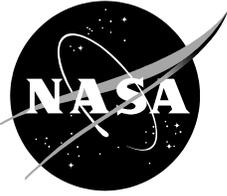


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# **Commercial Off-The-Shelf Graphics Processing Board Radiation Test Evaluation Report**

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August 2014

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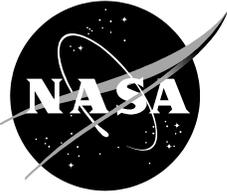
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## **Abstract**

Large round-trip communications latency for deep space missions will require more onboard computational capabilities to enable the space vehicle to undertake many tasks that have traditionally been ground-based, mission control responsibilities. As a result, visual display graphics will be required to provide simpler vehicle situational awareness through graphical representations, as well as provide capabilities never before done in a space mission, such as augmented reality for in-flight maintenance or Telepresence activities. These capabilities will require graphics processors and associated support electronic components for high computational graphics processing.

A preliminary test was performed on five commercial off-the-shelf (COTS) graphics cards in an effort to understand the performance of commercial graphics card electronics operating in the expected radiation environment. This paper discusses the preliminary evaluation test results of five COTS graphics processing cards tested to the International Space Station low Earth orbit radiation environment. Three of the five graphics cards were tested to a total dose of 6000 rads (Si). The test articles, test configuration, preliminary results, and recommendations are discussed in this paper.

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## Acronyms

BEO	beyond Earth orbit
CAT 5	Category 5
COTS	commercial off-the-shelf
DUT	device under test
FI	functional interrupt
GPC	graphics processing card
HD	high definition
HDMI	High Definition Multimedia Interface
IUCF	Indiana University Cyclotron Facility
ISS	International Space Station
LEO	low Earth orbit
MTTFI	Mean Time to Functional Interrupt
PCI-e	Peripheral Component Interface-extension
Si	silicon
3D	three-dimensional
VGA	Video Graphics Array

## 1.0 Introduction

NASA is investigating deep space mission concepts and the systems necessary to support those missions. Large round-trip communications times for deep space missions will require more onboard computational capabilities as the space vehicle is required to take on more of what used to be mission control responsibilities. Architecture concepts under development require the use of graphics processing hardware to enable increased situational awareness of the vehicle through high-resolution graphics. Additionally, applications targeting the maintenance of astronaut health, both psychological and physiological (i.e., Telepresence/Telemedicine and augmented reality for just-in-time training or maintenance), will be necessary. However, no known radiation test of graphics processing cards (GPCs) has been identified to understand how well they would work in the space environment.

Five commercial off-the-shelf (COTS) GPCs were tested to the International Space Station (ISS) low Earth orbit (LEO) radiation environment to obtain initial radiation test data of electronic components found in commercial GPCs. The testing occurred at the Indiana University Cyclotron Facility (IUCF). It should be understood that COTS GPCs were not designed or intended to operate in the space environment—they were designed to operate in an ambient terrestrial application. However, the radiation testing served to get an initial rough assessment of how well these specialized processing cards would operate if their design were deployed in a space application.

This report is organized as follows. First, the test articles description is presented, including specifications. Next, the test setup is described along with the methodology used to test the cards. Then, the test results are disseminated. Finally, the report concludes with a brief summary of the test results and recommended future GPC testing.

## 2.0 Testing

### 2.1 Test article description

Five COTS GPCs were acquired to perform a limited GPC radiation test evaluation. The selection of the GPCs was based on immediate availability and cost. However, at least one of the five was required to be a high-performance GPC. Table 1 shows the GPCs that were selected along with their key performance specifications. Note that the GTX 650 has a high-speed core and memory clock frequency as well as a large number of processing graphics cores. It also scored the highest/best based on the three-dimensional (3D) Mark 11 benchmark program. The 3D program is used to assess performance of a graphics card 3D rendering and CPU workload processing capabilities.

All cards had a Peripheral Component Interface-extension (PCI-e) bus to a computer. In addition, all cards have a High Definition Multimedia Interface (HDMI). HDMI was used to transmit the output of the graphics card to a display monitor located in the control room to view anomalies during the irradiation of the card. The lowest-performing card based on the 3D Mark 11 benchmark was the GE Force 8400 GPC.

**Table 1. Graphic Processing Unit Key Specifications**

Specification	Product				
	MSI HD6450	Diamond HD 5450	PNY GE force GTX 650 Ti	MSI GE force GT 640	EVGA GE Force 8400
<b>Chipset Mfg.</b>	AMD	Radeon	NVIDIA	NVIDIA	NVIDIA
<b>GPU</b>	Radeon HD 6450	Radeon HD 5450	GeForce GTX 650 Ti	GeForce GT 640	GeForce 8400 GS
<b>Core Clock</b>	625 MHz	650 MHz	928 MHz	797 MHz	520 MHz
<b>Memory Clock</b>	1333 MHz	600 Mhz	5400 MHz	891 MHz	1200 MHz
<b>Memory Size</b>	1 GB	1 GB	1GB	1 GB	1 GB
<b>Memory Interface</b>	64-bit	No data	128-Bit	128-bit	64-bit
<b>Memory Type</b>	DDR3	GDDR3	GDDR5	DDR3	DDR3
<b>OpenGL</b>	OpenGL 4.1	OpenGL 3.2	OpenGL 4.3	OpenGL 4.3	OpenGL
<b>RAMDAC</b>	400 MHz				
<b>Max Resolution</b>	2560 X 1600	2560 X 1600	2560 X 1600	2560 X 1600	2048 X 1536
<b>Cooling</b>	Fan	Fanless	Fan	Fan	Fan
<b>Power Requirement</b>	Min. 400 Watt Power Supply	Min. 300 Watt Power Supply	Min. 400 Watt Power Supply	Min. 350 Watt Power Supply	Min. 350 Watt Power Supply
<b>Processors/CUDA Cores</b>	160 Stream Processors	80 Stream Processors	768 CUDA Cores	384 CUDA Cores	8 CUDA Cores
<b>3D Mark 11 Score</b>	480	330	2860	2180	300

## 2.2 Test approach

Resources and time limitations resulted in performing a coarse rather than a fine test of each GPC. This meant that the entire card was irradiated rather than selective shielding of the different sections of the GPC to determine what components were susceptible to radiation.

All five GPCs were first evaluated by an initial irradiance screening to determine how much fluence each GPC accumulated after at least six data points of failures occurred. The top three performers were selected to continue irradiating them until they reached a total ionizing dose of 6000 rads (Si). A demo graphics benchmark program called Tropic from Unigine Corporation was launched, the entire card irradiated, and the output of the GPC viewed on a display and recorded.

Figure 1 shows the setup used for testing each GPC. The chamber room contained the motherboard that connected to the GPC via a PCIe extender cable. In addition to the motherboard, a hard disk and power supply that powered the motherboard and GPC were co-located on the test table. The hard disk contained the Windows Operating System files and the graphic card benchmark program used to run the GPC.

Four 100-foot cables ran from the control room to the system in the chamber: Category 5 (CAT 5) Ethernet, Video Graphics Array (VGA), HDMI and a 2-wire remote switch. The CAT 5 Ethernet cable was used to send keyboard commands from the laptop to the motherboard. The VGA cable provided output status of the motherboard to a display in the control room. The HDMI cable provided the output of the graphics card device under test (DUT) to another display in the control room. A high-definition (HD) camera was used to record the GPC display and capture any anomalies that occurred.

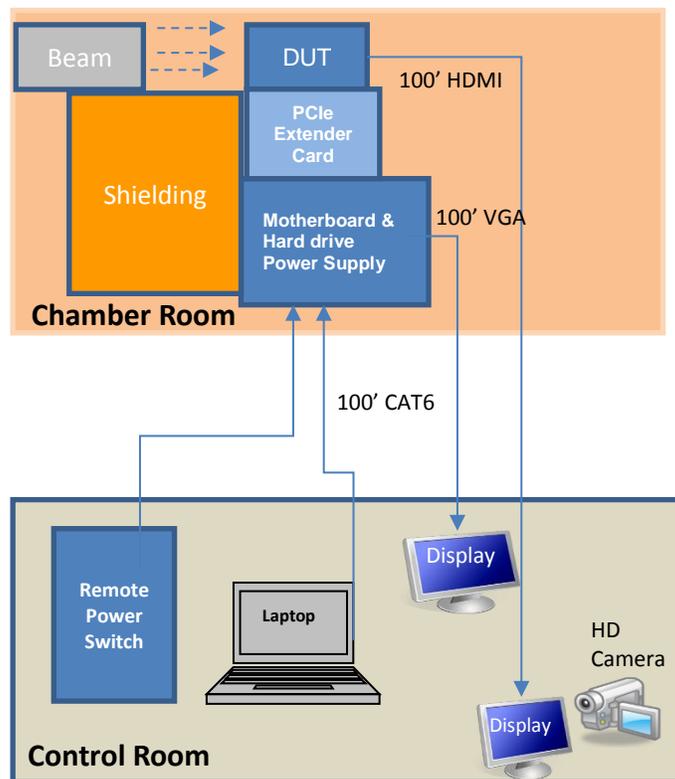
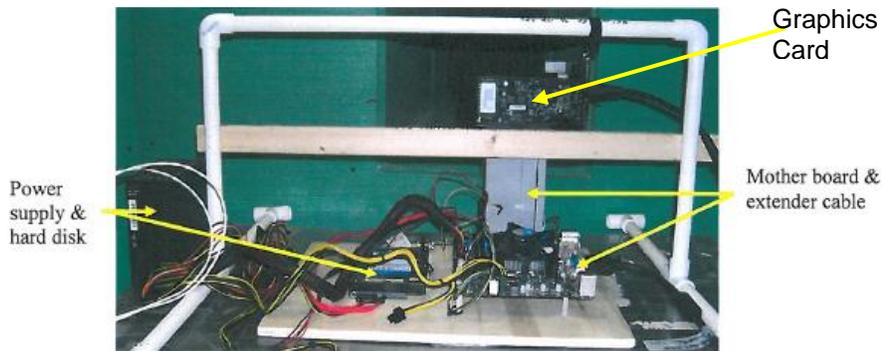
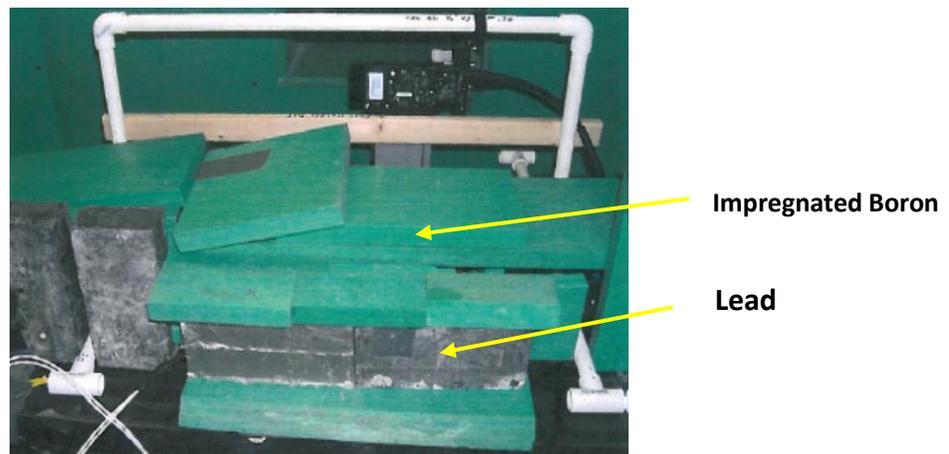


Figure 1. GPC radiation test setup.

Since the test objective was to irradiate the GPC and not the electronics that drove the card, a GPC test jig was developed to permit radiation to reach the GPC DUT but protect the motherboard from the beam. Figure 2 shows a block diagram of the test jig used to separate the motherboard and associated support components and the GPC via the PCIe extender cable. Figure 3 shows the motherboard and associated support components shielded with lead bricks and boron impregnated plastic.



**Figure 2. Graphics processing card jig.**



**Figure 3. Motherboard and support components radiation shielded.**

The 100-foot two-wire cable was used to provide a remote power switch function to control power to the motherboard in case of a latch up or other hardware problem. In the event of a hard failure, a momentary push button could be depressed to power cycle the motherboard and GPC. The motherboard power supply contained over voltage/power and short circuit protection.

### 2.3 Test results

Screening all five GPCs resulted in selecting the top three performers. All the failures that occurred were functional interrupts (FIs) where the program stopped working and required a reboot or power cycle to regain control of the system. Table 2 shows the results of the screening and the top three winners highlighted in red.

Table 2. Radiation Screening Results

	<b>MSI HD6450</b>	<b>Diamond HD 5450</b>	<b>PNY GE force GTX 650 Ti</b>	<b>MSI GE force GT 640</b>	<b>EVGA GE Force 8400</b>
<b>Fluence (protons/cm<sup>2</sup>)</b>	1.46E9	5.26E8	6.24E8	7.76E8	5.86E8
<b>Number of FIs</b>	6	6	7	7	7

The top three GPCs were each tested until the card reached a total ionizing dose of 6000 rads (Si). Though the cards had several failures, none of the cards experienced a permanent failure.

Initially, the plan was to use the graphic card benchmark program while the card was irradiated. However, it became evident from the number of reboots/restarts and time to do the reboots/ restarts (due to FIs) that running the benchmark program was not the best approach. Hence, rather than run the benchmark program, a decision was made to use the Windows startup screen as seen in Figure 4 as the test case for the radiation test. This provided a simpler and faster way of testing the GPCs. The reasoning was that since the graphics card displayed the Windows startup screen, radiation upsets to the card would result in the screen displaying anomalies.

Figure 5 is a representation of some of the display output anomalies captured with the video recording. Also, during the irradiation, the mouse was moved around the screen. If the mouse stopped moving, it suggested that the graphics card stopped operating. Typically, when the graphics card stopped responding or output became corrupted, a common failure message that Windows operating system outputted was “D3D11 Appwindows.swap(device remove)”, which suggested the card had become unstable and timed out. However, there were a few times where the screen went blank as well. A power cycle regained control of the system.



Figure 4. Windows startup display screen.



Figure 5. Example graphic failure display errors.

The Mean Time to Functional Interrupt (MTTFI) of each card, including the two that did not make the final selection, is shown in Table 3. The MTTFI calculation is computed using the Bendel A method.

Table 3. Mean Time to Functional Interrupt Results

	<b>MSI HD6450</b>	<b>Diamond HD 5450</b>	<b>PNY GE force GTX 650 Ti</b>	<b>MSI GE force GT 640</b>	<b>EVGA GE Force 8400</b>
<b>MTTFI ((Days)</b>	43.1	15.5	15.7	19.6	14.8

## **3.0 Conclusion and Recommendations**

### **3.1 Conclusions**

Several design factors affect a system or card's MTTFI performance, which includes the inherent radiation tolerance of the components, operating voltages, and radiation single event effects mitigation strategies. Commercial card manufacturers are not interested in designing for the radiation environment—that market is small compared to the commercial market (i.e., gaming). The radiation test levels environment for LEO, and to which these cards were subjected, is benign (Earth's magnetic shielding and spacecraft shielding) compared to beyond Earth orbit (BEO) where places such as the moon or Mars have little to no magnetic shielding.

Though the radiation test of the five GPCs did not meticulously test the board, it did provide preliminary data regarding the use of commercial GPCs operating in the LEO environment. However, because each board was entirely irradiated, it is not known what component(s) caused each board's failures. Further detailed testing would be required to make that determination.

Based on the GPCs specifications and the MTTFI results, no correlation appears between high-performing GPUs and radiation tolerance. The HD 6450 fared the best with respect to MTTFI of 43.1 days, though it was not the highest performing GPC when measured against the 3D Mark 11 benchmarking program. The highest performing GPC (GTX 650) scored near the bottom with respect to MTTFI performance. The lowest 3D Mark 11 benchmark performing GPC was the GE Force 8400, which also scored the lowest in MTTFI performance. However, the performance of an HD 6450 may suffice depending on the LEO space application.

### **3.2 Recommendations**

Based on the results of the testing, some recommendations are presented:

1. To identify/understand radiation-susceptible parts on the HD 6450 GPC, further testing should include more detailed pre-test planning that includes x-raying each board, identify components used on the board, and determining beam positions/shielding out components not of interest in the beam position.
2. Since the testing was performed to the LEO radiation environment, it is unclear how well the best performing board would operate in a BEO environment. Extrapolating the LEO results from LEO-to-BEO results is not possible. Therefore, performing heavy ion testing is the only way to understand BEO performance of the candidate GPC.

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