PDI

2012

Radiation Hardness Testing for Space Application Electronic Devices

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I. Introduction to Radiation Hardness Assurance

Precision Devices, Inc. (PDI) is a manufacturer of quartz crystal frequency control devices. Its business is centered on production and design of high-end quartz crystal filters and oscillators for commercial, military, and aerospace applications. In 2006, PDI became the first quartz crystal manufacturer to meet MIL-PRF-38534 – General Specification for Hybrid Microcircuits (Chris Harden, personal communication, March 9, 2012). In addition, PDI is listed on the Qualified Manufacturing List (QML) as a manufacturer of high-reliability frequency control devices produced in compliance with MIL-PRF-55310 – General Specification for Crystal Controlled Oscillators. In 2005, qualification to the MIL-PRF-55310 helped PDI to win an oscillator production bid for the GeoEye satellite program. Therefore, GeoEye became the first space program for PDI. As of the first quarter of 2012, PDI has participated in 19 space programs across the globe.

Devices intended for use in space programs have to pass extended screening processes after production. Screening processes include different reliability tests which are designed to accelerate failure modes that would occur during the operational life of the devices. One of these screening steps is radiation hardness testing. The purpose of the radiation hardness testing is to assure resistance of electronic components in a natural space radiation environment. Space agencies' research shows that Integrated Circuit (IC) microelectronic devices change their analog properties or can be damaged after exposure to natural space radiation (Fleetwood, 1998). The natural space radiation environment (see Figure 1) includes radiation belts, Galactic Cosmic Rays (GCR), and sun radiation caused by Solar Proton Events (SPE).

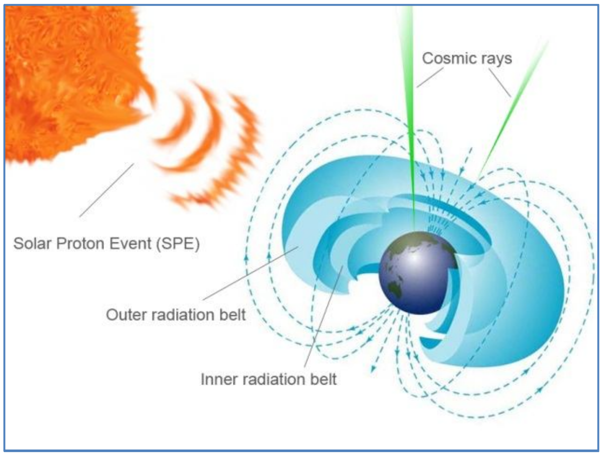

Figure 1: Sources of the space radiation. *The space radiation sources are Earth radiation belts, Galactic Cosmic Rays (GCR), and the sun radiation caused by Solar Proton Events (SPE). Solar proton events are associated with a massive burst on the sun when solar wind with highly energetic particles is released into space. Furthermore, released towards the Earth SPE flux forms Earth outer radiation belt. The outer radiation belt mainly consists of protons trapped in the Earth magnetosphere. Also, the Earth has the inner radiation belt. The inner radiation belt was discovered by James Van Allen in 1958. It consists of very energetic protons which are a by-product of collisions by cosmic ray ions with atoms of the atmosphere. Finally, galactic cosmic rays are highly accelerated particles that originate inside of our Galaxy. However, the source of the GCR is still under study. Adopted from (Stern, 2001).*

Therefore, radiation hardness testing provides a close simulation to natural space radiation environments and includes the following test methods: ionizing radiation (also called total dose) test and dose rate induced latchup tests. However, these tests are optional in the screening process and can be performed only if customers require the component manufacturer to perform these tests. Radiation hardness tests may be performed later on the subassembly level by the customer, as well.

Prior to 2011, PDI had received only one order for a space application product with requirements for a radiation hardness test. Since 2011, over 80 percent of PDI space program contracts have required the suppliers to perform radiation hardness tests. Radiation hardness assurance by a supplier helps to mitigate electronic components' failure on the component production stage. This method of radiation hardness assurance is called radiation-hardening-by-process (RHBP) and it has advantages over the radiation-hardening-by-design (RHBD) method because: electronic components are traceable from design to manufacturing stages and components are more reliable (Barnaby, 2005).

Since the increased number of potential customers requires radiation hardness assurance for space application electronic devices, in 2012 PDI implemented radiation hardness testing for components used for space application products. The radiation hardness testing helps PDI's design engineers develop high-reliability products for space applications. Furthermore, knowledge of the radiation hardness process helped PDI to receive approval from Defense Logistics Agency Land and Maritime to begin the qualification process for class K space products.

This report covers sources of space radiation and describes methods on how to simulate space radiation in a laboratory environment. Furthermore, this document describes the PDI radiation hardness testing plan and flow for space application products.

II. Radiation Study and Assurance Methods

A. Study of radiation sources in the natural space environment

This section describes three major sources of the radiation in the natural space environment: solar particle events, galactic cosmic rays, and Earth radiation belts. Space agencies have studied radiation sources for over 60 years. The study includes sources of the radiation, the measurement of radiation, and materials that are not sensitive to radiation (shielding materials).

Two expeditions on the International Space Station (ISS) in 2000 and 2001 were assigned to perform active radiation measurements (Shelfer, 2002). In the Shelfer's research paper, the radiation environment in and around the ISS was studied by the National Aeronautics and Space Administration (NASA). This research covered measurement of the radiation caused by SPE and measurement of GCR radiation as a function of the ISS altitude.

In accordance with Shelfer's report, first expedition started with a bang as a large solar proton event stroked the Earth early in the morning of November 9, 2000. Figure 2 shows the first ten hours of measured data.

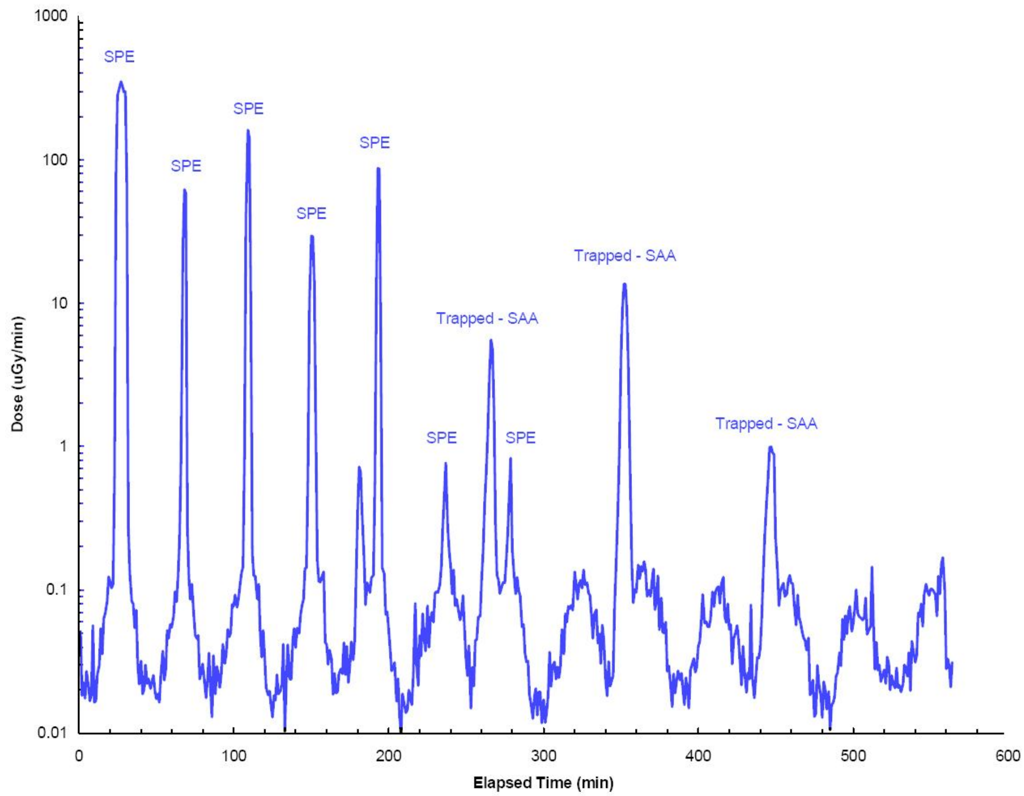

Figure 2: Radiation measurements on ISS. *This graph shows radiation dose rate measurement verses time. Measurements were made on November 9, 2000. In addition to Solar Proton Events (SPE), graph indicates radiation measurements of trapped radiation from South Atlantic Anomaly (SAA). Adopted from (Shelfer, 2002).*

Furthermore, at the time of the first expedition, GCR radiation was measured on altitudes from 357 kilometers (km) to 381 km in different locations of the ISS (see Table 1).

Table 1: GCR radiation measured on ISS. *The measured data is grouped as a function of measurement apparatus location inside the ISS at similar altitudes. The change in average GCR dose rate from 100 to 143 µGy/day is unexplained and still under investigation. Adopted from (Shelfer, 2002).*

Location of radiation measurement on ISS	Expedition 1			Groups
	GCR Dose (µGy/day)	Trapped Dose (µGy/day)	Average Altitude (km)	
SM-338	144	64	359	Group 1
SM-STBD-CQ	143	90	359	
SM-110	142	158	362	
SM-327	109	76	369	Group 2
SM-428	96	119	374	Group 3
SM-STBD-CQ	143	119	374	
US LAB O3/O4	126	159	377	
SM-110	100	152	381	Group 4
SM-338	101	121	379	
SM-STBD-CQ	144	150	380	

During the second expedition, as reported by the same author, monitoring of the GCR radiation was continued at altitudes between 374 km and 394 km. In addition, another SPE was measured on April 21, 2001. Active Radiation Monitoring on the ISS report concludes that only the high energy proton flux significantly influenced dose measurements inside the ISS (Shelfer, 2002). However, deep space missions may be affected more by GCR as it was noticed during Apollo missions.

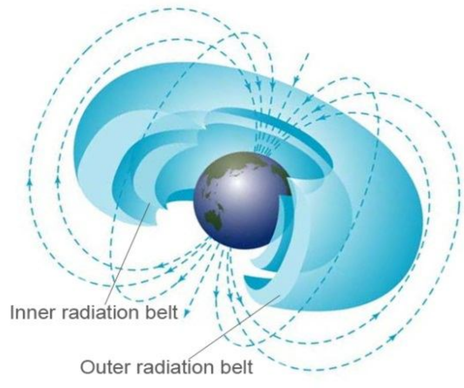

Figure 3: Earth radiation belts. *The figure illustrates inner and outer radiation belts within the Earth magnetic field. The outer radiation belt mainly consists of protons trapped in the Earth magnetosphere from SPE. The inner radiation belt was discovered by James Van Allen in 1958. It consists of very energetic protons which are a by-product of collisions by cosmic ray ions with atoms of the atmosphere. Adopted from (Stern, 2001).*

Other sources of space radiation are the Earth radiation belts (see Figure 3). The inner radiation belt was discovered by Van Allen. The belt is 6371 km in length and it consists of very energetic protons in the 10 to 100 Meg electron Volts (MeV) range. These protons are a by-product of collisions by cosmic ray ions with atoms of the atmosphere. Unlike the inner belt, the outer radiation belt is seen as part of the SPE plasma trapped in the magnetosphere. The outer belt's current energy is about 1MeV and mainly carried by ions, most of which are protons (Stern, 2001). The Radiation Belt Storm Probe spacecraft is scheduled for lunch in August 2012 to collect more data on the belts' radiation (Fox, 2012).

Described sources of the radiation may cause failure of integrated circuit components, which are used in the electronic devices for the space application. Highly accelerated particles can modify characteristics of an electronic device, so that the device will be forced to operate outside of its specification requirements. Therefore, manufacturers use shielding materials and radiation hardness testing to assure reliability of electronic components performance in the space environment.

B. Radiation hardness assurance methods

Use of the shielding materials is one of the ways to protect electronic devices on board of space-craft. A recent study of shielding materials published in 2009 by Dr. Richard Wilkins and Dr. Brad Gersey, shows that the mitigation property of shielding materials depends on the material thickness (Atwell, 2009). Therefore, it is impossible to shield all electronic systems of the satellite, especially electronic devices which are located outside of the spacecraft. Moreover, thick shielding materials add extra mass to a satellite with weight restrictions.

Therefore, to assure the radiation hardness of microelectronic devices, the radiation effect community developed the radiation hardness test guidelines as MIL-STD-883, Method 1019, JESD57, and ASTM F1192 (Schwank, 2008). Radiation hardness assurance test methods are used to define tests which will provide significant insight into electronic device behavior in radiation environments.

Ionizing radiation test procedure, specified in method 1019 of MIL-STD-883, defines requirements for total dose radiation effects from a cobalt-60 gamma ray source (Spour, 1988). This test is performed in two phases as illustrated on the Figure 4. The first phase of the test is intended to determine parametric or functional failure of an electronic device. Large shifts in threshold voltage, initiated by positive charge trapped in the microelectronic devices, will cause current leakage. This phase of the test requires irradiation at room temperature with a dose rate between 50 and 300 rads(Si)/s until specified dose rate will be reached (Shaneyfelt, 2008). Electrical measurements are required before and after the irradiation process using the same measurement system and sequence (MIL-STD-883, 2010). The second phase requires irradiation of specimens up to 50% of the specified dose, followed by the annealing at 100°C for 168 hours under worst-case conditions. The second phase is used to define worst-case bias conditions (Shaneyfelt, 2008).

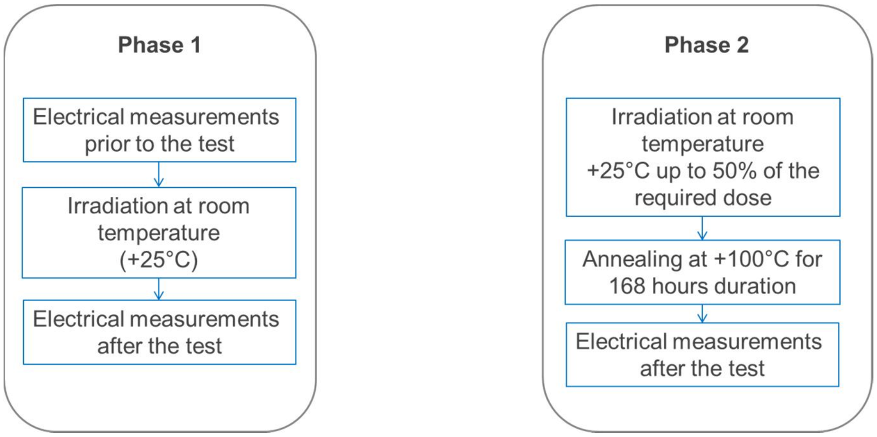

Figure 4: The ionizing radiation test flow phases. *The first phase of the test requires irradiation at room temperature (+25°C) with a dose rate between 50 and 300 rads(Si)/s until specified dose rate will be reached. The second phase requires irradiation of test specimens up to 50% of the specified dose, followed by the annealing at 100°C for 168 hours under worst-case conditions. Electrical measurements are required in both phases before and after the irradiation process using the same measurement apparatus (MIL-STD-883, 2010).*

In the early 1990s researchers found that the degradation level of bipolar transistors and ICs is greater at lower dose radiation rates (Shaneyfelt, 2008). Therefore, enhanced low-dose-rate sensitivity (ELDRS) tests are used on bipolar microelectronic devices for space applications. Devices have to pass ELDRS test performed in the sequence as illustrated on Figure 5. The test procedure for ELDRS requires irradiation dose rate less or equal to 10 mrad(SiO_2)/s and burn-in[1] prior to the radiation test (MIL-STD-883, 2010).

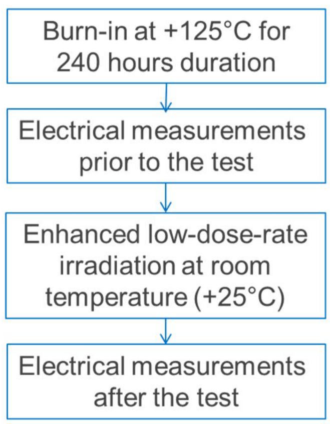

Figure 5: The ELDRS test flow. *The test procedure for ELDRS requires irradiation dose rate less or equal to 10 mrad(SiO_2)/s and burn-in prior to the radiation test. Electrical measurements are required before and after the irradiation process, as well (MIL-STD-883, 2010).*

The Single Event Effect (SEE) is another radiation hardness assurance test which is frequently requested for space application electronic devices. In comparison to other tests, the SEE test

[1] Burn-in is the test process outlined in the military standard MIL-STD-883. This process require electronic devices (test samples) aging at elevated temperature (usually +125°C) for 240 hours. Furthermore, test samples must be in its operational conditions.

refers to single interactions in the electronic component's material, but not to a cumulative effect. In other words, during an SEE test, the tested component may temporarily or permanently stop operating in assigned tolerances. The SEE test may be performed in conjunction with the ionizing radiation test. It can be accomplished by repetition of the first phase of the ionizing radiation test with monitoring of the device output signal and constant irradiation before one of the SEE will occur. Single event effects that are closely monitored during this test are described in the following paragraph.

The first event is called the Single Event Upset (SEU) and is usually referenced to logical errors in memory circuits. For example, a memory cell may change its record from logical 0 to 1 or inverse. Rarely, SEU affects digital signals in logic circuits. The Single Event Latchup (SEL) is the second known effect of the SEEs. A latchup event may be triggered by the deposited charged particle within bipolar transistors. This effect can cause a short circuit state and can be cleared by removing power from the device (Schwank, 2008). The last event is the Single Event Burnout (SEB). This effect is destructive and observed in heavy ion environments when a deposited particle triggered a short circuit event. As a result, the component's circuit is burned out.

III. Radiation Hardness Testing Plan

Since 2011, over 80 percent of PDI space program contracts require suppliers to perform radiation hardness tests. It is clear that the increase of requests for radiation hardness assurance is related to customers' desire to prevent electronic component failures and extend components' life in the natural space environment. Therefore, beginning 2012 PDI offers radiation hardness testing to its clients.

A. Neutron and total ionizing dose test plan

The neutron and total ionizing dose test is performed as one of the screening procedures outlined in military preference MIL-PRF-55310. The radiation hardness testing procedure in MIL-PRF-55310 is referencing another military standard (MIL-STD-883) and has disagreement between standards on the test sample size (MIL-PRF-55310, 2006). In particular, the MIL-STD-883 requires 21 test samples for the neutron and total ionizing dose test, while another military document requires only 4 testing units. The Defense Logistics Agency (DLA) Land and Maritime is aware of this issue and working toward standards revision (Johnnie Schneider, personal communication, April 16, 2012).

Because the screening process of electronic devices is in accordance with MIL-PRF-55310, PDI uses four samples for radiation hardness testing and one control sample to compare shift in electrical parameters (see Figure 6).

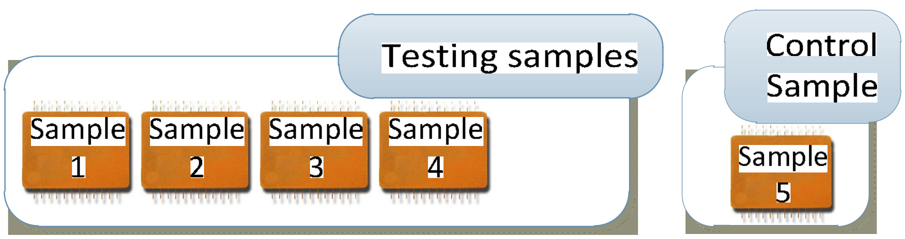

Figure 6: Neutron and total ionizing dose test sample selection. *The figure illustrates two groups of test samples. First group is consists of testing samples and second group consists of control samples. Samples from both groups are electrically tested prior and after the irradiation process. However, the control sample is not irradiated and used to measure shift in electrical parameters of irradiated samples.*

This test is performed in two phases as mentioned before. Both phases of the test are illustrated on Figure 7 and have to be performed as follows:

1. **Phase 1**
   a. Perform electrical measurements of all samples (four test units and one control sample).
   b. Select radiation dose and rate in accordance with Source Control Drawing (SCD) or as specified in military standard MIL-STD-883, method 1019 for particular electronic device design.
   c. Irradiate four test samples to required dose with required rate.

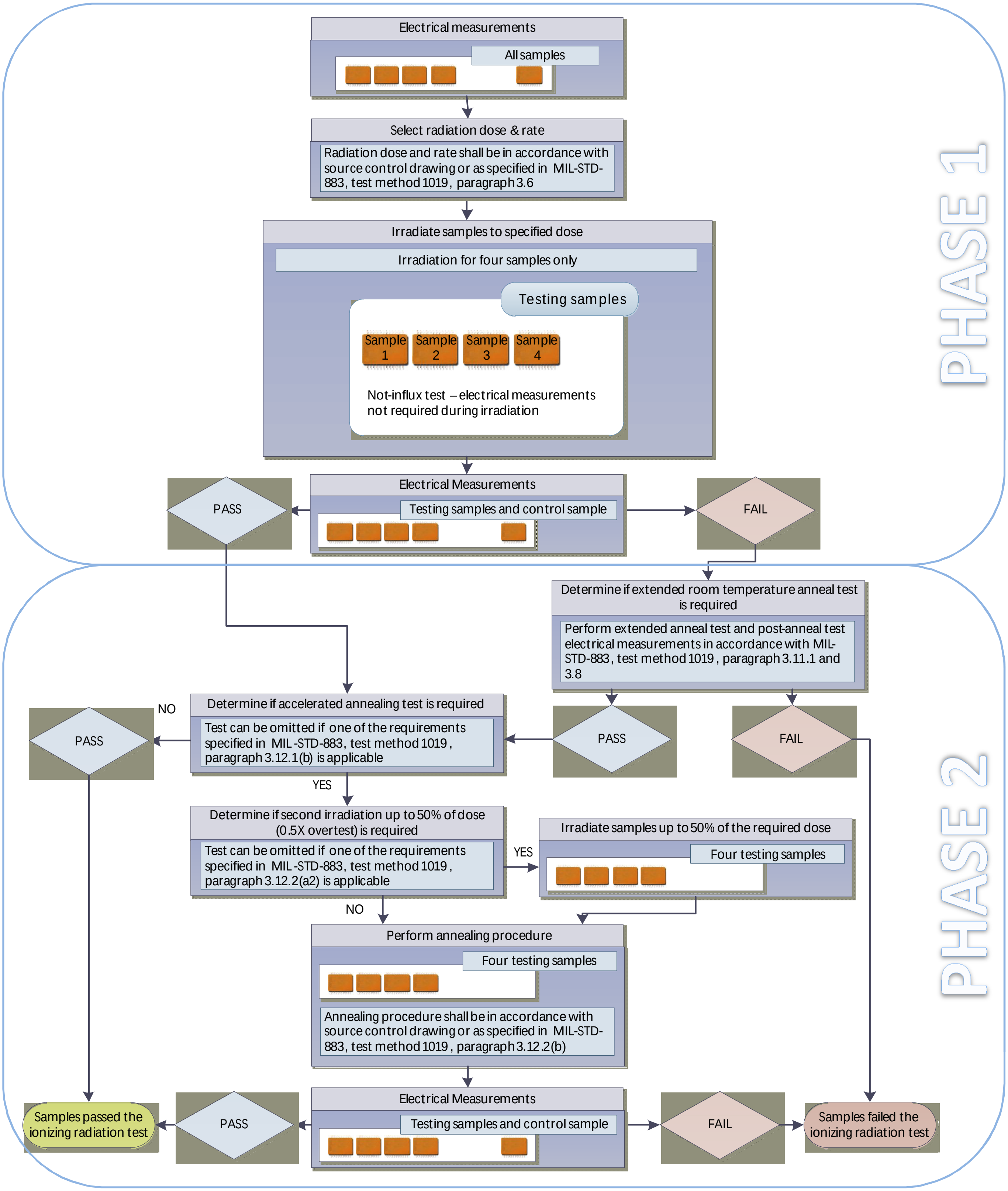

Figure 7: Neutron and total ionizing dose test flow diagram. *The figure illustrates sequence of the ionizing dose test radiation. Adopted from (MIL-STD-883, 2010).*

   d. Perform electrical measurements of all samples (four test units and one control sample).
   e. Analyze electrical data to make pass or fail decision. Extended room temperature annealing test may be used to qualify samples if parametric failure is observed. However, samples must be considered as rejects if functional failure determined (MIL-STD-883, 2010).

2. **Phase 2** (this phase may be omitted if test samples are not designed with metal-oxide-semiconductors (MOS) or if the ionizing dose is below 5krad).
   a. Determine if accelerated annealing test is required using criteria outlined in military standard MIL-STD-883, method 1019 for particular electronic device design.
   b. Irradiate four test samples to 50% of the required dose with required rate.
   c. Perform accelerated annealing test if it required (see step 2a above).
   d. Perform electrical measurements of all samples (four test units and one control sample).
   e. Analyze electrical data to make pass or fail decision.

Estimated time for the test performance is two weeks, since performance of the neutron and total ionizing dose test takes a place at the Crocker Nuclear laboratory at the University California – Davis.

B. Enhanced low-dose-rate sensitivity test plan

Enhanced low-dose-rate sensitivity test (ELDRS) is another test required at screening process for electronic devices which contain bipolar microelectronic devices. As mentioned before, the degradation level of bipolar transistors and ICs is greater at lower dose radiation rates (Shaneyfelt, 2008). Therefore, PDI designed an ELDRS test performance flow chart in accordance with military standard MIL-STD-883, method 1019 (see Figure 8).

It should be noted that the ELDRS test requires burn-in procedure before the test. However, the PDI test plan does not include burn-in procedure because it is performed on a previous screening step and this approach is acceptable in accordance with military preference MIL-PRF-55310. Therefore, the ELDRS test procedure offered by PDI is performed as follows:

1. Perform electrical measurements of all samples (four test units and one control sample).
2. Select radiation dose and rate in accordance with SCD or as specified in military standard MIL-STD-883, method 1019 for particular electronic device design.
3. Irradiate four test samples to required dose with required rate.
4. Perform electrical measurements of all samples (four test units and one control sample).
5. Analyze electrical data to make pass or fail decision.

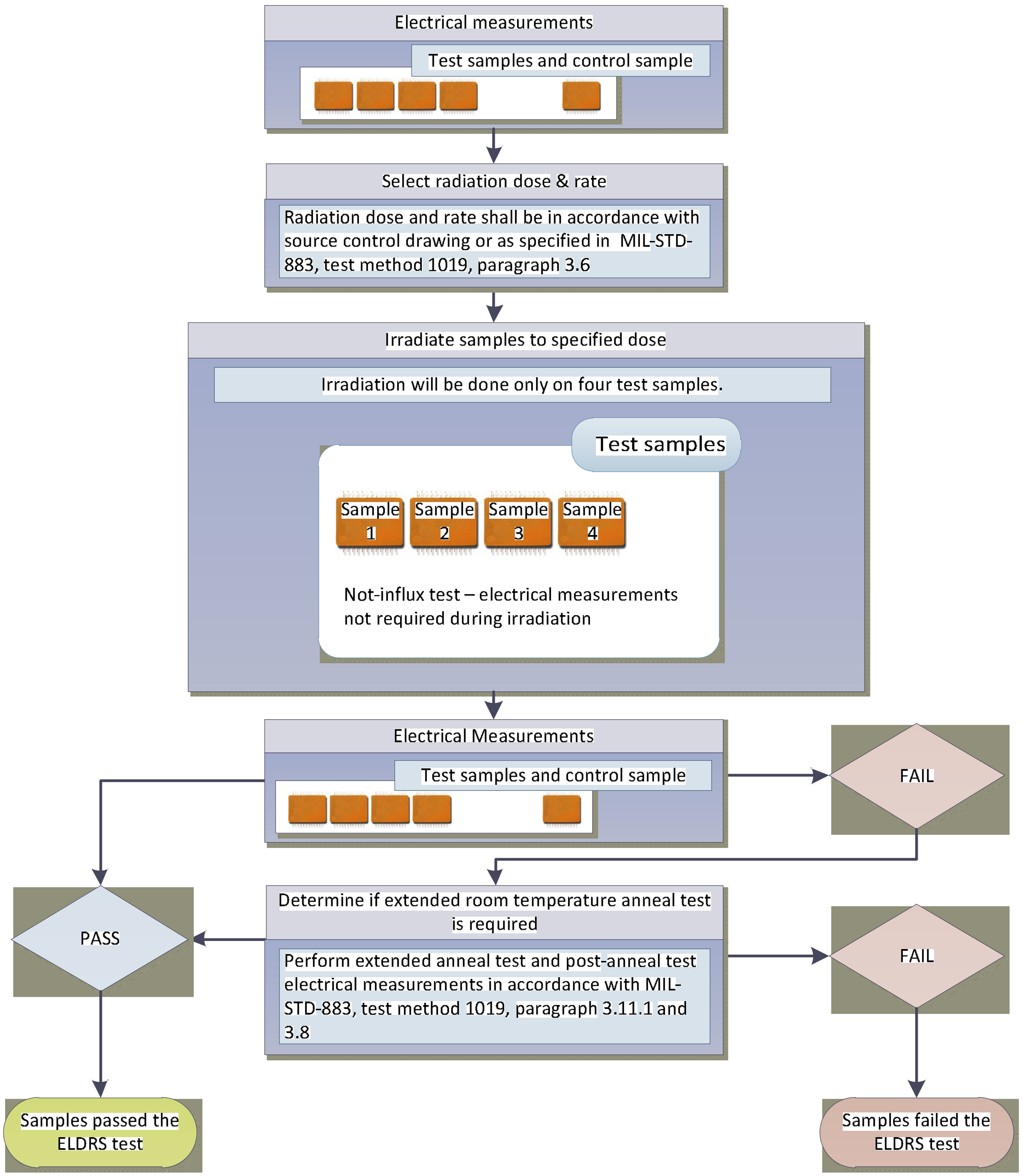

Figure 8: ELDRS test flow diagram. *The figure illustrates sequence of the ELDRS test performance procedure. Adopted from (MIL-STD-883, 2010).*

The ELDRS test is performed after the total ionizing dose test and estimated time for both tests performance is two weeks. Furthermore, it should be noted that total ionizing dose test samples are used for the ELDRS test.

C. Single event effect test plan

The single event effect test is not required in screening process per military preference MIL-PRF-55310. However, PDI adopts this test into a screening procedure because of the SEE test demand on recent contracts. PDI performs this test at Crocker Nuclear laboratory and it can be performed together with other radiation tests.

The SEE test sample size must be defined within the SCD. Testing is performed in accordance with military standard MIL-STD-883, method 1020 as follows:

1. Setup test unit on the front of the radiation beam source.
2. Power up device and verify its electrical parameters in accordance with electrical specification.
3. Irradiate test unit while device in its operating conditions.
4. Stop irradiation when one of the SEEs is identified (ie. upset, latchup, or burnout).
5. Record irradiation time and dose.
6. Determine what type of SEEs was experienced by test unit.
7. Compare test results with radiation requirements outlined on the SCD to determine pass or failure criteria.

Successful completion of the SEE test is the final step in the radiation hardness assurance program for PDI's space application products.

IV. Related Work

In 2005 PDI performed neutron and total ionizing dose testing on crystal oscillators. This test was performed in accordance with MIL-STD-883, Method 1019. The ELDRS test was performed at the same time. The results of these tests were used to qualify PDI's crystal oscillators for space application.

A. Neutron and total ionizing dose test

Six devices were used for this test program (two specimens for each frequency group as shown on Figure 9). One specimen from each frequency group was used as the radiation sample. The second specimen from each frequency group was used as a control sample and were never exposed to radiation (Precision Devices, Inc., 2005).

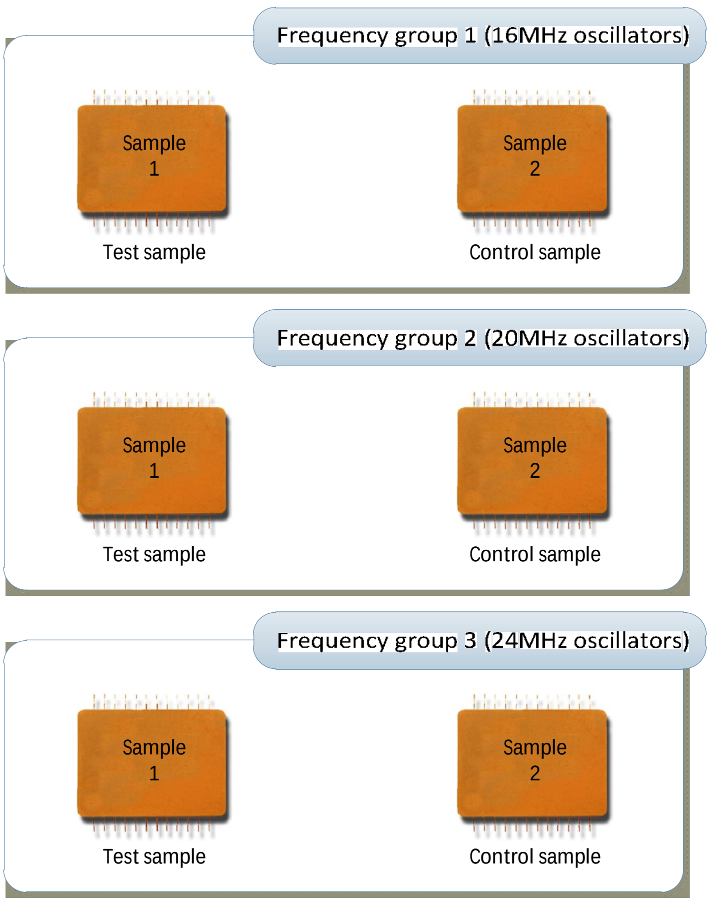

Figure 9: Test sample size selection. *The figure illustrates samples used for radiation hardness testing. Samples are grouped into three different frequency groups. Each frequency group contains one test sample (used for irradiation) and one control sample (never being exposed to radiation).*

The test samples were irradiated and tested in the following sequence:

1. Samples from both frequencies were electrically tested prior to the radiation exposure.
2. Samples from group one were exposed to 1MeV radiation equivalent.

3. Control samples from second group were electrically tested before the irradiated samples to ensure that the electrical test equipment operates properly before testing the irradiated samples.
4. Irradiated samples from the first group were electrically tested to confirm electrical performance in assigned tolerances.
5. Group one samples were irradiated approximately at the 13.7 rad(SiO_2)/s dose rate until 100 Krad(SiO_2) dose was reached.
6. Control samples from the second group were electrically tested before the irradiated samples to ensure that the electrical test equipment operates properly before testing the irradiated samples.
7. Irradiated samples from the first group were electrically tested to confirm electrical performance in assigned tolerances.

Electrical test data provided in Table 2 indicates that the output frequency showed very negligible change in all test samples. Furthermore, the test report states that the output frequency wave form did not change after radiation exposure (Precision Devices, Inc., 2005).

Table 2: Neutron and total ionizing dose test data. *Table shows negligible frequency shifts after exposure to the radiation of 50kRad and 100kRad. Current drifts are in required tolerances (current measurements are not available after exposure to 50kRad dose). Adopted from (Precision Devices, Inc., 2005).*

Sample group	Serial Number	Radiation Target Level	Actual Radiation Level	Frequency shift (Hz)	Current (mA)
1	1	Pre radiation	N/A	N/A	44.5
		3.5e11 n/cm2	3.50E+11	22	48
		50kRad(SiO2)	54.5	79	no data
		100kRad(SiO2)	111.6	126	61
	2	Pre radiation	N/A	N/A	44
		3.5e11 n/cm2	3.50E+11	14	46
		50kRad(SiO2)	54.5	26	no data
		100kRad(SiO2)	111.6	3	47
2	1	Pre radiation	N/A	N/A	48
		3.5e11 n/cm2	3.50E+11	26	51
		50kRad(SiO2)	54.5	37	no data
		100kRad(SiO2)	111.6	116	67
	2	Pre radiation	N/A	N/A	48
		3.5e11 n/cm2	3.50E+11	20	48
		50kRad(SiO2)	54.5	54	no data
		100kRad(SiO2)	111.6	64	50
3	1	Pre radiation	N/A	N/A	40
		3.5e11 n/cm2	3.50E+11	288	50
		50kRad(SiO2)	54.5	456	no data
		100kRad(SiO2)	111.6	566	58
	2	Pre radiation	N/A	N/A	45
		3.5e11 n/cm2	3.50E+11	345	52
		50kRad(SiO2)	54.5	388	no data
		100kRad(SiO2)	111.6	296	60

Evaluation of the test results confirms that the tested oscillators' design is suitable for use in the natural space environment.

B. Enhanced low-dose-rate sensitivity test

Identically to a previous test, the total of six devices were used for the ELDRS test. One specimen from each frequency group was used as the radiation sample. The second specimen from each frequency group was used as a control sample and was never exposed to radiation (Precision Devices, Inc., 2005).

The test samples were irradiated and tested in the following sequence:

1. Samples from both frequencies were electrically tested prior to the radiation exposure.
2. Group one samples were irradiated with 0.05 rad(SiO_2)/s dose rate until a 50 Krad(SiO_2) dose was reached.
3. Control samples from the second group were electrically tested before the irradiated samples to ensure that the electrical test equipment operates properly before testing the irradiated samples.
4. Irradiated samples from the first group were electrically tested to confirm electrical performance in assigned tolerances.

The report concludes that the output frequency showed very negligible change in all test samples. Furthermore, the test report states that the output frequency wave form did not change after radiation exposure (Precision Devices, Inc., 2005). Therefore, oscillators were considered suitable for space application.

V. Conclusion

In 2012 PDI made the decision to adopt a radiation-hardening-by-process method into a screening process of space application products. The radiation hardness testing helps PDI's design engineers develop high-reliability products for space applications. In addition, implementation of the radiation hardness assurance program is constantly increasing PDI's client base in the aerospace market. Furthermore, knowledge of radiation hardness process helped PDI to receive approval from Defense Logistics Agency Land and Maritime to begin the qualification process for class K (highest class of hybrid microcircuits for space application) space products.

VI. Notes

A. Acronyms and abbreviations

DLA	Defense Logistics Agency
ELDRS	Enhanced low-dose-rate sensitivity
GCR	Galactic Cosmic Rays
IC	Integrated Circuit
ISS	International Space Station
MeV	Meg electron Volt
MOS	Metal-oxide-semiconductors
NASA	National Aeronautics and Space Administration
PDI	Precision Devices, Inc.
QML	Qualified Manufacturing List
RHBD	Radiation-hardening-by-design
RHBP	Radiation-hardening-by-process
SCD	Source Control Drawing
SEB	Single Event Burnout
SEE	Single Event Effect
SEL	Single Event Latchup
SEU	Single Event Upset
SPE	Solar Particle Event

VII. Bibliography

Atwell, W., Boeder, P., Wilkins, R., Gersey, & B., Rojdev, K. (2009). Analyses of Several Space Radiation-Mitigating Materials: Computational and Experimental Results. *SAE Technical Paper 2009-01-2338*. Retrieved from: http://papers.sae.org/2009-01-2338

Barnaby H.J. (2005). Will Radiation-Hardening-by-Design (RHBD) Work? *Nuclear and Plasma Sciences News*.

Department of Defense. (2006, March 31). *Performance specification*. Retrieved February 19, 2012, from http://www.dscc.dla.mil/Downloads/MilSpec/Docs/MIL-PRF-55310/prf55310.pdf

Department of Defense. (2010, February 26). *Test method standard for microcircuits*. Retrieved February 19, 2012, from http://www.dscc.dla.mil/Downloads/MilSpec/Docs/MIL-STD-883/std883.pdf

Enlow E.W., Pease R.L., Combs W., Schrimpf R.D., & Nowlin R.N. (1991). Response of advanced bipolar processes to ionizing radiation. *Nuclear Science, IEEE Transactions on, 38(6), 1342-1351.*

Fleetwood, D.M. (1998). Total ionizing dose effects on MOS and bipolar devices in the natural space radiation environment. *SAE Technical Paper SAN098-2040C.*

Fleetwood, D.M., & Eisen, H.A. (2003). Total-dose radiation hardness assurance. *Nuclear Science, IEEE Transactions on, 50(3), 552- 564.*

Precision Devices, Inc. (2005, December 9). *ELDRS test report*. Retrieved March 8, 2012, from PDI intranet database.

Precision Devices, Inc. (2005, November 3). *Neutron and total dose test report*. Retrieved March 8, 2012, from PDI intranet database.

Precision Devices, Inc. (2012, March 8). *Space Heritage*. Retrieved March 8, 2012, from PDI intranet database.

Schwank J.R., Shaneyfelt M.R., & Dodd P.E. (2008). Radiation Hardness Assurance Testing of Microelectronic Devices and Integrated Circuits: Radiation Environments, Physical Mechanisms, and Foundations for Hardness Assurance. *Sandia National Laboratories Document SAND-2008-6851P*.

Shaneyfelt, M.R., Schwank, J.R., Dodd, P.E., & Felix, J.A. (2008). Total Ionizing Dose and Single Event Effects Hardness Assurance Qualification Issues for Microelectronics. *Nuclear Science, IEEE Transactions on , 55(4), 1926-1946.*

Shelfer, T., Semones, E., Johnson, S., Zapp, N., Weyland, M., Riman, F., ... Smith, G. (2002). Active Radiation Monitoring on the International Space Station. *SAE Technical Paper 2002-01-2456.*

Spour, J.R., & McGarrity, J.M. (1988). Radiation effects on microelectronics in space. *Proceedings of the IEEE, 76(11), 1443-1469*.

Stern D.P. (2001). Radiation Belts. Retrieved from The Exploration of the Earth's Magnetosphere Blog, http://www.phy6.org/Education/Intro.html