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Single-Event Effects Test Report Micron MTFDHBK256TDP-1AT12AIYY NVMe Solid-State Drive

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1. Introduction and Purpose

This test explored the single-event effects (SEE) response of an off-the-shelf, automotive/industrial product line solid state drive (SSD). Testing with 200 MeV protons served to identify error signatures, the presence of unrecoverable single-event effects, and to verify a complex test setup prior to then-planned heavy-ion testing.

2. Test Result Summary

The MTFDHBK256TDP-1AT12AIYY is susceptible to both recoverable (with power cycle) and unrecoverable SEE with 200 MeV protons.

3. Device Description

The MTFDHBK256TDP-1AT12AIYY is a 256 GB, triple level cell (TLC), NVMe solid state drive (SSD) from the Micron 2100AI/AT family of devices. The devices are available in a ball grid array (BGA) package with an automotive rating with -40 to +105C temperature range, or a M.2 board with an industrial -40 to +95C temperature range. The specific devices as tested are an industrial grade product, described in Table I.

Table I Part Description

Part Number	MTFDHBK256TDP-1AT12AIYY
REAG Tracking ID	23-009
Flight Part Number	NA
Manufacturer	Micron
Lot Date Code	3BA22
Quantity Tested	8
Part Function	NVMe SSD
Part Technology	NAND Flash
Package	M.2 2230

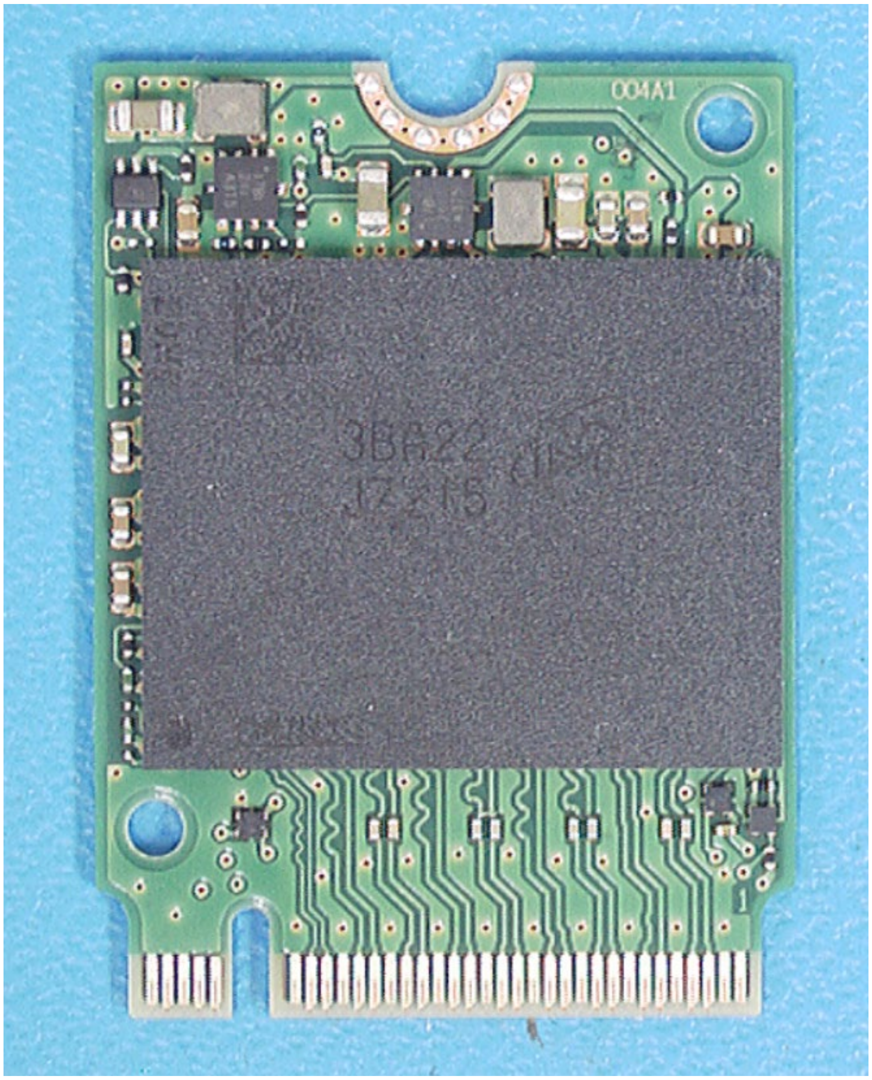

Fig. 1 Photograph of device as procured

4. Test Setup

The NVMe SSDs were inserted into a passive M.2 extender with a flexible cable, shown in Fig. 2 and Fig. 3. The power (nominally 3.3 V; as-tested 3.5 V) pins on the M.2 header for the extender were filed off and power was externally supplied from a Keysight N6702C power supply module for independent control of DUT voltage and current. The other end of the flexible extender was inserted into an off-the-shelf NVMe-to-USB adapter which itself was connected to a PC with a 10m USB cable (USB 3.2 Gen 1).

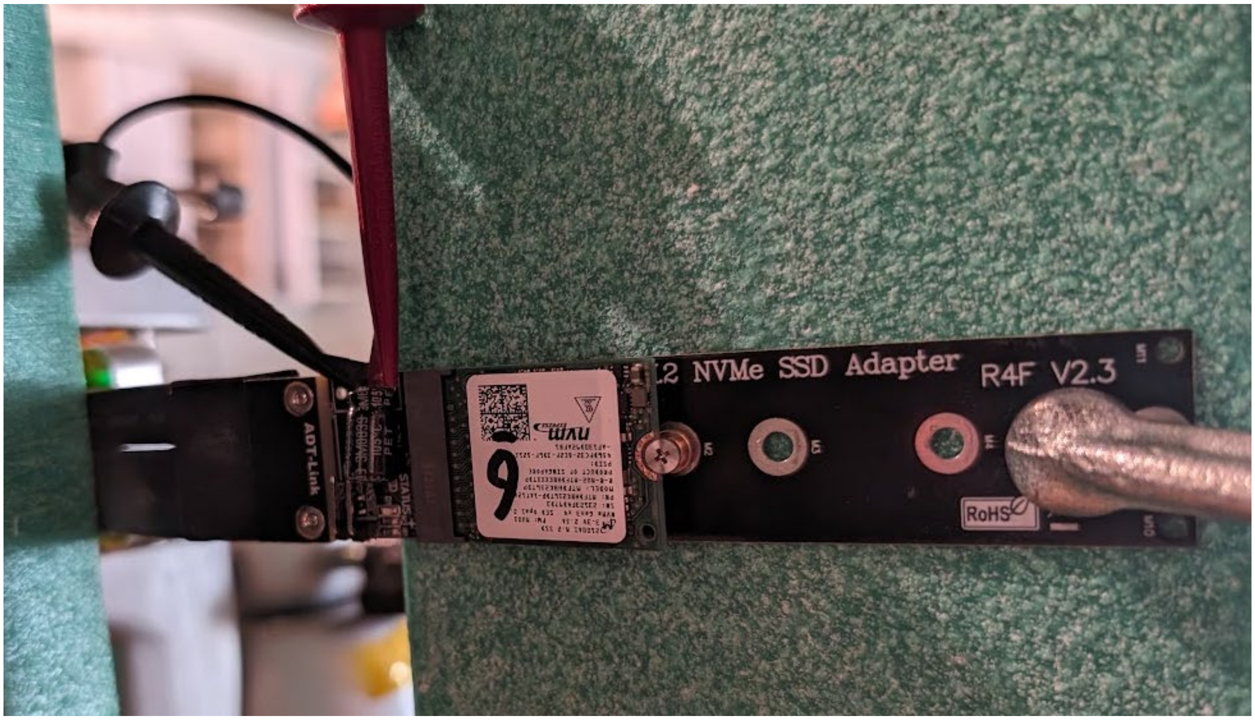

Fig. 2. The device installed on a passive M.2 extender cable.

Fig. 3. From left, USB extender, USB-to-NVMe adapter, M.2 extender cable, power supply connection, and DUT during pre-test demo at GSFC

At the proton facility, the controlling PC was setup around a corner from the beamline to minimize or eliminate effects on the computer from either direct proton or secondary neutron strikes (no issues occurred). The USB-to-NVMe converter module was shielded by ~2” of lead and ~1” of borated polyethylene. Several small active ICs exist on the M.2 SSD module alongside the automotive/industrial grade single-chip SSD itself. These small components were not shielded.

The PC simultaneously controlled (via a Python test routine) the flow of data to and from the SSD under test as well as the remotely-monitored power supply and a National Instrument NI-USB-6501 module. The NI module was configured with two digital outputs to inhibit the power supply and the test facility’s beam while reconfiguring from any observed SEE.

When an SEE occurred, the SSD operation would timeout. An error-handling routine in the Python script would catch the exception and trigger an autonomous recovery sequence. The power to the device under test (DUT) was immediately cut off and a beam inhibit signal sent to the facility, both driven by digital I/O from the National Instruments NI-USB-6501. A 3s delay allowed the device to fully power down, after which power was restored for 20 seconds while the beam was still inhibited. After this delay, read/write operations resumed and the beam was uninhibited. In this manner, testing could proceed without intervention unless an unrecoverable (catastrophic) error occurred.

5. Test Facility

Facility:	Massachusetts General Hospital Francis H. Burr Proton Therapy Center
Type of Radiation:	Protons
Facility Configuration:	200 MeV
Flux:	Approximately $1x10^{8}cm^{-2}s^{-1}$.
Fluence:	Testing was generally conducted until failure. In the case of recoverable failures the beam was paused until recovery.
Beams / LET:	200 MeV protons

6. Test Conditions

Temperature:	Ambient room temperature
In-Air or Vacuum:	In-air
Supply Voltages:	3.5 V

7. Test Methods and Procedures

Three test methods were available – unbiased irradiations, powered read-only operations, and powered write-read operations.

7.1. Unbiased Irradiations

During an unbiased irradiation, the power supply is disabled and the USB connection is physically unplugged. The purpose is to evaluate whether upsets in the non-volatile memory (which can occur while unbiased) are a contributor to unrecoverable failure mechanisms. A secondary purpose is to evaluate the effects of total ionizing dose while unbiased, though the levels obtained during testing were not significant.

7.2. Read-Only Irradiations

Read loop tests repeatedly read 1 GB from the device until failure. No attempt is made to prevent the SSD controller from performing any background operations nor can the effects of data caching be observed directly.

7.3. Read-Write Irradiations

The primary test method for this campaign is the repeated write-read operation. During each loop a pseudorandom 1 GB of data is written and then readback. The data is distributed to 1,024 random locations on the drive, each containing 1 MB. The selected 1,024 locations are randomly chosen for each loop within a test, ensuring broad coverage across the device and minimizing the effects of caching on results.

Power supply logs are timestamp-correlated to the data operations, and individual read/write operation power consumption to the SSD (which is independently powered) can be obtained to investigate any possible single-event functional interrupt or single-event latchup.

8. Test Results

Error signatures always appeared as the sudden failure of a commanded read or write operation. After three seconds without response from the hardware, the software considered the operation to have timed out. In many cases, the autonomous power supply cycling would clear the event and the testing could resume – these are binned as recoverable events.

Devices 2-5 were all tested until unrecoverable failures were observed. As with the recoverable events, a power cycle was initiated, and while the device appeared operational again, subsequent *write* operations failed immediately.

Devices 6, 7, and 8 were *not* tested until failure. Testing was intentionally halted after several 10^{10} of fluence to allow post-test characterization of surviving devices.

In Table II, the results of each device are provided with a count of total events observed and the total biased fluence. The term *total biased fluence* excludes the $4.28 \times 10^{10}/cm^2$ of fluence received by Device 6 in an unbiased test, as this mechanism appears different from the active read-write mode failures. Including that fluence would artificially reduce the mean fluence to failure (MFTF) for the device.

Table II. Events observed by device

Device #	Total Timeout Events	Total Biased Fluence	MFTF	Tested until unrecoverable error occurred?
Micron_2	2	4.28E+09	2.14E+09	Yes
Micron_3	7	6.97E+09	9.96E+08	Yes
Micron_4	4	8.82E+09	2.21E+09	Yes
Micron_5	14	1.46E+10	1.04E+09	Yes
Micron_6	13	2.06E+10	1.58E+09	No
Micron_7	9	2.38E+10	1.98E+09	No
Micron_8	9	1.26E+10	9.42E+08	No
sum	*58*	*9E+10*	*1.56E+09*	

A trend of increasing fluence to unrecoverable failure (no failure at all for #6-#8) is present in the data, but unexplainable. The test setup (including power supply configuration) was unchanged and this may simply be a statistical anomaly. A different part from another manufacturer was tested between Micron devices 5 and 6, and showed no such effect.

The mean fluence-to-failure (MFTF) for each device is charted in Fig. 4. The cumulative MFTF for all devices is a red horizontal line. Error bars computed as fluence/(events-sqrt(events)) and fluence/(events+sqrt(events)) are present for each device.

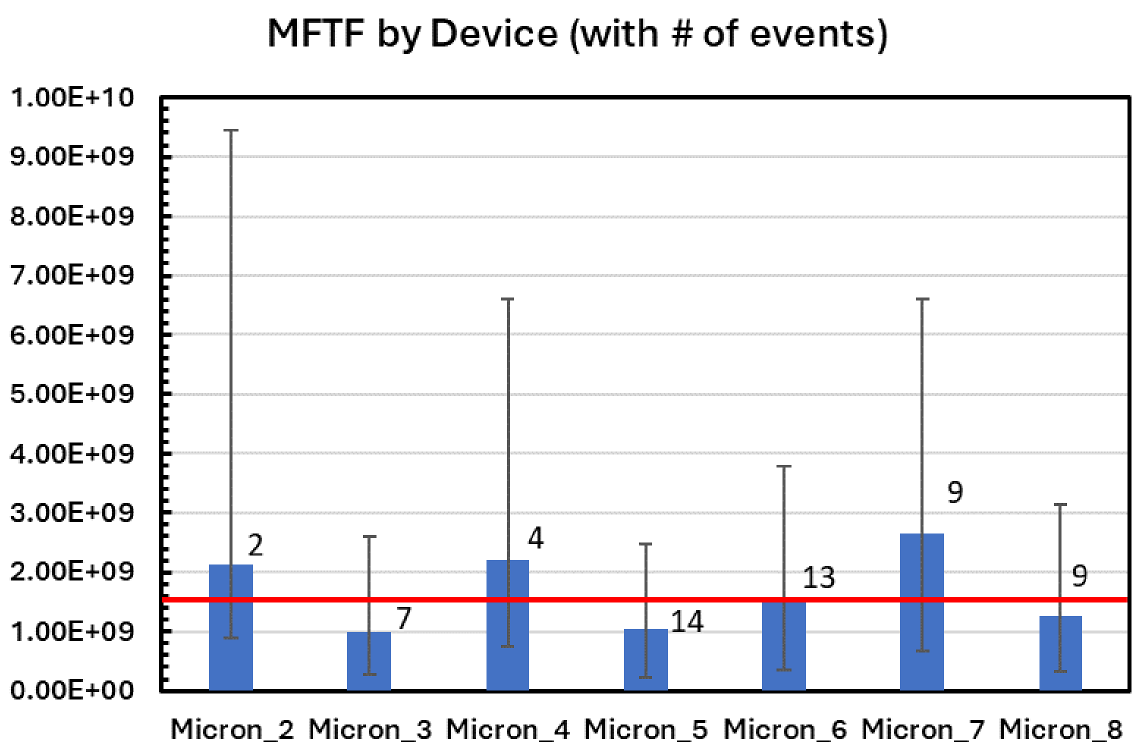

Fig. 4. Chart of fluence to failure (both recoverable and non-recoverable events) per device, with error bars and a cumulative average (red)

Device #1 was primarily tested while adjusting the test setup and the fully-autonomous test/recovery setup was not operating. This is the only device tested in a read-only manner and thus no meaningful statistics in the read-only configuration exist. It was observed to also suffer an unrecoverable failure despite running read only at the operating system level – it cannot be proven whether the low-level flash controller on-board was programming or erasing under irradiation. The total fluence on the device was $2.02x10^{10}/cm^2$, but due to the read-only nature of the testing and the write-failure error signatures observed consistently, it can only be determined that final failure occurred between 1.41 and $2.02x10^{10}/cm^2$.

Device #6 was irradiated twice to $2.14x10^{10}cm^{-2}$ (total $4.28x10^{10}cm^{-2}$) in a completely unpowered and disconnected condition, more than any other device was tested to while actively reading and writing. The device was subsequently powered up and operated nominally. The total ionizing dose from these two runs totals approximately 2.46 krad(Si).

8.1. Operation Timing and Power Supply Current

The following charts illustrate the errors observed. In Fig. 5, a single set of random write and read commands is depicted. Each is 1 GB of random data spread over random locations on the drive and lasts for ~5 seconds. The write current is slightly elevated compared to the read current, and the higher pulse in the middle of the write operation was consistently observed throughout testing. The duty cycle and current levels are representative of those observed on all devices tested.

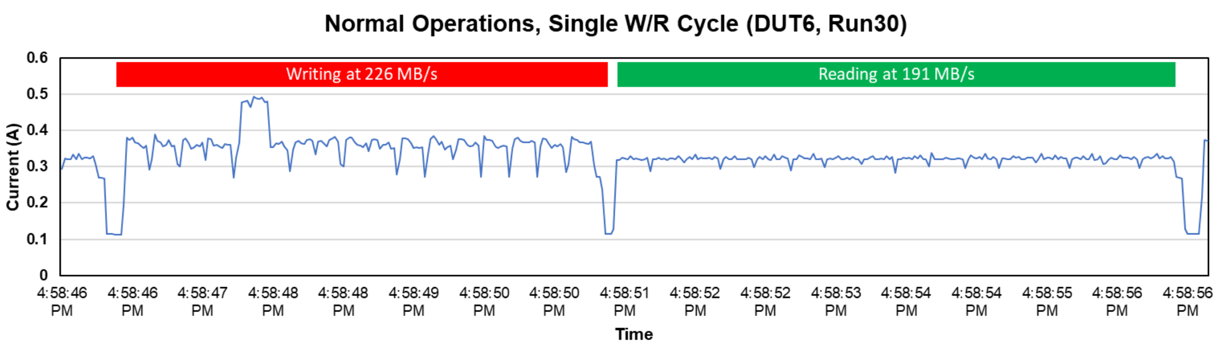

Fig. 5. Write and read currents of normal operation

The autonomous error detection and recovery routine is shown in Fig. 6:

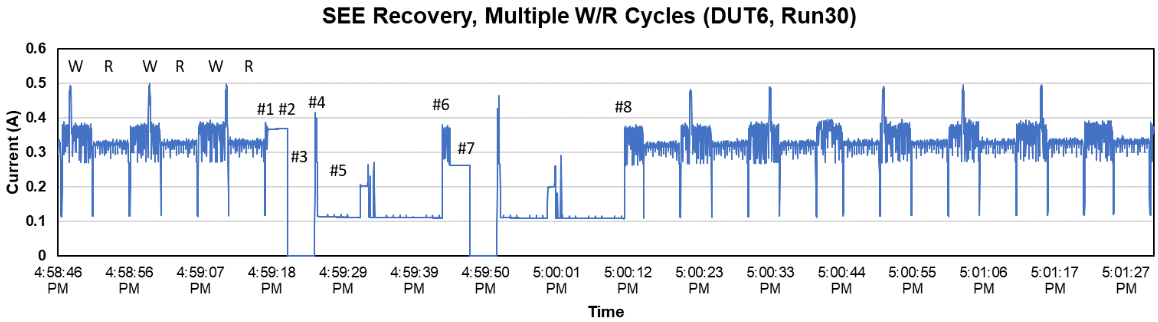

Fig. 6. Write and read cycles interrupted by two single-event effects, both successfully recovered

In Fig. 6, the starting time is the same as Fig. 5, but the chart extends for about two and a half minutes. The device performs three sets of write (W) and read (R) operations successfully, followed by an error event in the following write. The sequence below describes the subsequent events, marked with numbers on the chart in Fig. 6:

1. Initiation of a write command at 4:59:17 PM. The supply current elevates but is uncharacteristically flat.
2. Three seconds later at 4:59:20 PM the test software throws an exception when the write has failed to complete. This is classified as a timeout error.
3. The power supply is disabled for four seconds and the proton beam is inhibited.
4. At 4:59:24 PM power is restored
5. The device is allowed 20 seconds to initialize, still without beam applied.
6. At 4:59:44 PM the beam is uninhibited and testing (the incomplete write) resumes
7. Writing proceeds successfully for about 2 seconds until it again hangs for 3 seconds, triggering a timeout error and a repeat of the recovery in steps 3-6).
8. Writing resumes after the second recovery and completes. The subsequent read operation is successful, along with the depicted write and read cycles afterwards.

Over the course of an experiment, several devices continued to operate (i.e., read and write random data correctly) but with significantly slower write times. Looking at the same device (#6), Fig. 7 shows write speed significantly degraded partway through the experiment compared to earlier in the run (Fig. 5), though read speed remains essentially unchanged. The write operation now includes a period lasting several seconds where write current decreases. Note that no data errors or timeouts occurred in this portion of the random write/read operation.

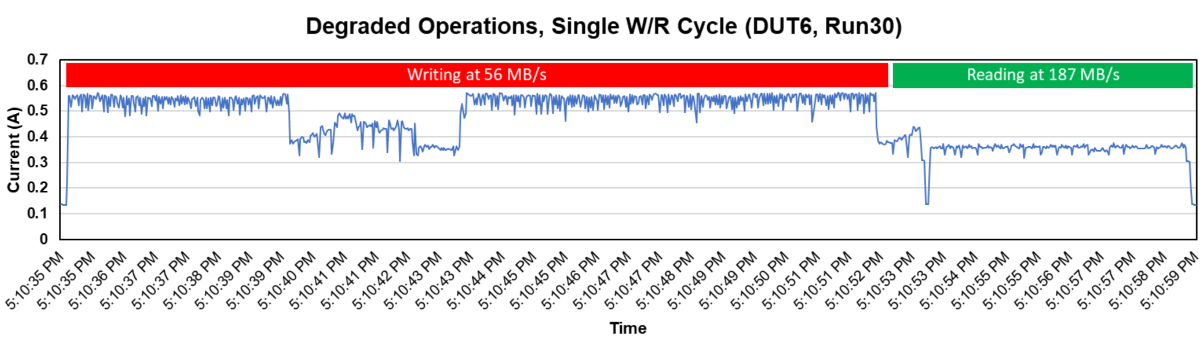

Fig. 7. A single write/read cycle with degraded write speed

8.2. Unrecoverable Failure

Several devices reached an unrecoverable state during which neither the autonomous power supply cycling nor subsequent manual debugging could restore full functionality. In these cases, the device would communicate with the host PC and appear to initialize, but any write command would fail. Read commands were generally successful in areas that had previously been written to before the failure.

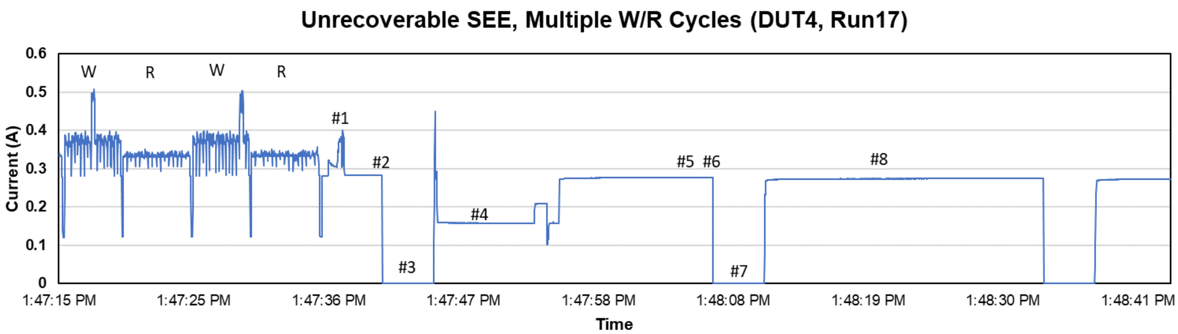

Fig. 8. Write/read cycle ending with unrecoverable SEE

In Fig. 8 an unrecoverable event is shown. The following sequence of events follows the normal W/R cycles shown at the left:

1. At 1:47:36 a new write cycle begins. A portion (about 10%) of the operation completes successfully before the power supply level drops and no further data is written.
2. After no data is written for three seconds, the software considers the operation to have timed out at 1:47:40. The power supply and proton beam are inhibited to attempt recovery.
3. The power supply remains inhibited for 4 seconds before it is restored at 1:47:44. The proton beam remains inhibited.
4. A delay of 20 seconds allows the device to reinitialize after the power cycle.
5. The write operation attempts to resume at 1:48:04 but the supply current does not change at all and no data is written.
6. At 1:48:07 a timeout occurs and a second autonomous recovery cycle begins.
7. The power supply is inhibited as part of the second recovery cycle
8. When power is re-applied, the supply current returns to the non-functional level of #5 and #6. Subsequent recovery cycles have no effect on the device.

8.3. Total Ionizing Dose

It is worth noting that a single device (not one tested with protons) was exposed to 18.6 krad(Si) of gamma irradiation at the NASA GSFC Radiation Effects Facility prior to testing. The device was actively biased and performed a continuous series of read loops with a rewrite every 5 krad. A full TID characterization was not performed, and only a single device was exposed. The intent was to ensure that low amount of TID received from the protons was unlikely to render the part untestable. The device functioned normally at 18.6 krad(Si). Based on this, it is considered unlikely that TID played a role in device failures during proton testing. The highest fluence put on any one part during proton testing was equivalent to 3.66 krad(Si).

9. Equipment List

Table III. Equipment List

Manufacturer and P/N	Function	S/N or ECN	Calibration Status
Keysight N6702C	Power Supply Mainframe	NA	NA
Keysight N6775A	DC Power Supply Module	SG45000178 / M161858	Due 9/12/2024
NI-USB-6501	Power supply and beam line inhibits	1E273FE	NA
Dell Precision Laptop	Test Control and Data Collection	5065858	NA