often placed into Low Earth Orbit (LEO) where the space radiation environment is modest (see Figure 1).[3-5] They also typically have mission durations on the order of a year or less. However, they are increasingly exposed to more intense radiation environments such as polar, auroral, or geosynchronous environments[4,5] (see Figure 1) and have longer lifetimes, leading to requirements for resistance to higher total ionizing dose (TID).

These issues lead to a need for measurements to determine radiation tolerance for key components. Such measurements, particularly for COTS electronics components, are rather limited.[2,6-14] Further, the large number and rapid design changes of such components make the need for additional tests always necessary. This paper focuses on radiation tolerance tests of one such key electrical COTS component, micro-SD cards.

Radiation Damage of Micro-SD Cards

The long-term damage done by radiation in space environments is typically due to the TID, which is the cumulative amount of absorbed radiation energy per unit mass (measured in Gy or equivalently J absorbed per kg) an object is exposed to. Exposure to higher fluence radiation UV[15,16] and ionizing radiation[14,15,17] can generate atomic scale defects in materials leading to changes in the optical, electrical, and mechanical properties. Environmentally-induced problems, particularly for electrical and electronics components, are dominated by spacecraft charging[5,19,20] and single-event interrupts.[4,14] This energy deposition can damage the satellite components and, if severe enough, cause the spacecraft to not operate as designed or in extreme case fail altogether.[4,14,19,21,22]

This susceptibility to radiation damage can be exacerbated for CubeSats because of the reduction in shielding necessitated by size and mass constraints of small satellites. For example, if fully 10% (~0.1 kg) of a CubeSat's mass were devoted to a ~1 mm thick Al shield over all CubeSat faces, this shield would be insufficient to stop electrons with ≳300 keV. Kimura, et al. estimate an annual TID of ~20 Gy/yr for a mission in an ISS-like LEO orbit where there is 2 mm Al shielding.[11] Kingsbury, et al estimate an annual TID of 12 Gy/yr for their shielded small satellite in LEO.[2]

Radiation damage of electronics is often classified as two types.[14,23] "Soft errors" which include SEU (and SEFI for SDRAM), are reversable damage which do not permanently damage the device; they can most often be corrected for by software and rebooting.[10,24] A SEU happens when the state of a storage element changes (bit-flip). A Single Event Functional Interrupt SEFI occurs when a SEU happens on a critical system control register and causes the device to malfunction. Functionality can be restored generally through a reset or reboot sequence, which will rewrite the bit location of the SEU bit-flip. SD memory card modules are complex devices containing a flash memory array as well as a controller/interfce circuit.[2] The controller/interface circuit is often the source of SEFI.[2]

By contrast, "Hard errors" which include TID and SEL (single event latch-up) errors, create irreversible damage and permanently damage the device when the TID threshold has been reached.[24] The Read/Write speed tests used here extend the pass/fail formatting tests.

TID failures are most likely the result of beta or gamma radiation, while "soft errors" typically result from very high energy proton or ion radiation that imparts large energies in a single event. TID tests typically involve formating and verifying (reading) written data blocks; they are usually pass/fail. TID tests can be powered (biased) and unpowered (unbiased) tests; the tests here are all unbiased.. Literature suggests baiased/unbiased does not make a significant difference for TID error rates.[2]

SD cards have been tested with gamma,[2,8,11] proton,[7,11] and ion radiation.[8] Similar electronics have been tested with gamma and ion (SDRAM) radiation.[10] Similar TID failure thresholds were seen for other TID

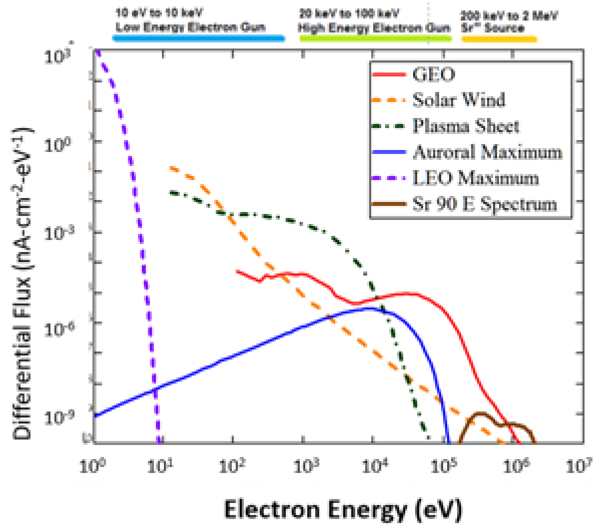

Figure 1: Representative space electron flux spectra for geostationary earth orbit,[4] solar wind at the mean earth orbital distance,[18] plasma sheet environment,[18] maximum aurora environment,[18a] and low earth orbit.[4] Energy ranges for SST chamber electron sources and the β source are shown above the plot. The ^{90}Sr source electron emission spectrum is also shown. Bars above graphs show the ranges of the chamber source emissions.

tolerance tests using gamma,[2,8,10,11] proton,[7,11] and ion[8,10] radiation.

Structure and Failure Mechanisms of Micro-SD Cards

Increasing demand for higher memory densities in space and aircraft electronics has generated significant interest in the use of flash NAND based devices. However, there are several features of NAND flash memory that require additional care when they are used in these applications.[25] NAND Flash is a type of non-volatile storage technology that does not require power to retain data. NAND flash chips are roughly the size of a fingernail and can retain huge amounts of data. In the simplest terms, the data stored on NAND Flash is represented by electrical charges that are stored in each NAND cell. The difference between Single-Level Cell (SLC) and Multi-Level Cell (MLC) NAND is in how many bits each NAND cell can store at one time. SLC NAND stores only 1 bit of data per cell. As their names imply, 2-bit MLC NAND stores 2 bits of data per cell and 3-bit MLC NAND stores 3 bits of data per cell. The fewer bits per cell, the smaller the capacity; however, data are written and retrieved faster, and the NAND chip has a higher endurance level and so will last much longer.[26] One of the most common errors in NAND Flash is a simple retention error. Over time, electrons trapped within the NAND array will sometimes escape.

Table 1: Micro-SD Cards Tested

Category	SD-Card Manufacture (Designation) / Part Number [Reference]	Memory Capacity
Lower-grade Commercial	SanDisk / SDSDQ-008G-A46 [27] PNY (Four DUT: Alpha, Beta, Gamma, Delta) / P-SDU16G4-GEX20 [28]	8 GB 16 GB
Higher-grade Commercial	Samsung Evo Plus / MB-MC32GA/AM [29] SanDisk Ultra / SDSQUA4-032G-AN6MA [30] SanDisk Extreme Plus / SDSQXVF-032G-AN6MA [31]	32 GB 32 GB 32 GB
Industrial grade	Delkin Devices S308MMZAL-U1000-4 [32] Delkin Devices (Four DUT: (Sigma, Omega, Kappa, Lambda) S304TLNCN-U1000-3 [32]	8 GB 4 GB

In great enough numbers, this can change the read state of the affected cell, switching a logic zero to a logic one during a page read operation.[33]

INSTRUMENTATION

Micro-SD Card Selection and Preparation

Test were performed on 13 micro-SD card ranging in memory capacity from 4 GB to 32 GB; these devices under test (DOT) are identified in Table 1. They are divided into three main categories—Low-grade commercial micro-SD cards, High-grade commercial micro-SD cards, and industrial-grade micro-SD cards. All the lower-grade and higher-grade micro-SD cards were Multi-Level Cell (MLC) NAND types and the industrial grade micro-SD cards were all Single-Level Cell (SLC) NAND types. In two cases, four identical SD-cards (designated alpha through lambda in Table 1) were measured to establish the reproducibility of the test results and uncertainties in Read/Write speeds.

After pre-radiation baseline tests (see below), micro-SD cards were prepared for the radiation exposure process. All components were thoroughly cleaned prior to insertion in the vacuum chamber: SD-cards and the polycarbonate mount were cleaned with isopropyl alcohol, while metal and polymeric hardware components were cleaned with acetone and methanol, respectively.

The micro-SD cards were inserted in a custom polycarbonate sample mount, with closely spaced, shallow, numbered depression to reproducibly reposition each numbered micro-SD card after each TID exposure interval [see Figure 2(a)]. A thin (~0.25 mm) polycarbonate top mask, readily penetrated by the ^{90}Sr beta radiation, secured the micro-SD cards in the mount and was held using four Nylon screws. The mount was positioned 16 cm from the ^{90}Sr source using four threaded posts [see Figure 2(b)]. The mount, mask, mounting hardware, and graphite sample stage backing the mount[34] were all made of lower atomic number materials to minimize scattered, more penetrating bremsstrahlung x-ray production by the beta radiation.

Table 2: TID Intervals Tested

TID Interval	TID Increment (Gy)	Cumulative TID (Gy)	Exposure Duration (hrs)
1	10	10	3.6
2	10	20	3.6
3	20	40	7.3
4	20	60	7.3
5	40	100	14.6
6	100	200	36.3
7	200	400	72.7
8	200	600	72.7
9	400	1000	145.5

Once the micro-SD cards were inserted into the SST chamber, they were maintained at room temperature (24.3±2) ^{0}C over the full experimental duration of 15 days. The vacuum chamber was then pumped to a base pressure of <20 mPa in about 30 min using an oil-free diaphragm-backed turbomolecular pumping station. Low vacuum minimized atmospheric scatter of the beta radiation and possible harmful effects of reactive species (*e.g.,* O^+, H^+, OH^-) produced by the radiation. Photographs of the repositioned micro-SD cards were taken at the beginning, middle, and end of each radiation interval [see Figure 2(b)].

Space Survivability Test Chamber

Radiation exposure was conducted in the Utah State University (USU) Space Survivability Test (SST) chamber, a versatile test facility designed to study space environments effects on small satellites and system components [see Figure 3]. This high vacuum system is particularly well suited for cost effective tests of multiple small-scale materials samples over prolonged exposure to simulate space environmental components.[34,35] The SST chamber simulates several critical characteristics of the space environment: electron flux, ionizing radiation, photon flux, temperature, and neutral gas environment. The energy ranges of SST electron and ionizing radiation are shown above Figure 1.[34] An automated data acquisition system can periodically record real-time environmental conditions—and *in situ* monitoring of key satellite/component/sample performance metrics and characterization of material properties and calibration standards—during the sample exposure cycle.

(a)

(b)

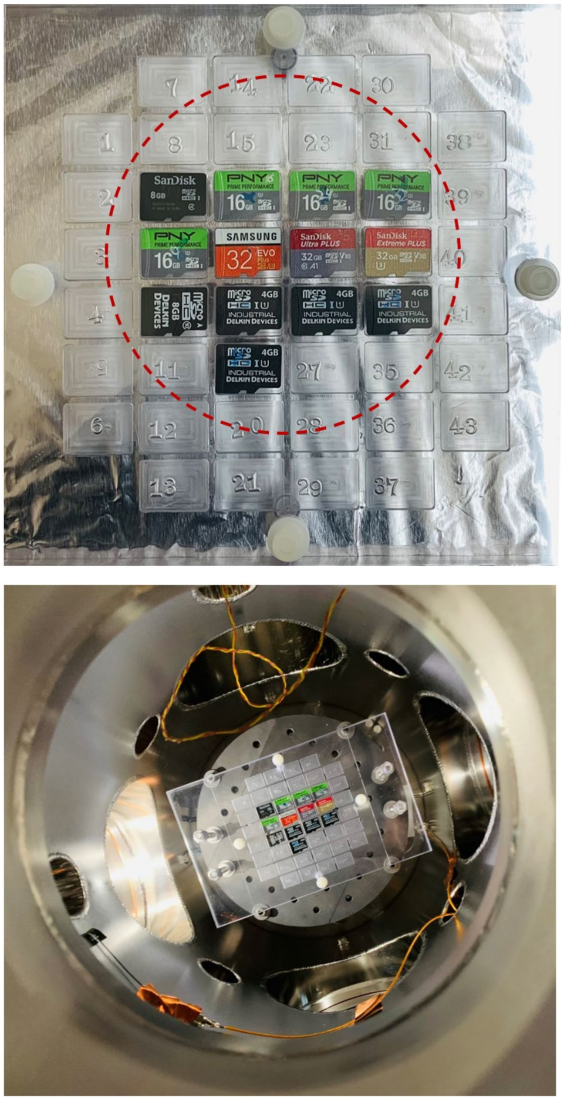

Figure 2: Micro-SD cards under investigation. (a) Cards mounted on polycarbonate mount. Circle indicates the 8 cm diameter region of radiation exposure. (b) Bird's-eye view of cards and mount positioned in the SST chamber below the ^{90}Sr source (retracted to allow view of samples).

The test described herein used a ~90 mCi ^{90}Sr source emitting broadband penetrating beta radiation of approximately 0.2 to 2.5 MeV. Figure 1 compares the ^{90}Sr emission spectrum with representative electron spectral fluxes for several common space environments. Previous researchers have identified ^{90}Sr beta emission sources as a convenient option for safely emulating the high energy electron radiation space environment and testing the effects of electron displacement damage on devices and materials.[36,37]

The ^{90}Sr source (29 yr half-life) provides a stable electron flux, with <5% variation over the >10 cm X 10 cm sample area. Internal shielding of the ^{90}Sr (nearly) point source provides a conical beam profile with 30° full-angle at distances up to >28 cm. The source intensity, which falls off as the inverse square of the source-to-sample distance, provides dose rates up to ~15 Gy/hr for accelerated testing,

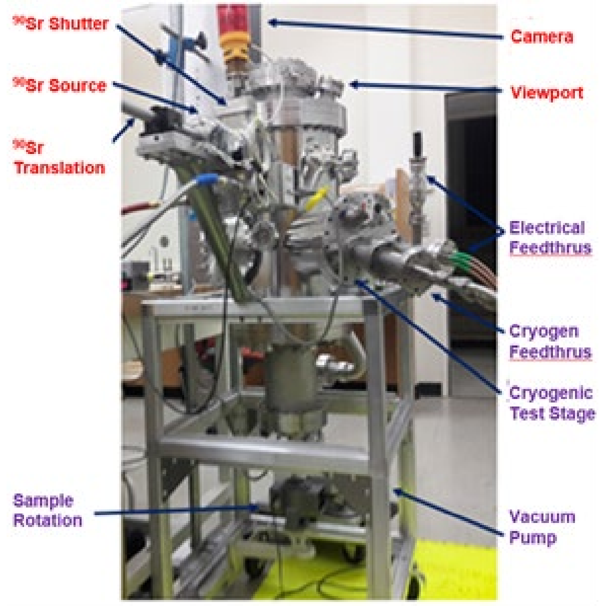

Figure 3: Space Survivability Test (SST) chamber.

Dose Rate Calculations

The mounted micro-SD cards were positioned inside a 8 cm diameter circle [red circle, Figure 2(a)] of radiation exposure at a 16 cm source-to-sample distance. The experimental dose rate was calculated as 2.75 Gy/hr. This is ~350X an annual dose rate (~70 Gy/yr) received on the exterior of a typical CubeSat in LEO[4] and an ~1300X accelerated test rate for typical shielded LEO CubeSat missions. As noted above, Kimura, *et al.* estimate an annual TID of ~20 Gy/yr for a mission in an ISS-like LEO orbit where there is 2 mm Al shielding[11] and Kingsburg, *et al.* estimate an annual TID of 12 Gy/yr for their shielded small satellite in LEO;[2] these are similar to measured values on the ISS with similar shielding.[38] This was one to two orders of magnitude less than the acceleration rates used for other SD-card tests using gamma rays (Kingsbury, *et a.l* used 80 Gy/hr ($4 \cdot 10^4$X) and 240 Gy/hr ($1 \cdot 10^5$X);[2] Kimura, *et al.* used 108 Gy/hr ($5 \cdot 10^4$X);[11] and Oldam, *et al.* used 1080 Gy/hr ($5 \cdot 10^4$X) [8]).

Preliminary tests at USU using this system for a limited number of micro-SD cards found 1 of 8 cards failed a formatting test after ~340 Gy.[6] Hence, a target maximum cumulative TID of 1000 Gy was chosen for the current experiments, well in excess of both the TID threshold where at least some micro-SD card failures were expected and TID for typical small satellite missions. To reach this target cumulative TID of 1000 Gy, micro-SD cards were irradiated for ~365 hrs or ~15 days. To better determine the TID failure threshold, a set of nine approximately logarithmically-spaced exposure intervals over two decades of TID from 10 Gy to 1000 Gy were accomplished; these are noted in Table 2. These planned beta radiation intervals spanned the TID measured for SD cards using gamma radiation in previous studies (Kingsbury, et al. of 80 Gy and 240 Gy TID;[2] Kimura, *et al*. of 200 Gy TID;[11] and Oldam, *et al.* of 100, 200, 300, 500, 750, and 1000 Gy TID[8]). Previous TID tolerance tests using gamma radiation for SD-cards[2,8,10,11] and similar memory[10] showed TID pass and fail results consistent with this planned TID range.

RADIATION TEST METHODS

The radiation testing process of the 13 micro-SD cards was divided into three main categories: (i) pre-radiation baseline tests conducted prior to radiation; (ii) post-radiation tests conducted after each TID interval; and (iii) radiation damage recovery tests performed only on micro-SD cards that failed the post-radiation tests after a particular TID exposure interval. The common elements of these hardware tests are detail below. The procedures specific to the three categories are described in the following subsections.

All 13 micro-SD cards were tested simultaneously, by inserting each micro-SD card in an individual SD-card-to-USB-3 adapter into a designated port of a 16-port USB-3 hub that was connected to a computer. This allowed multiple copies of the test software to be run in parallel, executing under a custom script.

The micro-SD cards were tested, based on three main criteria: (i) a format test, (ii) an originality test, and (iii) sequential and random Read/Write speed tests. Three different test software packages were used for this, used commonly in SD-card tests.[39]

1. *SD card Formatter 5.0.1*: This test was used to maintain the card's full [40]speed performance, preserve its storage capacity, and reduce the risk of storage errors. This test took ~1 min to perform once on the full set of 13 micro-SD cards. This was a pass/fail test.

2. *FakeFlashTest 1.1.1*:[41] The program verified the actual capacity of the disk by writing blocks of data with a size corresponding to the declared capacity of the media. This test was used to verify the true capacity of micro-SD cards and flash drive media. This test took ~1 min to perform once on the full set of 13 micro-SD cards. This was a pass/fail test. This was similar to other block read/write tests preformed in other studies.[2,8,11]

Table 3: Analysis of Baseline Read/Write Speeds

Read/Write Tests		Read/Write Speeds (MB/s) (±std. dev.) All Tests	Read/Write Speeds (MB/s) (±std. dev.) Filtered Tests	Number of Tests Filtered
R1	Sequential Read SEQ1M Q8T1	42±8 (±18%)	40±3 (±6%)	15 of 195 (8%)
R2	Sequential Read SEQ1M Q1T1	44±8 (±17%)	43±7 (±1%)	12 of 195 (6%)
R3	Random Read RND4K Q32T1	8.7±0.1 (±1%)	8.81±0.07 (±1%)	16 of 195 (8%)
R4	Random Read RND4K Q1T1	7.2±0.2 (±3%)	7.2±0.2 (±2%)	14 of 195 (7%)
W1	Sequential Write SEQ1M Q8T1	29±4 (±13%)	29±4 (±14%)	7 of 195 (4%)
W2	Sequential Write SEQ1M Q1T1	32±4 (±14%)	32±4 (±13%)	6 of 195 (3%)
W3	Random Write RND4K Q32T1	1.2±0.3 (±23%)	1.31±0.08 (±6%)	12 of 195 (6%)
W4	Random Write RND4K Q1T1	1.2±0.3 (±23%)	1.22±0.08 (±6%)	10 of 195 (5%)
All Read/Write Tests		(±14%)	(±8%)	92 of 1560 (6%)

3. *CrystalDiskMark 8.0.1*:[42] This series of tests was used to measure sequential and random Read/Write speeds of each card with varying number of queues and threads. A total of eight tests were performed, two tests of sequential read speed (SEQ1M: Q8T1 and SEQ1M: Q1T1), two tests of random read speed (RND4K: Q32T1 and RND4K: Q1T1), two tests of sequential write speed (SEQ1M: Q8T1 and SEQ1M: Q1T1), and two tests of random write speed (RND4K: Q32T1 and RND4K: Q1T1). A script was written to test all the micro-SD cards simultaneously and port the data automatically to an Excel file for further analysis. These tests took ~15 min to perform five times on the full set of 13 micro-SD cards. These Read/Write speed tests were in some way similar to tests of "low-current latch-up" tests, where continuous/standby current consumption for biased TID tests increased temporarily by a factor of ~2X.[7]

Pre-Radiation Baseline Tests

The *SD card Formater* and *FakeFlashTest* tests were straightforward and were performed just once on each card. As expected, all micro-SD cards passed these initial tests.

The sequential and random *CrystalDiskMark* Read/Write speed tests produced a set of values for each micro-SD card for the read/write speed for each of the eight tests, along with an average value an estimated uncertainty (standard deviation of the mean) for each of the eight tests. Each pair of tests returned the same read/write speed for each type of card within the reproducibility of the tests (see Table 3).

These preliminary tests were performed a total of 15 times to provide lower statistical uncertainties for the read/write speeds of the pre-radiation baseline tests. This reduced the uncertainty in subsequent calculations of the change in the various read/write speeds (differences between the read/write speeds measured after each TID interval and the baseline values). Approximately 6% of these 1560 tests were found to yields anomalous speeds well outside the expected range (that is exceeding Chauvenet's criterion or a z-score in excess of 2 standard deviations[43]). Elimination of these few outliers reduced the uncertainties in the sequential read and random write speeds by more than a factor of 6 on average to ≤8% (see green shaded cells in Table 3). Based on these results, changes in speeds were deemed significant if they exceeded the average uncertainties in Table 3, or greater than ~10%.

Post-Radiation Tests

When the each TID interval was finished, the radiation source was shuttered, the source was backed out of the SST chamber, the chamber was brought to atmospheric pressure, and the micro-SD cards were removed from the chamber. This process took approximately 20 min.

The SD cards were then inserted into USB-3 adapters in their respective slots in the 16-port USB-3 hub and post-radiation tests were initiated. The *SD card Formater* and *FakeFlashTest* tests were performed first and pass/fail status recorded. The sequential and random *CrystalDiskMark* Read/Write speed tests were performed a total of 5 times, requiring ~15 min to complete. This reduced number of Read/Write speed tests allowed the subsequent Radiation Damage Recovery tests for those micro-SD card exhibiting failure to begin more rapidly, typically within ~30 min of the end of the previous TID interval. It also allowed the micro-SD cards that passed the tests to be reintroduced into the SST chamber and the next TID interval to begin typically with ~45 min of the end of the previous TID interval. This allowed our tests to easily meet the standards for maximum time intervals for TID testing (1 hr after exposure to start of electrical characterization and 2 hrs to the beginning of the next radiation exposure).[8,24,44] Note that the few cards that failed these post-radiation tests were reintroduced to the sequence of TID intervals once full recovery was indicated or 24 hr had elapsed..

The outcomes of all the Post-Radiation Test data were recorded and compared with the baseline tests. The *SD card Formater* and *FakeFlashTest* failure tests were pass/fail. Failure for the sequential and random *CrystalDiskMark* Read/Write speed tests were determined by comparison of changes in the read/write speeds to two predetermined criteria. A card failed if the fractional change in read/write speed (differences between the read/write speeds measured after each TID interval and the baseline values divided by the baseline speed) exceeded the fractional uncertainty in this calculated change of speed (the sum of the fractional SDOM of the baseline speed and fractional SDOM of the post-TID speed). In mathematical format the failure criterion for Read/Write tests was

$$\left| \frac{\left[\dfrac{S_{TID}^{R/W} - S_{Baseline}^{R/W}}{S_{Baseline}^{R/W}} \right]}{\left[\dfrac{\sigma_{TID}^{R/W} / \sqrt{N_{TID}^{R/W} - 1}}{S_{TID}^{R/W}} + \dfrac{\sigma_{Baseline}^{R/W} / \sqrt{N_{Baseline}^{R/W} - 1}}{S_{Baseline}^{R/W}} \right]} \right| = \begin{matrix} < 1 & \textbf{Pass} \\ \geq 1 & \textbf{Fail} \end{matrix}$$

$$\cong \left| \left(\frac{S_{TID}^{R/W}}{\sigma_{TID}^{R/W}} \right) 2 \cdot \left[1 - \left(\frac{S_{TID}^{R/W}}{S_{Baseline}^{R/W}} \right) \right] \right| = \begin{matrix} < 1 & \textbf{Pass} \\ \geq 1 & \textbf{Fail} \end{matrix} \qquad (1)$$

Here $S^{R/W}$ is the average read/write speed, $\sigma^{R/W}$ is the standard deviation of the read/write speed, $N^{R/W}$ is the number of times the read/write speed was measured, and the subscripts *Baseline* and *TID* indicate measurements before irradiation or after a particular TID interval, respectively.

Figure 4 shows a typical comparison between a typical post-radiation test for one micro-SD card and baseline read/write speed tests. The percentage change and percentage uncertainty were reported separately for each of the four read tests and four write tests for each of the 13 micro-SD cards. A green box indicated the test passed; a red box indicated that the particular card failed that test. The micro-SD card, TID interval, and cumulative TID are listed in the caption for the specific results in Figure 4.

Radiation Damage Recovery Tests

The cards which failed after a TID interval according to our criteria outlined above were held out for Radiation Damage Recovery tests to determine if the damage would recover and the time for such recovery. Cards passing the tests were reintroduced into the SST chamber to start the next round of radiation tests. Note that the few cards that failed these post-radiation tests

SD Card: PNY 16 GB (Beta) — READ SPEED (MB/s)									
Speed Tests	Baseline		Post-Radiation		Change	% Change	Uncertainity in Difference	% Uncertainity in Difference	% Fail Condition
	Average	SD	Average	SD					
R1 SEQ1M Q8T1	40.51	16.17	60.05	31.36	19.54	48.23%	47.53	117.31%	OK
R2 SEQ1M Q1T1	66.18	19.11	59.01	33.01	7.18	10.84%	52.12	78.76%	OK
R3 RND4K Q32T1	9.68	0.23	9.61	0.32	0.07	0.71%	0.54	5.60%	OK
R4 RND4K Q1T1	8.00	0.65	8.66	0.57	0.65	8.15%	1.22	15.19%	OK

SD Card: PNY 16 GB (Beta) — WRITE SPEED (MB/s)									
Speed Tests	Baseline		Post-Radiation		Change	% Change	Uncertainity in Difference	% Uncertainity in Difference	% Fail Condition
	Average	SD	Average	SD					
W1 SEQ1M Q8T1	26.82	12.68	24.82	20.57	1.99	7.43%	33.25	123.98%	OK
W2 SEQ1M Q1T1	38.74	13.25	10.72	6.70	28.02	72.33%	19.95	51.50%	Fail
W3 RND4K Q32T1	1.62	0.50	1.20	0.68	0.43	26.26%	1.18	72.83%	OK
W4 RND4K Q1T1	1.33	0.58	0.79	0.70	0.55	40.99%	1.28	95.65%	OK

SD Card: SanDisk Extreme Plus 32 GB — READ SPEED (MB/s)									
Speed Tests	Baseline		Post-Radiation		Change	% Change	Uncertainity in Difference	% Uncertainity in Difference	% Fail Condition
	Average	SD	Average	SD					
R1 SEQ1M Q8T1	41.85	3.80	39.93	6.47	1.92	4.58%	10.27	24.55%	OK
R2 SEQ1M Q1T1	30.84	4.04	35.97	8.52	5.13	16.64%	12.57	40.74%	OK
R3 RND4K Q32T1	9.54	0.39	9.67	0.18	0.13	1.34%	0.57	6.02%	OK
R4 RND4K Q1T1	8.76	0.29	8.74	0.38	0.02	0.26%	0.67	7.64%	OK

SD Card: SanDisk Extreme Plus 32 GB — WRITE SPEED (MB/s)									
Speed Tests	Baseline		Post-Radiation		Change	% Change	Uncertainity in Difference	% Uncertainity in Difference	% Fail Condition
	Average	SD	Average	SD					
W1 SEQ1M Q8T1	48.43	10.24	37.78	8.17	10.65	22.00%	18.41	38.01%	OK
W2 SEQ1M Q1T1	37.29	14.35	44.77	14.04	7.48	20.06%	28.39	76.15%	OK
W3 RND4K Q32T1	2.71	0.05	2.67	0.02	0.04	1.36%	0.07	2.47%	OK
W4 RND4K Q1T1	2.66	0.03	2.62	0.03	0.04	1.50%	0.06	2.30%	OK

SD Card: Delkin Devices 4 GB (Sigma) — READ SPEED (MB/s)									
Speed Tests	Baseline		Post-Radiation		Change	% Change	Uncertainity in Difference	% Uncertainity in Difference	% Fail Condition
	Average	SD	Average	SD					
R1 SEQ1M Q8T1	42.02	2.27	24.52	0.02	17.50	41.66%	2.29	5.45%	Fail
R2 SEQ1M Q1T1	31.14	4.26	24.61	0.10	6.53	20.96%	4.36	13.99%	Fail
R3 RND4K Q32T1	9.19	0.41	7.35	0.10	1.85	20.10%	0.50	5.48%	Fail
R4 RND4K Q1T1	6.71	0.18	5.48	0.15	1.23	18.35%	0.34	5.04%	Fail

SD Card: Delkin Devices 4 GB (Sigma) — WRITE SPEED (MB/s)									
Speed Tests	Baseline		Post-Radiation		Change	% Change	Uncertainity in Difference	% Uncertainity in Difference	% Fail Condition
	Average	SD	Average	SD					
W1 SEQ1M Q8T1	35.85	6.75	19.72	0.87	16.13	44.99%	7.63	21.28%	Fail
W2 SEQ1M Q1T1	35.13	10.72	22.12	0.97	13.01	37.03%	11.69	33.29%	Fail
W3 RND4K Q32T1	0.04	0.00	0.04	0.00	0.00	1.19%	0.00	4.03%	OK
W4 RND4K Q1T1	0.04	0.00	0.04	0.00	0.00	3.09%	0.00	4.66%	OK

Figure 4: Analysis of Read/Write Speed tests for post-radiation tests. (Top) Typical lower-grade micro-SD card [PNY (beta) after 100 Gy TID] with higher variability in Read/Write speeds. (Middle) Typical higher-grade micro-SD card [ScanDisk Extreme Plus after 100 Gy TID] with no failures in Read/Write speeds. (Bottom) Typical Industrial-grade micro-SD card [Delkin (Sigma) after 400 Gy TID] with many failures in Read/Write speeds.

were reintroduced to the sequence of TID intervals once full recovery was indicated.

For Radiation Damage Recovery tests, a sequence of five iterations of the Post-Radiation Tests were executed at three intervals—2 hrs after radiation, 4 hrs after radiation and 24 hrs after radiation. Each iteration required ~1/2 hr and the sequence of five iterations required ~2½ hr. This allowed the recovery time to be determined at ½ hr intervals for a single iteration with lower statistics and at 2 hr, 4 hr and 24 hr with statistics similar to the standard Post-Radiation tests.

After the last TID interval (cumulative TID of 1000 Gy), recovery tests on the failed cards were performed continuously for 3 days to determine if and when any of the errors recovered; they did not.

RESULTS

Table 4 summarizes the results of the TID tests for all 13 micro-SD cards tested. Results of the Formatting, Capacity, and Read/Write speed tests for each micro-SD card tested at each TID interval are listed. Read and Write speed errors were approximately equally as likely. The time for recovery from the Capacity tests and Read/Write speed tests are noted in the right column; failures that did not recover in the initial 4 hr after the end of the radiation interval are denoted with red shading while those that recovered faster are denoted with yellow shading.

For TID <400 Gy, there were few failures (2 Capacity test failures and two Read/Write speed errors after the first small 10 Gy TID interval. The first TID interval with only 10 Gy had 14 Read/Write speed errors and a Capacity test failure; these seem to have been attributable to unusually large variations in the Read/Write speed measurements for this TID interval. Only one Read/Write speed error for all 6 initial TID intervals took more than 2 hr to recover.

Table 4. Distribution of Test Failures

SD-Card Category	Lower-grade Commercial					Higher-grade Commercial			Industrial grade					Recovery
SD-Card	Scan Disk	PNY 16 GB				Scan Disk	Samsung	Scan Disk	Delkin	Delkin 4 GB				
	8 GB	A	B	Γ	Δ	Evo+	Ultra	Extreme+	8 GB	Σ	Ω	Λ	κ	
TID Interval/ Cumm. TID	1	2	3	4	5	6	7	8	9	10	11	12	13	
1 / 10 Gy	C	Pass	Pass	W3 (48%) W4 (60%)	R3(38%) R4(30%) W4(75%)	Pass	Pass	R1(27%) W3(4%) W4(2%)	Pass	Pass	R1 (25%) W2 (24%)	R1 (26%)	R1(69%) R2(87%) W3 (2111%)	≤4 hrs
2 / 20 Gy	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	-
3 / 40 Gy	Pass	C	Pass	Pass	Pass	Pass	W4(9%)	Pass	Pass	Pass	Pass	Pass	Pass	≤24 hrs
4 / 60 Gy	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	-
5 / 100 Gy	Pass	Pass	W2 (72%)	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	≤4 hrs
6 / 200 Gy	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	-
7 / 400 Gy	Pass	Pass	Pass	Pass	Pass	Pass	Pass	W4 (2%)	Pass	R1(42%) R2(21%) R3(20%) R4(18%) W1(45%) W2(37%)	Pass	Pass	Pass	>24 hr
8 / 600 Gy	C	Pass	Pass	Pass	W3 (<1%)	W4 (<1%)	Pass	W4 (<1%)	Pass	Pass	W2 (<1%)	Pass	Pass	≤2 hrs ≤4 hrs >24 hr ≤2 hrs
9 / 1000 Gy	Fail	Pass	Pass	Pass	Pass	Fail	Pass	Pass	Fail	Pass	Pass	Pass	Pass	>120 hr

Entry Key: **Pass**-Passed all tests. **Purple Text**-Failed Read/Write speed Criterion 1 (Eq. 1). Type of failed test identified as W1,W2,W3,W4,R1,R2,R3,R4 (see Table 3). Percent change in Read/Write speed in parentheses. **Black Text**—Failed Read/Write speed Criterion 1 (Eq. 1), but had less than 5% change in speed. **C**—Failed Capacity Test. **Fail**—Failed Formatting and Capacity Tests; Read/Write speed tests could not be performed. Yellow Shading—Failure recovered; right column lists recovery time. Red Shading—Failure did not recover.

There were significantly more Read/Write speed errors for the last three TID intervals at >400 Gy. Most of these errors at higher TID did not recover within 24 hr.

At full TID of 1000 Gy, three micro-SD cards—one lower-grade commercial card, one higher-grade commercial card, and one industrial-grade card failed completely. These cards failed both the Formatting and Capacity Tests; Read/Write speed tests could not be performed. The cards did not recover even after 120 hrs of recovery time, unlike the cards that failed the Capacity test or various Read/Write speed tests at lesser TID.

CONCLUSION

For the most part micro-SD cards were tolerant to up to 400 Gy TID, with almost all failure recovering in ≤4 hr. This is tolerance threshold much less than the ~20 Gy received for typical small satellite missions in LEO with modest shielding. At higher TID > 400 Gy, the micro-SD cards experienced more failure with less recovery. At the highest TID exposure of 1000 Gy three cards failed altogether and did not recover. This suggests an upper bound on the TID micro-SD cards can sustain.

While lower-grade commercial micro-SD cards exhibited more Capacity test failures than either higher-grade commercial or industrial-grade micro-SD cards, there was no noticeable difference in the number of Read/Write speed failures or recovery times for any of the micro-SD card grades.

The results of TID failures over the range of TID intervals due to beta radiation were consistent with the results of gamma radiation for SD-cards These previous tests found:

- Kimuria*, et al*. found no failures up to 200 Gy [11]
- Lamorie*, et al* found no failures at TID intervals from 20 Gy up to 100 Gy [7]
- Kingsbury*, et al* found no failures at 80 Gy and 240 Gy [2]

- Oldam found no failures at six intervals from 100 Gy up to 1000 Gy [8]
- Wang found no failures at 500 Gy and 1000 Gy TID for SDRAMM memory.[10]

Acknowledgments

Industrial-grade micro-SD cards were provided by Delkin Devices. We acknowledge support for the SST chamber development from the USU Materials Physics Group, a Utah NASA Space Grant Consortium Faculty Research Infrastructure Program award, and a USU Space Dynamics Laboratory Enabling Technologies Program IR&D award. Support for AD for the initial project design was provided by a USU Physics Department Blood Graduate Fellowship. We gratefully acknowledge help with the micro-SD card project and SST chamber development from USU colleagues Alex Souvall, Ben Russon, Gregory Wilson, Heather Tippets and Katie Gamaunt.

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