National Aeronautics and Space Administration

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NASA Electronic Parts and Packaging (NEPP) Program
Office of Safety and Mission Assurance

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Summary

4th generation iPads were exposed to total ionizing dose (TID) from a Co-60 gamma source and to the proton beam at Indiana University Cyclotron Facility as part of the FY2013 NASA Electronic Parts and Packaging (NEPP) system on a chip (SOC) Devices task. The task focused on TID as a first study of the radiation response of these complex tablet computers. Findings include failures of several systems in the iPads, with the first failures (when the tablet is equivalently dosed throughout) being of the charging circuit and the display driver. The former results in iPads that no longer charge correctly, while the latter results in iPads that cannot be clearly viewed.

Testing was focused on characterizing the performance of the iPad in between radiation exposures. Testing was performed both unbiased (with the iPad in the "off" state after commanding the device to shut off – by holding the power button) and biased. Characterization was performed before and between exposures in order to verify proper operation of the test devices and note any change in current draw through the charging system.

The results reported here indicate that 4th generation iPads will have problems with their charging systems and display drivers as the first TID failures. The observed levels were relatively low, but sufficient for certain space applications. In contrast, however, two limiting issues must be kept in mind. First is that the iPad is a commercial unit with no configuration control imposable by the space user, so from one unit to the next radiation results may change significantly – including the possibility of strong lot-to-lot dependence of devices inside the iPad. The second is that space environments also include heavy ions and associated single event effects (SEE). The proton testing performed here was not targeted at studying SEE exhaustively, and protons cannot simulate a significant portion of the particles that make up the space environment. These issues easily combine to make the iPad unacceptable for flight outside of very limited cases, without significant additional testing. Nevertheless, the results here show that these commercial devices have complex and highly problematic radiation response from protons and TID.

1.0 PURPOSE

This task focused on the total ionizing dose (TID) response of the 4th generation iPad as a study of failure mechanisms in complex systems and to highlight the issues in testing and failure observations. Although it is possible to perform a component-by-component examination of the failure mechanisms of this device, we instead focused on the overall behavior of the entire system. The work was carried out by exposure to Co-60 and protons. The proton exposure also provided rough single-event upset (SEE) response, but the focus of the proton exposure was proton-based TID, and thus the SEE results are indicative rather than comprehensive.

2.0 CONTEXT

The testing reported here is part of an effort by the NASA Electronic Parts and Packaging System on a Chip (NEPP SOC) task to determine radiation qualification methods for modern SOCs. As such, this iPad work was performed as an example of a complex system to be studied for radiation effects.

The iPad is built with essentially four subsystems. The processor and electronics to support computation is one subsystem. The power system, including the battery, is another. And the other two are the data storage and user interface subsystems. The processor is the Apple A6X, which is a multicore advanced RISC [reduced instruction set computing] machine) ARM SOC, and is a candidate device for study. However, the focus of this test effort was the general behavior of the system, so the SOC was not studied in the same manner as other devices in this NEPP task.

3.0 BACKGROUND

This section provides brief background material explaining the interest in testing the iPad, including goals and impact on the system on a chip (SOC) Devices task.

3.1 General Importance of iPad Exploration

The 4th Generation iPad is a tablet computer built with the Apple A6X, which has a dual-core advanced RISC [reduced instruction set computing] machine) ARMv7-A and carries more computational power than the RAD750, which is used to control several space missions, such as the Mars Exploration Rover [1-2]. The iPad is a good example of a modern mobile computing system that is focused on power efficiency while delivering computational power sufficient for a great deal of applications. It also tracks an important trend in computing devices where traditional desktop computers are losing market share in favor of devices with mid-range computational power but dramatically improved mobility and efficiency. The iPad also demonstrates complex multicore systems with heterogeneous processing capability where various subsections are tailored to specific stand-alone operations. Careful management of resources may enable only the required portions of the device to be fully functional, thereby saving power.

Complex systems similar to (and possibly including) the iPad are being considered for some flight systems. Though these flight systems have an inherently higher risk posture than those for which the NEPP program is generally targeted, there is interest in understanding what the issues are with radiation effects in this type of system. This follows from current trends towards more capable computing devices on spacecraft, and general interest from NEPP in the behavior of SOC systems.

3.2 Focus of Testing - TID

The work here is focused on TID only, due to two reasons. First, these systems are expected to have significant SEE problems which mostly will result in requiring reset or power cycle of the unit to continue operation, making the error mode complexity higher than desired for this initial test effort. Second, TID failures are likely in these units at dose levels relevant for short, benign-environment missions. Third, SEE exploration is more difficult due to issues with performing the testing and identifying failing components. These points make TID the first logical step for this study.

3.3 SEE and TID in Complex Systems

One important aspect of this testing was the verification that a pre-irradiation survey of the system could lead to understanding of the potential failure modes in a way that enables a gross prediction of the iPad behavior under radiation. This type of prediction can be made by understanding the types of devices in the iPad and the expected radiation failure mechanisms they may see.

We expect the following rough failure modes may manifest for any given component (where we indicate which items are due to TID by adding a parenthetical note):

- Functionality loss due to single event latchup (SEL), single event gate rupture (SEGR), single event burnout (SEB), and threshold shifts (TID)
- Increased operational current (TID)
- Changes in sensitivity of detection circuits (TID)
- Permanent bit flips in program storage or system information (resulting in inability to operate the unity). (These can happen due to TID, but here we mean primarily SEE.)
- Temporary bit flips during operation of the unit (resulting in reset or lockup/hang)
- Single event functionality interrupt (SEFI)

- Changes in the output of amplifier circuits (primarily due to changes in the input detection capability) (TID)

3.4 Other Study of iPad Radiation Response

SEE data was reported on iPhones in [7]. Earlier iPads have also been sent to the International Space Station, though relevant radiation data is not available [8].

4.0 TEST SYSTEM DESCRIPTION

This section discusses the test software and hardware used to operate the devices under test (DUTs) and collect data for this test.

4.1 General Test Setup

The iPad test system consisted of using the sealed units (i.e., we did not open up the test units to enable targeting of specific devices or exclude some parts of the units). These units were either biased or unbiased. (It is impossible to fully remove bias from all parts of a sealed iPad, so ours were quasi-unbiased.) For proton beam studies, it was necessary to know the locations of target electronics, but final test articles were not opened.

The test units were used to characterize themselves before and after TID. For biased TID exposures, the test units were operated with standard applications. For some applications, the iPad was connected to a Mac computer for synchronization. For others it was necessary to ensure position of the iPad (for sensor tests and photos of the screen) and provide WiFi connectivity. The only other part of the general test setup of note is that we used a modified charging cable to measure the current draw of the test units. Other than these details, the test units and test operations were stand-alone. (For proton testing some additional resources were used but they required no change to the general test setup described here.)

4.2 Characterization Approach

Since this work was primarily a TID test (both for the Co-60 and proton exposures), an important element of the test system is the characterization approach for establishing the pre-exposure, and in-between exposure performance. We accomplished this with a detailed set of operations and tests on each device between exposure points. The tests are discussed below.

4.2.1 Current Measurements

We observed the health of the power distribution and battery charging system through observation of the charging current drawn over the iPad's Universal Serial Bus (USB) charging cable. An iPad USB charging cable was spliced through an ammeter to enable direct observation of the current draw on the USB +5 V and ground lines. In order to establish the nominal operating environment to observe the current, we used the home screen after bootup as the controlled state of the iPad to observe the current draw.

The iPad will not automatically charge through an arbitrary USB cable – we tried modifying an extension cable first (i.e., that extends the USB end of the iPad charging cable), and the iPad would not charge. It is unknown exactly what electromagnetic or communication requirement was not met that caused the iPad to refuse to charge. It is possible that this behavior is what actually causes charging problems reported later.

4.2.2 Power Up/Down

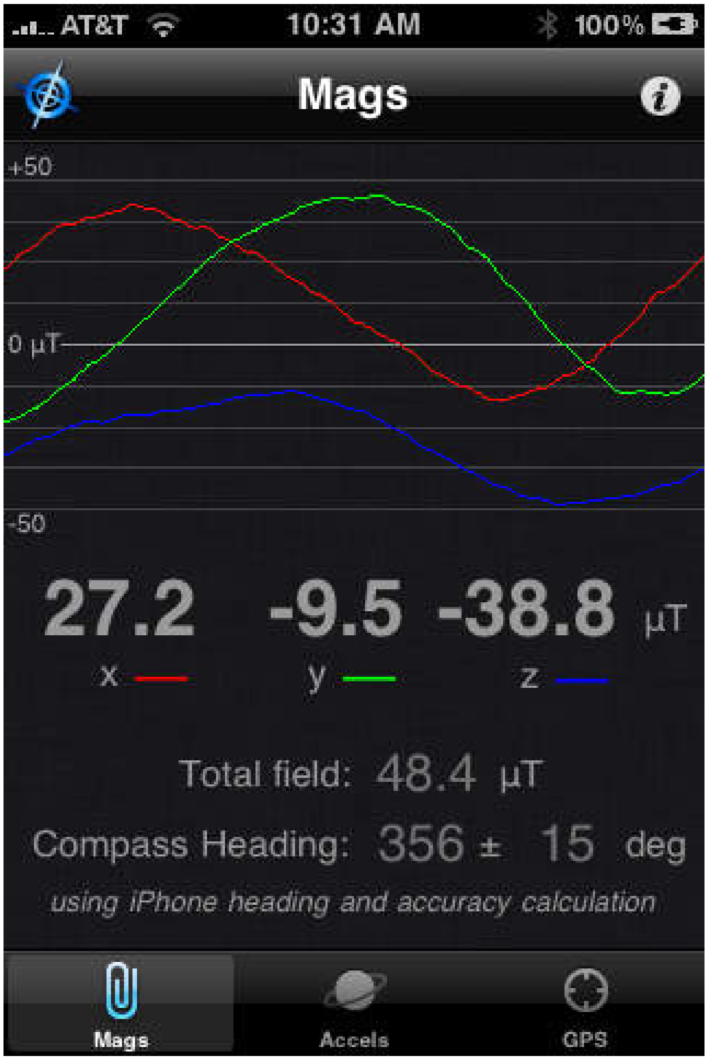
We performed all characterization after the subject iPad was fully powered down (via holding the home button and the power button until the device shuts off), and then allowed to fully boot. Test results were collected after the iPad was unlocked and reached the home screen.

4.2.3 Applications and Operations

We used several "apps" and performed some specific operations to determine the operating state of the DUTs between irradiation. These are described below.

4.2.3.1 xSensor

The xSensor™ by Crossbow Technology provides an easy interface to many of the sensors available in the iPad. The application screen for monitoring the magnetometers of an iPhone with xSensor is shown in Figure 4.2-1. More information can be found regarding xSensor in [5].



27.2 -9.5 -38.8 µT

Total field: 48.4 µT

Compass Heading: 356 ± 15 deg

using iPhone heading and accuracy calculation

Figure 4.2-1. The xSensor application, monitoring the magnetometer readings, is shown.

xSensor can be used to monitor the following sensors:

1. 3-axis accelerometer
2. 3-axis gyroscope
3. 3-axis magnetometer
4. Global Positioning System (GPS) location

4.2.3.2 Playing a Movie

We used the iPad to play a movie (Finding Nemo™) as a method to verify that the device was functioning properly. It is not known how effective this approach is, but it is likely that the iPad has specialized video and audio streaming accelerators that are exercised when playing a movie.

4.2.3.3 Playing a Song

This is a more specialized test than playing a movie, and was originally intended to target the quality of the audio playback (i.e., observe clipping or other anomalies in the output amplifiers). In practice, however, this is just a qualitative check by the test engineer.

4.2.3.4 Display Test Image

We expected the display of the iPad might have problems as a result of dose, primarily due to its use of analog drivers. As a result we defined part of the characterization approach to include calibrated photos of the screen of the iPad displaying a specific image. One of these photos can be seen in Figure 4.2-2. This photo was taken using a test jig that holds a camera a specific distance from the iPad and whose image corrections are not changed during the TID testing (so differences in the images are due to degradation of the iPad display).

Figure 4.2-2. Test image used to check the display of the iPad between irradiations.

4.2.3.5 Benchmark Software

We used the benchmarking software available from Passmark [6] in order to make measurements of the performance of the iPad between each irradiation step. This software runs on the iPad and performs the following tests:

a. Integer Mathematics

b. Floating Point Mathematics,

c. Prime Number Calculation

d. String Sorting

e. Data Encryption
f. Data Compression
g. Disk Write Test
h. Disk Read Test
i. Memory Write Test
j. Memory Read Test
k. Graphics Vector Tests
l. Image Rendering Test
m. Image Filtering Test
n. Simple 3D Graphics Test
o. Complex 3D Graphics Test

4.2.3.6 Photo Test

The iPad was used to take a photo at each irradiation step.

4.2.3.7 Synchronization Test

The iPad was connected to a Mac computer and the automatic synchronization was performed at each irradiation step.

4.2.4 Test Setup for TID Testing

The TID test setup is straightforward. For unbiased testing the iPad was powered off (using the power button and home button to force power down), then the iPad was positioned in the Co-60 irradiation room and exposed. For biased testing the device under test (DUT) was first setup to play the movie Finding Nemo™, in order to have it using a reasonable portion of its resources (i.e. biasing the audio system, using a significant amount of power, etc.). Then, as in the unbiased case, the DUT playing the movie is placed in the irradiation room and exposed.

4.2.5 Test Setup for SEE/Proton Testing

For SEE testing we modified the test setup to collect in-situ video showing the performance of the iPad. The test system is shown in Figure 4.2-3. The key feature of the test system is that for biased testing the iPad is connected via Facetime™ to a Mac in the counting room. The Facetime connection is recorded to allow later playback if needed. For both biased and unbiased testing, an additional camera is positioned in the beam chamber and is used to take video of the iPad being irradiated (this is especially helpful in determining the state of the iPad during irradiation when it stops communicating with the Facetime computer).

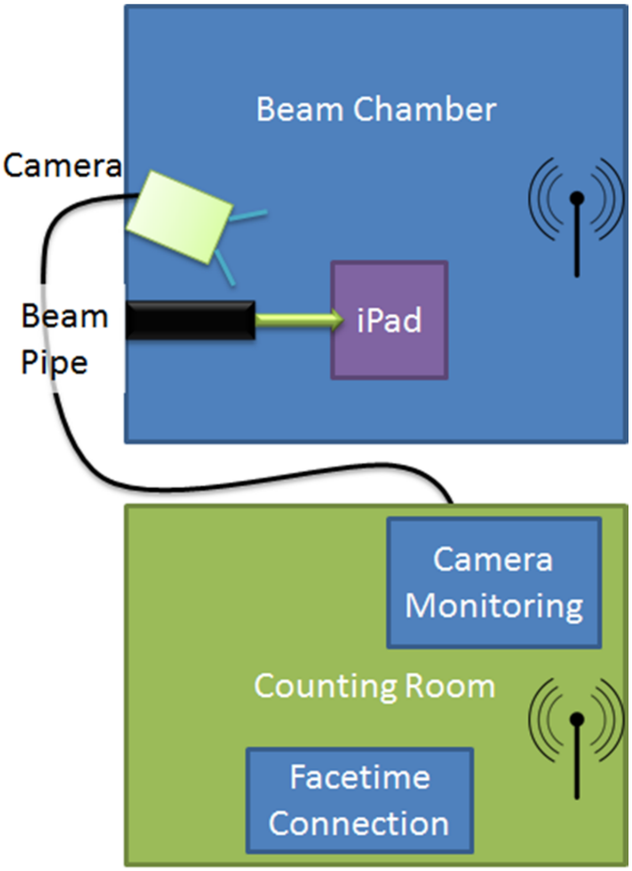


Figure 4.2-3. Test system layout for SEE testing of iPads.

5.0 TEST PLAN

The test plan for this work was straightforward. We had a matrix of beams for exposure and a set of test algorithms to use under each beam.

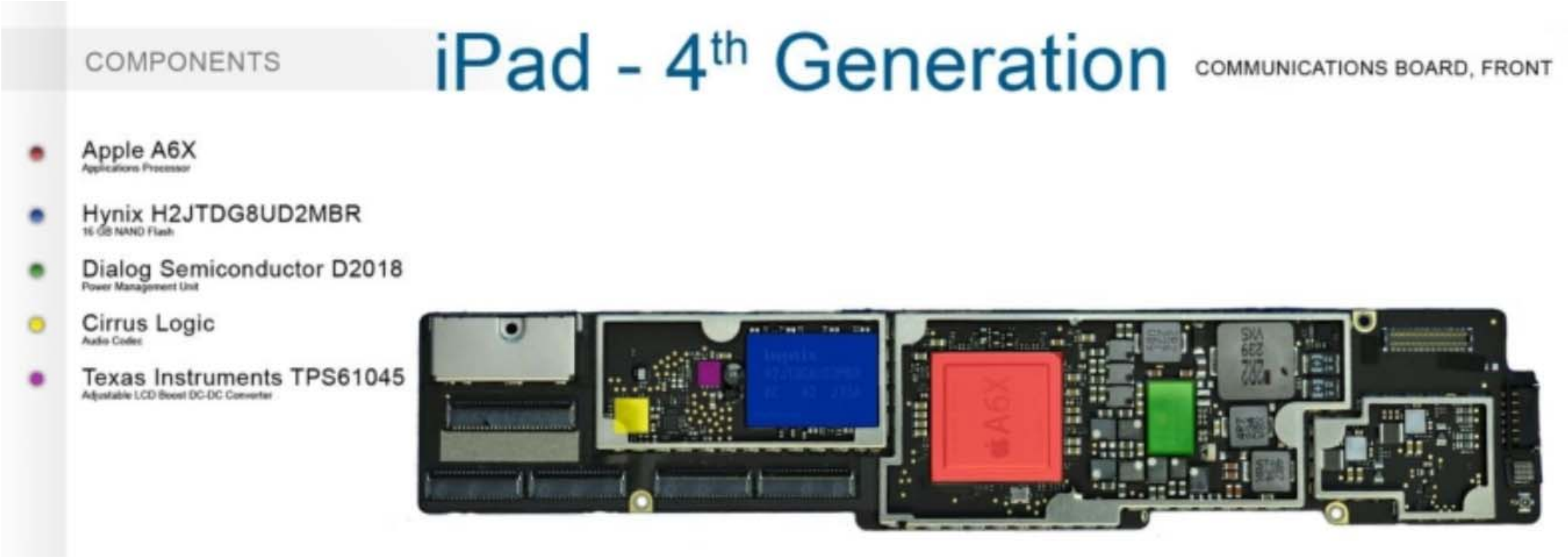
5.1 DUTs and Target Positions

Seven iPads were exposed for the work reported here. An image of an iPad similar to the devices studied is given in Figure 5.1-4 for reference. One additional device was used to examine the internal composition of the iPad and was destroyed.

Figure 5.1-1. 4th Generation iPad used in testing.

We utilized information provided showing teardowns of 4th Generation iPads [3-4]. These sources provided a fairly exhaustive list of components in the iPad. They are: Broadcom four-in-one combo wireless chip (BCM4334), Broadcom touchscreen controllers (BCM5974 and BCM5973), Cirrus Logic amplifier (CLI1583B0), Omnivision cameras (OV297AA, and OV290B), Dialog Semiconductor power management unit (D2018), Hynix Not And (NAND) flash (2-die package) H2DTDG8UD1MBR, Hynix DDR2 DRAM (H9TCNNN4KDBMUR), Texas Instruments display port driver, NXP Semiconductor display port multiplexer (CBTL1608A1), Paradise liquid crystal device (LCD) timing controller (DP635), Integrated Memory Logic programmable gamma buffer (iML7990), and RichTek touchscreen power management (RT9910). And the iPad is powered by the A6X system on a chip processing unit.

The teardowns also provided layout information of the two primary circuit boards in the iPad. Note that almost all of the active circuitry is located on the left edge (when looking at the screen with the home button on the bottom). Figures 5.1-2, 3, and 4 show the layout information provided in [3].



COMPONENTS

iPad - 4th Generation

COMMUNICATIONS BOARD, FRONT

- ● **Apple A6X** Applications Processor
- ● **Hynix H2JTDG8UD2MBR** 16 GB NAND Flash
- ● **Dialog Semiconductor D2018** Power Management Unit
- ● **Cirrus Logic** Audio Codec
- ● **Texas Instruments TPS61045** Adjustable LCD Boost DC-DC Converter

Figure 5.1-2. Front of the communications board, from [3].

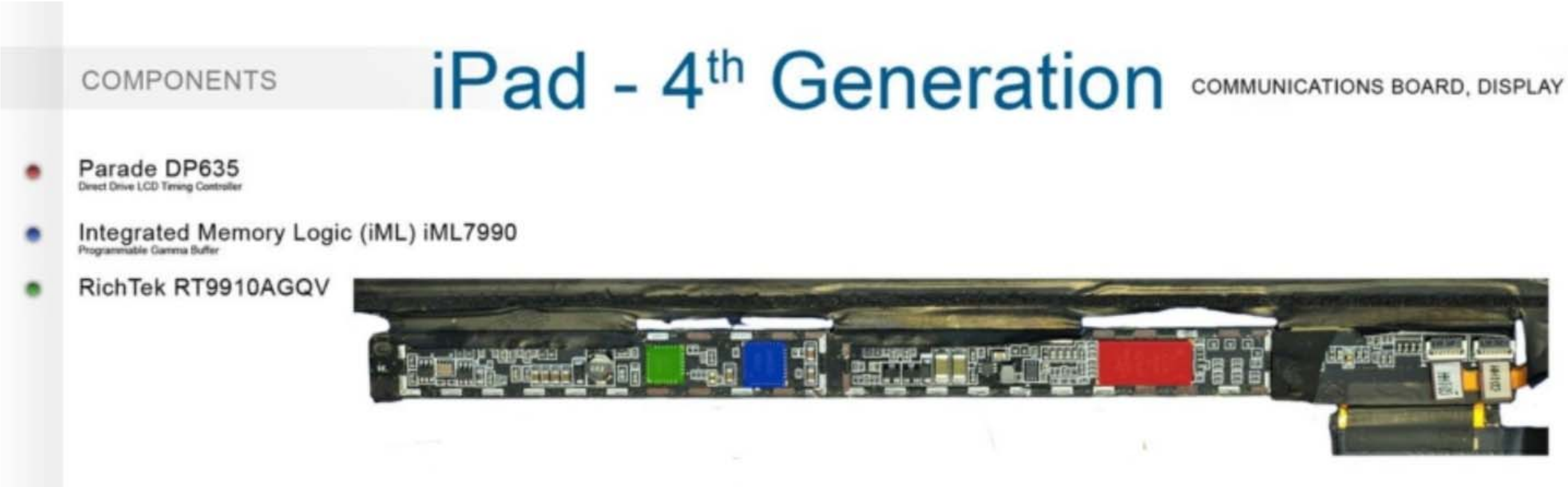
COMPONENTS

iPad - 4th Generation

COMMUNICATIONS BOARD, BACK

- 🔴 **Broadcom BCM5973A**
  Touchscreen controller for iPad, iPad 2, iPad 3, iPhone (1st Gen)
- 🔵 **Texas Instruments CD3240B0**
  Touchscreen Line Driver found in iPad, iPad 2, iPad 3
- 🟡 **Broadcom BCM5974**
  Touchscreen controller for iPad 2, iPad 3
- 🟣 **Broadcom BCM4334**
  Single-Chip Dual-Band Combo Device Supporting 802.11n, Bluetooth 4.0+HS & FM Receiver
- 🟠 **Hynix H9TCNNN4KDBMUR**
  Multichip Memory Package - 512 MB Mobile DDR2-S4 SDRAM x 2
- ● **Fairchild FDMC6683**
  MOSFET
- 🟢 **Fairchild FDMC6676BZ**
  30V N-Channel PowerTrench MOSFET

Figure 5.1-3. Back of the communications board, from [3].



COMPONENTS

iPad - 4th Generation

COMMUNICATIONS BOARD, DISPLAY

- 🟥 Parade DP635
  Direct Drive LCD Timing Controller
- 🟦 Integrated Memory Logic (iML) iML7990
  Programmable Gamma Buffer
- 🟩 RichTek RT9910AGQV

Figure 5.1-4. Display board components, from [3].

The mechanical construction, and part number information of the iPad was examined through teardown effort performed, and through cross-reference with work described by Yogasignam [4]. Our teardown of an iPad is shown in Figure 5.1-5.

Figure 5.1-5. Our tear-down of the 4th generation iPad, showing (clockwise from the top) the battery, the case, the main circuit board (in the case), the display, and the touch screen.

We utilized X-ray photos of the iPad and the physical disassembly to ensure appropriate beam positioning. The approximate position of the communications and display boards are shown in Figure 5.1-6.

Figure 5.1-6. Approximate position of communications and display boards.

5.1.1 *Co-60 DUTs*

Two DUTs were tested with Co-60. The source was the Jet Propulsion Laboratory's (JPL's) high dose rate room irradiator. Exposures were conducted in January and February of 2013. SN#6 was used for unbiased irradiation (where the device is powered off but the batteries are still connected). SN#3 was used for biased irradiation where the device was playing a movie during exposure.

For Co-60 exposures, DUTs were irradiated in a flat field. Only one exposure was required to apply a given dose level to the entire iPad.

5.1.2 *Proton Exposure DUTs*

Five iPads were tested with 63 MeV protons at the University of California Davis Crocker Nuclear Laboratory on Feb 26, 2013. The proton beam did not produce a large enough region of exposure, so a set of target locations were developed in order to ensure exposure of all active electronics and minimal overlap at edge regions.

The positions used for exposure were along the left and top edges in order to expose the two circuit boards, the cameras, and another component along the top edge between the cameras. The positions used for exposure are shown in the diagram in Figure 5.1-7, where the 2-inch (5-cm) square beam spot is superimposed for each position.

Figure 5.1-7. Beam positions used for proton exposure. The 2-inch (5-cm) square collimator was used for most exposures, and the locations reflect the beam spot size. In addition, positions A–D were alternately exposed with a 1-inch by 2-inch (2.5- × 5-cm) collimator designed to avoid exposure of the display board and battery pack.

5.1.3 DUT Summary

The total exposure of DUTs to gamma and proton radiation is summarized in Table 5.1-1 below.

Table 5.1-1. Summary of radiation exposures of test iPad units.

DUT #	Bias ?	γ or p?	Full Exposure	Position A Exposure	Position B	Position C	Position D	Position E	Position F	Position G
6	No	γ	11 krad	n/a	n/a	n/a	n/a	n/a	n/a	n/a
3	Yes	γ	9	n/a	n/a	n/a	n/a	n/a	n/a	n/a
12	Yes	p	n/a	2 krad	4	2	4	4	4	4
13	No	p	n/a	16	12	12	12	8	8	8
11	Yes	p	n/a	16	0	12.7	0	0	0	0
1	Yes	p	n/a	0	0	0	4	0	0	0
4	Yes	P	n/a	12	12	12	12	20	0	0

5.2 Sources Used

Co-60 γ exposures were performed using the high dose rate facility at JPL. Proton exposures were performed using the 63 MeV proton beam at University of California, Davis's (UCD) Crocker Nuclear Laboratory (CNL).

5.3 Power Status

We tested units both while biased and while unbiased. For unbiased TID testing, our test unit was exposed with the device powered off via the method of holding the home button and the power button until the unit powers down.

6.0 TEST RESULTS

In this section we provide the results of the testing. This section is divided into the following results sections: a general summary, Co-60 results, and finally proton results.

6.1 General Summary

The test results can be quickly summarized as follows. First, there was no observed degradation of performance of any of the characterization operations except for the following. The battery charging system had observed failures where charging no longer occurs. The display also had observed failures where it is not possible to observe the screen. We also observed failures where the unit can no longer properly boot. A summary of the TID level and observed failures as a result of exposure are given in Table 6.1-1.

Table 6.1-1. Summary of DUT exposures and resulting failures

DUT	TID Level	Observed Failure
6	2 krad(Si)	Battery No Longer Charges
6	12	Screen No Longer Viewable
3	8	Battery No Longer Charges
3	8	Screen No Longer Viewable
12	4 (on position B)	System No Longer Boots
13	4 (on positions A–C)	Battery No Longer Charges
13	16 (on position A), 12 (on positions B-D)	Screen No Longer Visible
1	4 (on position D)	Unit Now Shuts Down / Restarts On Its Own
4	12 (on positions A–D)	Unit Now Shuts Down / Restarts On Its Own

6.2 Co-60 Results

Co-60 results were fairly straightforward. The results break down into two categories. The first is the degradation of operation, and the second is the operation of the characterization tests that did not degrade. We discuss this information (sorted into unbiased, biased, and then combined results) in the following paragraphs.

The unbiased iPad test showed the unit stopped charging the battery after only 2 krad. We continued to irradiate the unit, since the battery was not required for operation. The iPad continued to work until the 11–12 krad point when the screen stopped functioning as seen in Figure 6.2-1 (it was totally grayed out). The failure of the screen was seen in a lot of the testing (biased, unbiased, and with protons). The device did still work, as was verified by plugging into an external monitor.

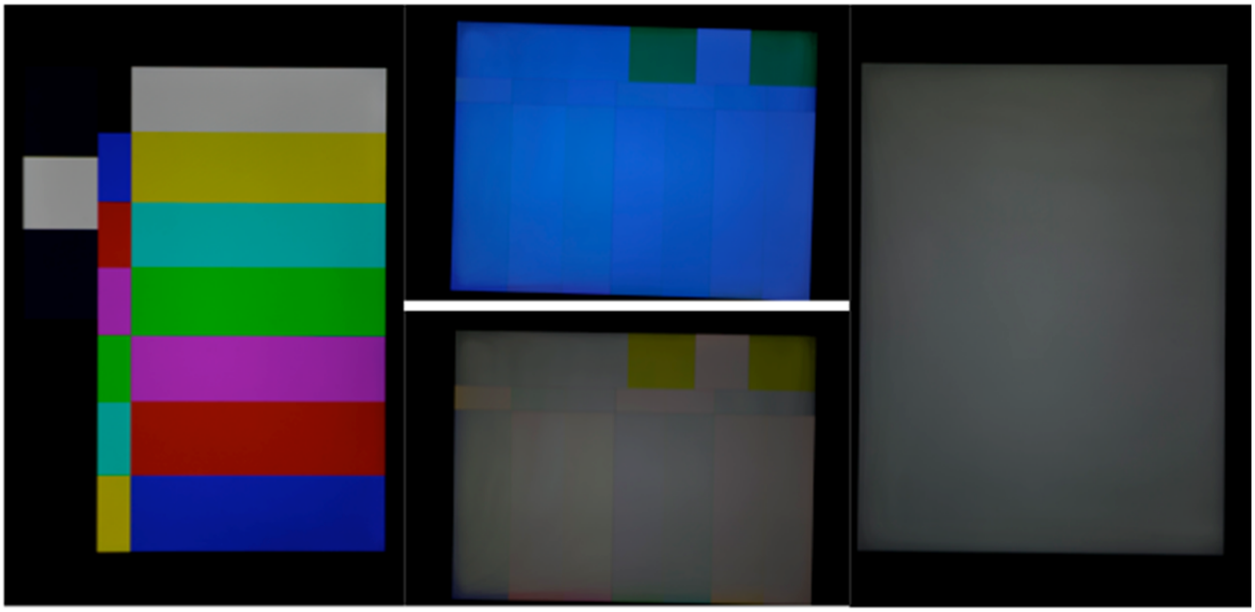


Figure 6.2-1 The unbiased iPad screen degradation occurred quickly, with the last three screen shots being the upper, lower, and right panels. The left panel shows what the iPad screen looked like from 0 to 8 krad.

The biased testing showed essentially the same failures as the unbiased testing, but at different TID levels. For biased testing both the power and screen failures occurred at 8 krad. The combined results for biased and unbiased testing for the battery charging current are shown in Figure 6.2-2.

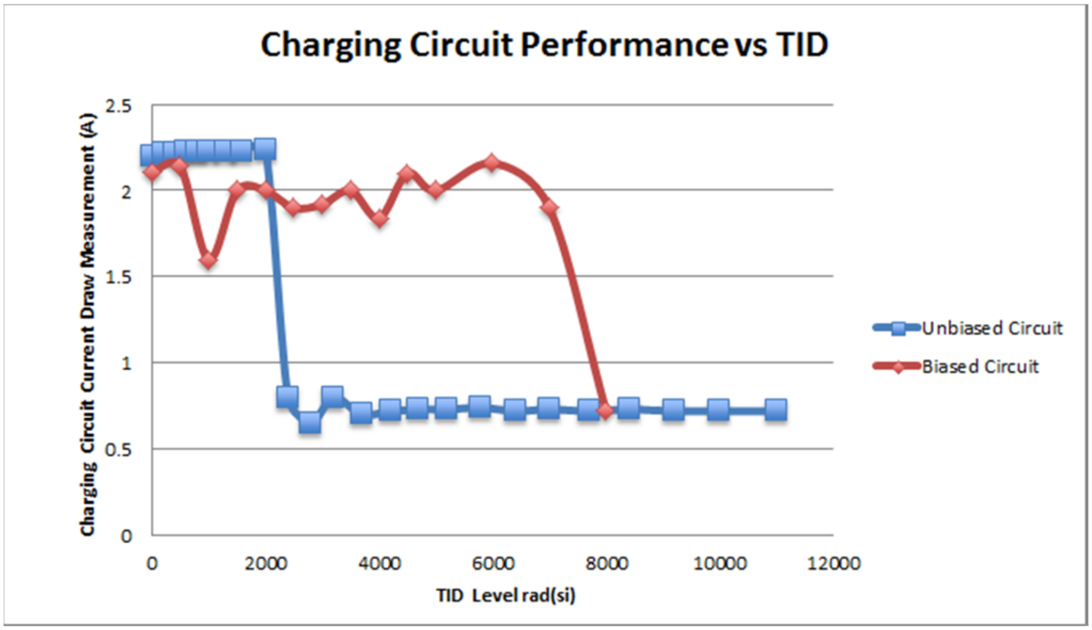


Figure 6.2-2 The charging current for the biased and unbiased TID testing. Results show that the charging essentially stopped abruptly at a given TID level. For unbiased this occurred at 2 krad(Si), while for biased it occurred at 8 krad.

The other observations during testing were essentially no changes – for both biased and unbiased test samples. Thus we continue this presentation of data by discussing both test samples together.

No changes were observed in the biased and unbiased samples when running the following tests:

1. Playing a movie,
2. Playing a song,
3. Running benchmark software,
4. Taking photos, and
5. Performing synchronization with a Mac computer.

We show the results for the xSensor sensor readings taken as a function of TID as examples of the observed null results for all operations besides charging and screen functionality. These results are shown in Figure 6.2-3 and Figure 6.2-4, which show results for the unbiased iPad. There is no observable difference in the accelerometer behavior, and the change in the magnetometer performance is consistent with minor changes in orientation and the sensitivity of the magnetometer performance.

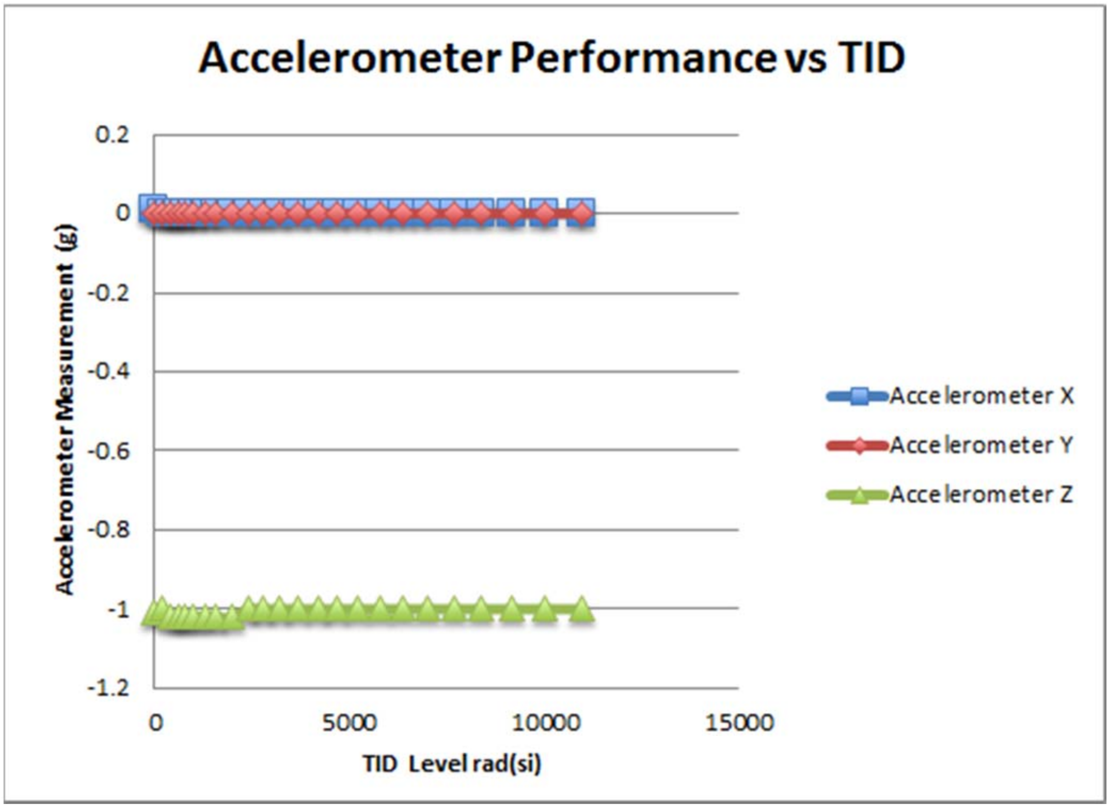


Figure 6.2-3 The response of the accelerometers in the unbiased iPad due to TID.

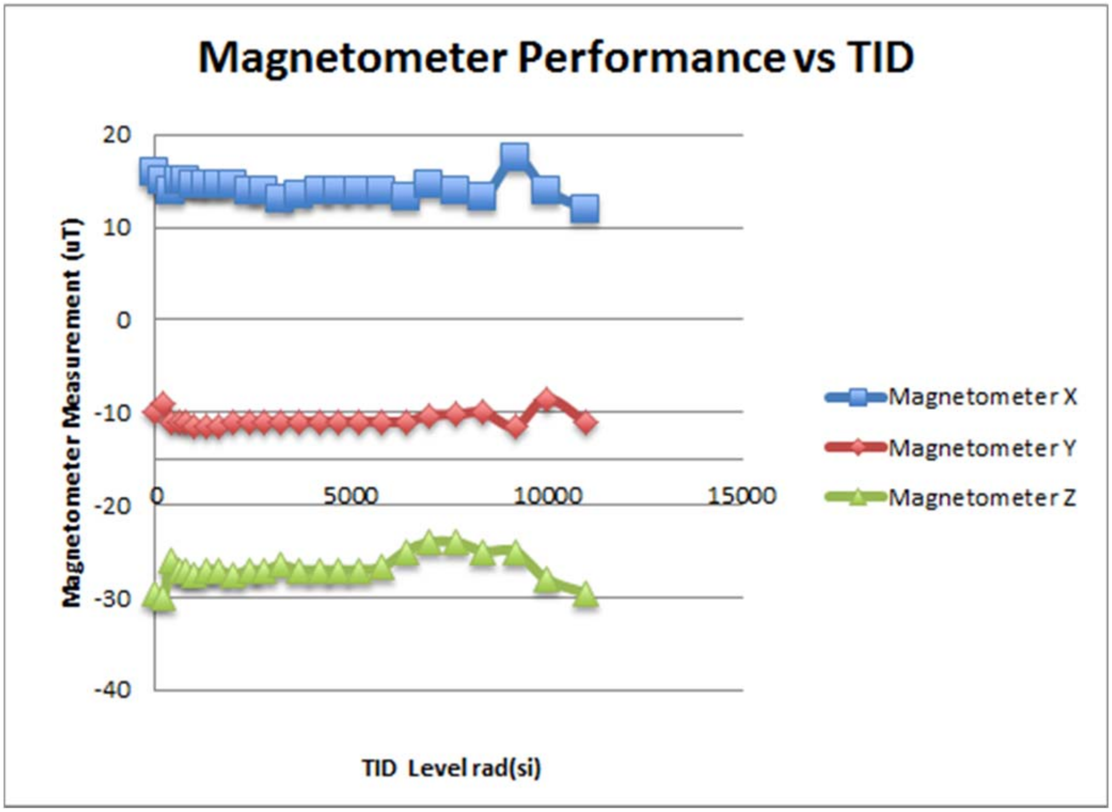


Figure 6.2-4 The response of the magnetometers in the unbiased iPad due to TID.

6.3 Proton Results

The proton testing exhibited the same types of problems observed in the TID testing. However, additional radiation-related behaviors were observed. We present these here. The proton exposure test log is given in section 8.0.

6.3.1 Unbiased Proton Results

The unbiased DUT produced similar observations to those seen during Co-60 testing. The main difference was the ability to isolate the exposure to sub-regions of the iPad due to the method used to deliver the beam. The summary of unbiased results follows.

1. At 4 krad delivered to positions A, B, and C, the charging circuit failed.
2. At 8 krad delivered to positions A–G, the screen was starting to show problems.
3. At 8 krad delivered to positions A–G, it was observed that the charge state of the iPad, as reported, changed from 96% to 75% during a brief period with the device turned off.
4. At 12 krad delivered to positions A–G, the screen was completely washed out.

6.3.2 Biased Proton Results – Dose Failures

The biased testing of the iPads resulted in a wide array of observations. We observed failure mechanisms that were identical to the Co-60 tests, and we observed other failures. The other failures typically showed no build-up of degraded performance before the device stopped functioning. In this section we report on those failure mechanisms that are believed to be dose-related.

The primary observations that are believed to be related to dose failures on the biased DUTs are the following.

1. No observed TID failure when position A is exposed to 16 krad
2. No observed TID failure when position B is exposed to 12 krad if the collimator is used to ensure the driver board for the display is not exposed.
3. No observed TID failure when position B is exposed to 2 krad (no collimator)
4. No observed TID failure when position C is exposed to 12.7 krad
5. No observed TID failure when position D is exposed to 12 krad if the collimator is used
6. No observed TID failure when position D is exposed to 4 krad (no collimator)
7. No observed TID failure when positions E is exposed to 20 krad
8. No observed TID failure when positions F and G are exposed to 8 krad

From the known failure mechanisms, we conclude that the screen driver and battery charging circuits that failed during Co-60 exposure were due to components in position B or D that are protected by the collimator (which shields the driver board).

6.3.3 Biased Proton Results – SEE Failures

We observed permanent SEE failures as a result of proton exposure of biased devices. These observations were quite varied, and we did not have enough DUTs to support statistical evaluation of the failure modes. We present a list of the failures observed below.

1. During irradiation of position B, observed permanent device failure – no longer functions for user interaction
2. During irradiation of position D, observed permanent device reboot behavior – unit no longer functions properly
3. During irradiation of positions A–D, observed the same reboot behavior observed in point 2 above.

6.3.4 Biased Proton Results – Other SEE Behavior

We observed some general SEE-related behavior of the DUTs as a result of exposure. The behaviors are summarized in Table 6.3-1. This table presents only qualitative data, primarily because the testing was not focused on determining the actual number of events that occurred during exposure. The observations must be taken to have occurred at least once, and possibly up to 100 times during exposure to 2 krad (about 1 × 10^{10} p/cm^2 at 63 MeV).

Table 6.3-1. Table caption in sentence case.

Position During Irradiation	Observation
D	Heavy snow on Facetime camera
E	Some snow on Facetime camera
F	Some snow on Facetime camera
A	WiFi connection lost
C	DUT crashed - restarted

6.4 Discussion

In this section we discuss the salient findings of this work.

6.4.1 First TID Failures Not Likely to Impact Flight

The first items observed to have TID failures were the screen and the battery. These devices are both of limited interest to a flight program unless they are to be used by astronauts. However, in this particular use case, the TID exposure to the iPad should be similar to that of the astronauts and therefore will be significantly lower than the 2 krad(Si) where the first failures were observed. The only situation where this may not be true is where the iPad is stored in an area where the TID is very high prior to being deployed to an astronaut.

6.4.2 Possible Issues with Charging Cable

One observation during setup of the charging test was that the iPad is aware of the cable used to connect it to the wall charger. The method used is unknown to us, and we did not try to reverse-engineer it. When a simple USB A-to-A extension was used to enable monitoring of the charging of the iPad, we observed that the iPad no longer charged at all. So instead, for charging, we used an Apple USB to Lightning cable, which we modified to enable monitoring of the charging current. It is possible that the modification results in a change in the way the cable is identified by the iPad, and this may result in an iPad that no longer charges through the given cable; however we did not observe this in our control unit, which was connected for charging through the same charger and charging cable as the DUTs. Another possibility is that TID may alter the iPad's ability to identify the charging cable and decide the cable cannot be used for charging the unit. This behavior may be unrelated to the actual charging circuit. Thus, we cannot say for certain if TID failures of the charging circuit are isolated to the charging hardware only because the failures may also be related to the sensing circuit not observing a standard iPad charging cable (due to TID degradation of the sensing circuit).

6.4.3 Multiple Screen Behaviors

Although the screen failures did result in iPad screens that were essentially unusable for viewing the output of the iPad, devices sometimes experienced in-between behavior. In these cases the degradation was usually manifest in a non-observable grey screen, but would sometimes show a less disrupted image when returning from various states of iPad sleep (there are several modes the iPad screen wakes up from – "full off" (via holding the power and home buttons until the device shut off) and "screen off" (where the screen turns off immediately upon pressing the on/off button on the top of the iPad), were the two used during this work. In some cases the screen would wake up in a completely unusable state, but then after going into "screen off" state, the iPad would show minimally visible display the next time it is woken from sleep. This alternate visibility screen would be sufficient for the test engineer to interact with the device. However the damage is still there and depending on the conditions for waking the screen up it may be essentially unusable even though it appears to be functioning ok.

6.4.4 Reboot Behavior

Two of our proton exposure DUTs failed in a way where the units now reboot infinitely if they are activated for power up. This behavior has the following description. Upon power up, the Apple boot logo shows on the screen. The device then appears to boot (as can be observed with booting an iPhone or iPad), for a period of time. Sometime during this operation, the logo appears to reset and restart. The unit never finishes the normal follow-up of going to the home screen and allowing the user to interact.

This infinite reboot behavior was expected as a possibility because there are at least two reasons it may occur. The first is that the operating system software was corrupted by the beam (for example, bits were flipped in the software image storage). If this occurs, the software may cause a fault condition that triggers an error handler (interrupt) that causes reboot. The second reason this may happen is if a system health check fails during boot. Normally a system health check failing would result in a message to the user indicating the failure, but it is not clear the iPad would do this, or the error could occur so early in the boot process that normal reporting is not available and special hardware and support from Apple would be required to accurately diagnose.

6.4.5 Dropped WiFi

We observed reliable loss of the WiFi signal when irradiating the iPads in position A. This is consistent with the region of the iPad identified as having the WiFi chips in Figure 5.1-6 – the region holding the Broadcom BCM4334. The signature of this behavior was the following. The exposure would begin with an active Facetime connection to the user room. Upon initiation of exposure, the connection would quickly be lost. In the user room this showed as Facetime waiting for data. But on the camera focused on the iPad it was possible to observe the WiFi signal indicator show that there was a problem and the Facetime connection was waiting. Upon entering the cave after exposure, sometimes the unit would recover the WiFi connection on its own, but the recovery response ranged all the way to a forced power-down being required to restart the WiFi.

6.4.6 Nature of Failures

The iPad is a complex device. Given the construction of the device and the types of components used to construct it, we were able to anticipate the general behavior of the unit. The failures we observed were consistent with our early predictions (in general). Because of this, we believe our recommendations for follow up work will actually be beneficial. In particular, the potential enhanced low dose rate sensitivity (ELDRS) response and the component-level response are likely of significant interest. Many of the components used have available optional parts that could improve radiation performance. But in reality, it is unlikely that a limited budget space mission – such as the type that would consider flying a pre-built commercial unit like the iPad – could engage Apple to have a custom unit built with alternate components that would have improved radiation response.

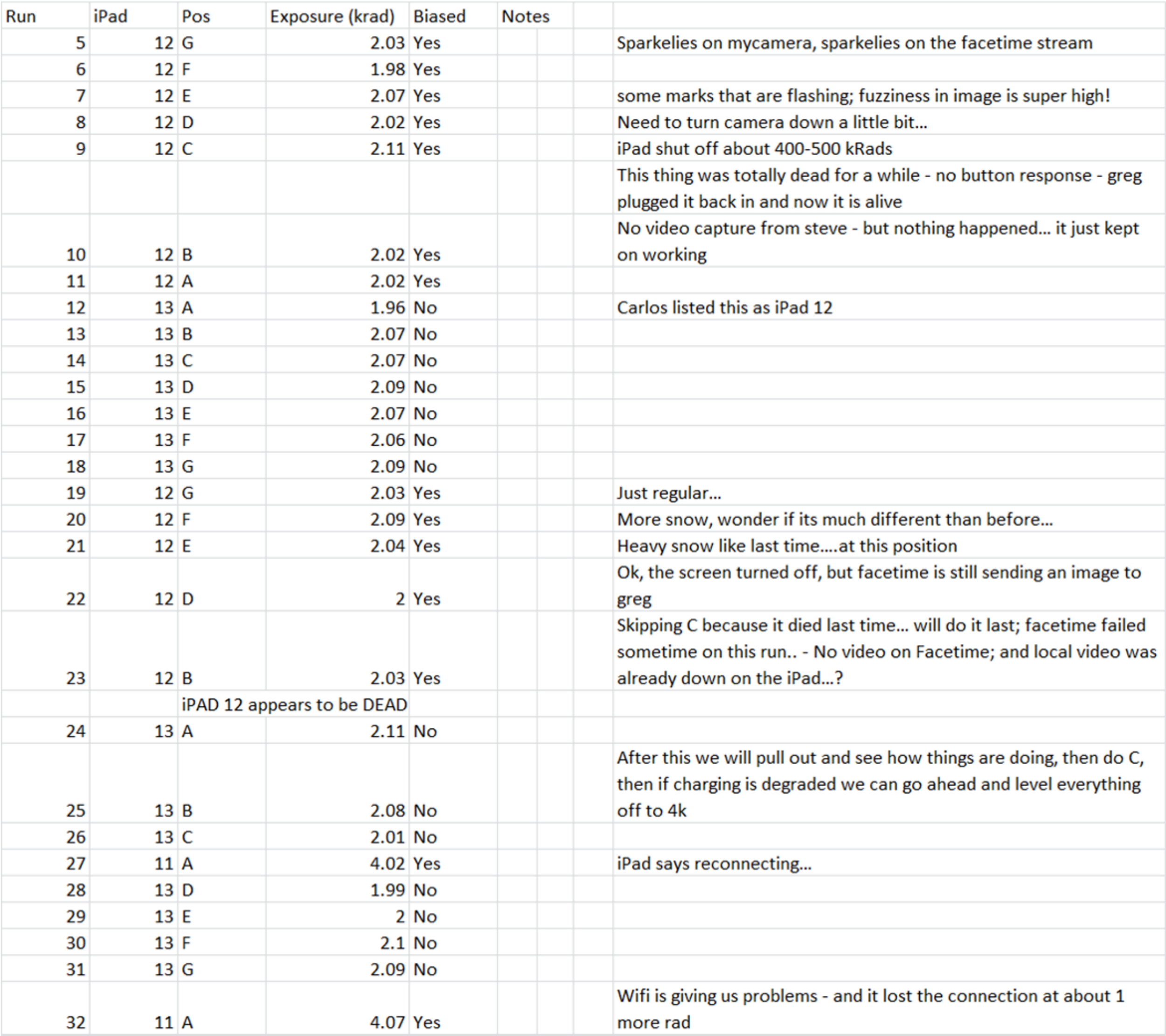
7.0 FUTURE WORK

This work is designed with the possibilities of future work to investigate additional radiation response and to characterize similar devices. In this section we quickly discuss how this work can carry over in the following areas. First is testing of similar devices other than the iPad. We also believe that the TID work discussed here is not complete due to not including ELDRS work. Finally, the radiation examination does not include detailed SEE examination, which may be very important.

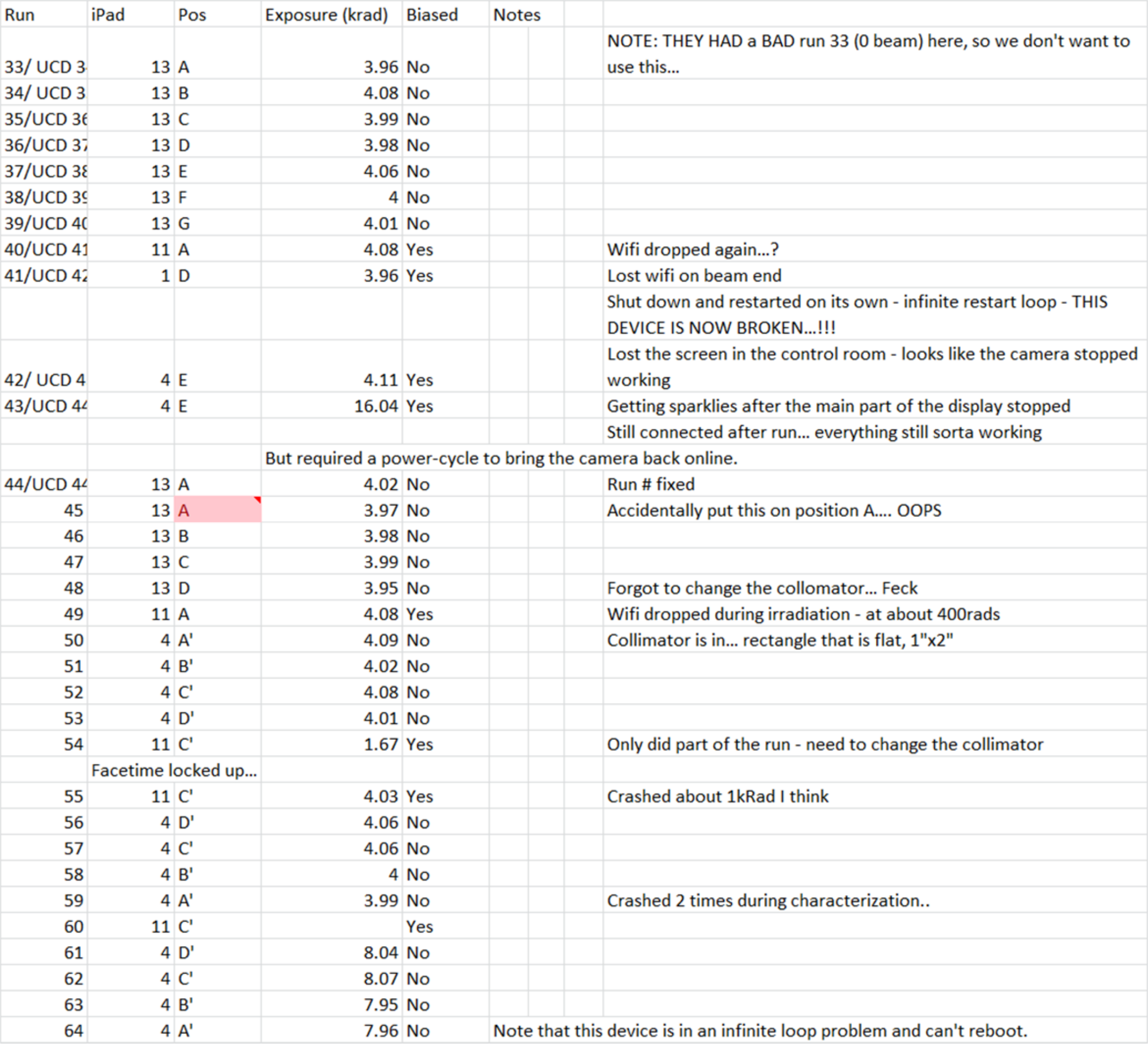
The iPad is one of several platforms that are now available for tablets and smart phones. This work can easily extend to study several Android and Windows smartphones and tablets. This sort of study would show similar trends in these complex devices while also highlighting any important differences that might show favor for use of one of the tested devices for potential space use.

ELDRS is an important effect in bipolar devices where TID failures may be seen at significantly reduced TID levels when the subject electronics are irradiated at low dose rates (below 10 mrad/s). This is expected to affect power electronics, sensors, and communications devices in the iPad.

8.0 TEST LOG FOR 4TH GENERATION IPAD EXPOSURES



Run	iPad	Pos	Exposure (krad)	Biased	Notes			
5	12	G	2.03	Yes				Sparkelies on mycamera, sparkelies on the facetime stream
6	12	F	1.98	Yes				
7	12	E	2.07	Yes				some marks that are flashing; fuzziness in image is super high!
8	12	D	2.02	Yes				Need to turn camera down a little bit...
9	12	C	2.11	Yes				iPad shut off about 400-500 kRads
								This thing was totally dead for a while - no button response - greg plugged it back in and now it is alive
10	12	B	2.02	Yes				No video capture from steve - but nothing happened... it just kept on working
11	12	A	2.02	Yes				
12	13	A	1.96	No				Carlos listed this as iPad 12
13	13	B	2.07	No				
14	13	C	2.07	No				
15	13	D	2.09	No				
16	13	E	2.07	No				
17	13	F	2.06	No				
18	13	G	2.09	No				
19	12	G	2.03	Yes				Just regular...
20	12	F	2.09	Yes				More snow, wonder if its much different than before...
21	12	E	2.04	Yes				Heavy snow like last time....at this position
22	12	D	2	Yes				Ok, the screen turned off, but facetime is still sending an image to greg
23	12	B	2.03	Yes				Skipping C because it died last time... will do it last; facetime failed sometime on this run.. - No video on Facetime; and local video was already down on the iPad...?
		iPAD 12 appears to be DEAD						
24	13	A	2.11	No				
25	13	B	2.08	No				After this we will pull out and see how things are doing, then do C, then if charging is degraded we can go ahead and level everything off to 4k
26	13	C	2.01	No				
27	11	A	4.02	Yes				iPad says reconnecting...
28	13	D	1.99	No				
29	13	E	2	No				
30	13	F	2.1	No				
31	13	G	2.09	No				
32	11	A	4.07	Yes				Wifi is giving us problems - and it lost the connection at about 1 more rad



Run	iPad	Pos	Exposure (krad)	Biased	Notes			
33/ UCD 3	13	A	3.96	No				NOTE: THEY HAD a BAD run 33 (0 beam) here, so we don't want to use this...
34/ UCD 3	13	B	4.08	No				
35/UCD 36	13	C	3.99	No				
36/UCD 37	13	D	3.98	No				
37/UCD 38	13	E	4.06	No				
38/UCD 39	13	F	4	No				
39/UCD 40	13	G	4.01	No				
40/UCD 41	11	A	4.08	Yes				Wifi dropped again...?
41/UCD 42	1	D	3.96	Yes				Lost wifi on beam end
								Shut down and restarted on its own - infinite restart loop - THIS DEVICE IS NOW BROKEN...!!!
42/ UCD 4	4	E	4.11	Yes				Lost the screen in the control room - looks like the camera stopped working
43/UCD 44	4	E	16.04	Yes				Getting sparklies after the main part of the display stopped
								Still connected after run... everything still sorta working
			But required a power-cycle to bring the camera back online.					
44/UCD 44	13	A	4.02	No				Run # fixed
45	13	A	3.97	No				Accidentally put this on position A.... OOPS
46	13	B	3.98	No				
47	13	C	3.99	No				
48	13	D	3.95	No				Forgot to change the collomator... Feck
49	11	A	4.08	Yes				Wifi dropped during irradiation - at about 400rads
50	4	A'	4.09	No				Collimator is in... rectangle that is flat, 1"x2"
51	4	B'	4.02	No				
52	4	C'	4.08	No				
53	4	D'	4.01	No				
54	11	C'	1.67	Yes				Only did part of the run - need to change the collimator
	Facetime locked up...							
55	11	C'	4.03	Yes				Crashed about 1kRad I think
56	4	D'	4.06	No				
57	4	C'	4.06	No				
58	4	B'	4	No				
59	4	A'	3.99	No				Crashed 2 times during characterization..
60	11	C'		Yes				
61	4	D'	8.04	No				
62	4	C'	8.07	No				
63	4	B'	7.95	No				
64	4	A'	7.96	No	Note that this device is in an infinite loop problem and can't reboot.			

9.0 REFERENCES

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10.0 ACRONYMS

ARM	advanced RISC machine (but often used without acronym connotation)
CNL	Crocker Nuclear Laboratory
ELDRS	enhanced low dose rate sensitivity
DUT	device under test
GPS	Global Positioning System
ISS	International Space Station
JPL	Jet Propulsion Laboratory
LCD	liquid crystal display
NAND	Not And
NASA	National Aeronautics and Space Administration
NEPP	NASA Electronic Parts and Packaging (Program)
RISC	reduced instruction set computing
SEB	single event burnout
SEE	single event effects
SEFI	single event functional interrupt
SEGR	single event gate rupture
SEL	single event latchup
SOC	System on a Chip
TID	total ionizing dose
UCD	University of California, Davis
USB	Universal Serial Bus
WBS	work breakdown structure