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Board Level Proton Testing Book of Knowledge for NASA Electronic Parts and Packaging Program

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Board Level Proton Testing for NASA Electronic Parts and Packaging Commercial- off-the Shelf Book of Knowledge

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ABSTRACT

This book of knowledge (BoK) provides a critical review of the benefits and difficulties associated with using proton irradiation as a means of exploring the radiation hardness of commercial-off-the-shelf (COTS) systems. This work was developed for the NASA Electronic Parts and Packaging (NEPP) Board Level Testing for the COTS task.

The fundamental findings of this BoK are the following. The board-level test method can reduce the worst case estimate for a board's single-event effect (SEE) sensitivity compared to the case of no test data, but only by a factor of ten. The estimated worst case rate of failure for untested boards is about 0.1 SEE/board-day. By employing the use of protons with energies near or above 200 MeV, this rate can be safely reduced to 0.01 SEE/board-day, with only those SEEs with deep charge collection mechanisms rising this high. For general SEEs, such as static random-access memory (SRAM) upsets, single-event transients (SETs), single-event gate ruptures (SEGRs), and similar cases where the relevant charge collection depth is less than 10 μm , the worst case rate for SEE is below 0.001 SEE/board-day. Note that these bounds assume that no SEEs are observed during testing. When SEEs are observed during testing, the board-level test method can establish a reliable event rate in some orbits, though all established rates will be at or above 0.001 SEE/board-day.

The board-level test approach we explore has picked up support as a radiation hardness assurance technique over the last twenty years. The approach originally was used to provide a very limited verification of the suitability of low cost assemblies to be used in the very benign environment of the International Space Station (ISS), in limited reliability applications. Recently the method has been gaining popularity as a way to establish a minimum level of SEE performance of systems that require somewhat higher reliability performance than previous applications. This sort of application of the method suggests a critical analysis of the method is in order. This is also of current consideration because the primary facility used for this type of work, the Indiana University Cyclotron Facility (IUCF) (also known as the Integrated Science and Technology (ISAT) hall), has closed permanently, and the future selection of alternate test facilities is critically important.

This document reviews the main theoretical work on proton testing of assemblies over the last twenty years. It augments this with review of reported data generated from the method and other data that applies to the limitations of the proton board-level test approach.

When protons are incident on a system for test they can produce spallation reactions. From these reactions, secondary particles with linear energy transfers (LETs) significantly higher than the incident protons can be produced. These secondary particles, together with the protons, can simulate a subset of the space environment for particles capable of inducing single event effects (SEEs). The proton board-level test approach has been used to bound SEE rates, establishing a maximum possible SEE rate that a test article may exhibit in space. This bound is not particularly useful in many cases because the bound is quite loose. We discuss the established limit that the proton board-level test approach leaves us with. The remaining possible SEE rates may be as high as one per ten years for most devices. The situation is actually more problematic for many SEE types with deep charge collection. In cases with these SEEs, the limits set by the proton board-level test can be on the order of one per 100 days. Because of the limited nature of the bounds established by proton testing alone, it is possible that tested devices will have actual SEE sensitivity that is very low (e.g., fewer than one event in 1×10^4 years), but the test method will only be able to establish the limits indicated above.

This BoK further examines other benefits of proton board-level testing besides hardness assurance. The primary alternate use is the injection of errors. Error injection, or fault injection, is something that is often done in a simulation environment. But the proton beam has the benefit of injecting the majority of actual SEEs without risk of something being missed, and without the risk of simulation artifacts misleading the SEE investigation.

Proton testing is often used to establish the displacement damage dose (DDD) and total ionizing dose (TID) capabilities of components and systems. For the types of missions considering this approach, it is expected that they are of short duration (less than one year) and consider the solar flare risk to be essentially mission-ending. It is also assumed they are not being positioned into a high-TID environment (for example, mid-Earth orbit). Because of these expectations, the potential impacts of DDD and TID are not considered in this BoK.

1.0 INTRODUCTION

This document is a book of knowledge (BoK) intended to summarize and present the relevant material available regarding to board level testing of commercial-off-the-shelf (COTS) systems using proton exposure. We refer to this method as the proton board level test method (PBTM). This work is focused on development of knowledge base for the NASA electronic parts and packaging program (NEPP). The purpose is to provide information to help establish the validity of this type of testing for hardness assurance reasons and to explore the other benefits provided by this type of testing. We have limited this BoK to information made available over the last twenty years, in hopes of keeping it relevant.

1.1 Current Applications

The PBTM is currently being applied in a limited way for hardness assurance. It is used for a significant amount of systems to be used in lower criticality applications on the International Space Station (ISS) [1]. It is also being used to establish basic radiation performance on brief missions such as ISS resupply, where reliable operation is only required for periods of time shorter than a day. The PBTM is also being considered for testing of CubeSat systems, where the budget is so low that even PBTM will put significant strain on funding.

Proton exposures (different from PBTM) are used to test fault tolerance (FT). FT is built into both space applications and high reliability terrestrial applications. This fault tolerance is often simulated with custom hardware or software capable of injecting environment-like faults [2]. Simulation of faults is heavily dependent on having an accurate model of the faults a system can manifest. Usually, however, the processes of developing software FT and testing devices for fault modes are decoupled, and often FT is developed against a reasonable simulation without actually knowing what hardware on which the FT system will be used. Proton testing of FT systems provides a useful way of determining the effectiveness of FT¹. Hardware is also designed with fault tolerance (for example, parity is common in level 1 (L1) microprocessor caches, and error detection and correction (EDAC) is common in level 2 (L2) microprocessor caches). Hardware fault tolerance can be tested/verified using protons as the medium for fault injection.

1.2 Principal Method Explored

PBTM is a low cost alternative to device-level radiation testing that exposes full assemblies or boards to 1×10^{10} p/cm² [1-2]. But, as we will discuss, it provides very minimal data and very loose bounds (which may be very conservative). When designing electronics for space systems it is important to understand the effects the electronics will exhibit—especially when those effects are not in the set of behaviors the manufacturer designed the device to handle or produce. For high reliability operations, testing is performed on individual devices in order to provide a list of behaviors that flight electronics designers must handle. This type of device-centric isolation provides a clear boundary between device behavior and system design that enables definition of behaviors and makes it relatively easy to define system response. That is, device-centric radiation data provides a clear delineation that enables system-level understanding – by enabling tracking of specific behaviors through the system structure. Individual device testing for radiation response is necessarily rather expensive, especially when considering all devices used in a system.

PBTM does not enable the collection of device-level behaviors. It does not provide estimates of rates for device behaviors (unless event rates are on the order of 1/day), so, except for very common events, it can only provide a relatively conservative upper bound on possible space rates for events such as device failure. It does not empower designers with boundaries of the performance of individual devices. But the overall approach does enable rapid evaluation of full system performance in a very mild terrestrial test setting. And as we shall see later, PBTM provides evidence that a system will have a relatively high probability of performing for a period of 100–1000 days in the very benign ISS environment. Application to any other

¹ Generally speaking, this requires that the tested systems are sensitive to protons or secondary heavy ions from proton collisions. This generally requires sensitivity to LETs below 20 MeV-cm²/mg.

orbit or trajectory necessarily results in lower confidence and reduced expected days of operations—possibly lowering rate limits to only a few days between events.

Device-level radiation testing for SEE is intended to collect signatures and rates for various upset behaviors a device can exhibit. PBTM, on the other hand, is intended to provide a screen for effects that cause failure of a system, and to a lesser extent provides stimulus to inject single-event upsets (SEUs) into a system. SEUs injected into a system can be studied, and if a significant enough number of them are observed, a rough estimate of how often they will be observed in flight can be determined (though in order for a statistically significant sample to be collected, during PBTM testing, the DUT must manifest a significant sensitivity to upset from protons— but this then indicates a very high rate for upsets during flight.

PBTM thus is useful for determining behavior of systems within a very narrow window. Individual device behaviors can be much more varied than PBTM can highlight. However, PBTM can provide test data for ten times less cost than individual device testing. And since it provides system behaviors, it can actually be very desirable for a flight project team. It is important to note, however, that lack of experienced radiation test operators can result in loss of any benefit in cost due to unexpected redundant testing and damage to test articles.

Another important issue for this BoK is the availability of facilities for this type of work. The primary facility being used for this type of testing currently is the Indiana University Integrated Science and Technology (ISAT) hall (formerly the Indiana University Cyclotron Facility [IUCF]). ISAT was effectively closed in late 2014, requiring finding new options for proton testing.

1.3 Alternate Proton Board-Level Testing

Testing of boards with protons can be performed with a different set of goals. The PBTM discussed above is targeted at setting specific bounds on SEE types that may be observed when a system is placed in the ISS orbit. However, proton testing of boards and assemblies can be conducted with other goals in mind. In this document we will discuss the limitations placed by the PBTM ($1 \times 10^{10}/\text{cm}^2$) approach, when used in different environments and test contexts.

PBTM is well-situated for producing loosely bounded upper limits on possible space event rates in the ISS orbit. But 200 MeV (or other energy) protons can also be used for board-level testing in the following ways. First, it can provide very rough information on whether a board or system has significant rates for damaging effects from SEE. It can be used for fault injection—by putting upset SEEs (e.g., single bit upsets [SEE], single event transients [SETs], etc.)— into the system and observing the response. The only significant problems with using protons for this type of testing are the limited sampling of space-like particles and linear energy transfers (LETs), possible hardware difficulties (such as ensuring protons are not traversing down the edge of the chip, which can lead to erroneous results), and ensuring that the operation of the test board close matches its operation in space.

Unfortunately, the best data that can come out of a proton board-level test—the PBTM or other types of tests—requires observing many upsets. This is because significant numbers of upsets can be closely correlated to estimated space rates of the observed upset types. However, systems upsetting this frequently will be very difficult to operate in a space application.

1.4 Purpose of BoK

This BoK is focused on critical review of the $1 \times 10^{10}/\text{cm}^2$ PBTM and similar approaches to estimating or bounding space rates for SEEs on full boards or assemblies. We surveyed available literature and communicated with several primary organizations involved in this type of testing, including Johnson Space Center (JSC).

In this document we will explore and analyze the material available and present conclusions about this type of testing. This method is gaining in popularity, partially due to increased use of pre-built COTS assemblies

and partially due to efforts to reduce cost. This BoK takes the position that the PBTM and similar uses of proton beams as sole radiation assurance testing will be used, at least in limited cases. Thus, the approach here is not to try to show that these methods are good or bad, but rather to discuss their merits in various environment and mission design situations.

1.5 Document Layout

This BoK will review materials related to board-level proton testing and application of this type of testing. The material we cover pertains to a general use practice that is currently applicable for low criticality programs running on the ISS. For this type of program, several reports regarding systems and devices running in this type of test are available. We will review these, as well as counter or breadth arguments such as the example of the HM65162 16 kb static random-access memory (SRAM), which would pass the proton board level test some of the time but would readily fail in ISS orbit with a mean time between failures (MTBF) of about 100 days.

Because of the possible uses of proton board level testing, there are a lot of sub-topics to cover. This BoK is arranged as follows. First we provide background information on the primary methods of testing and the limitations of their application-to-event rate calculation, focusing on available literature. We then discuss the PBTM and other board-level proton test approaches. A simple example is used to illustrate the situation in the following section. This BoK then concludes with some information regarding recommended future work.

2.0 PROTON BOARD-LEVEL TEST METHOD

This section presents background on proton testing of boards and systems for SEE. We begin with a brief presentation of the most relevant environment for using the PBTM. Then we review available literature and materials that describe or explain methods that use proton testing to establish mission reliability. This is divided into a general discussion of how particles cause upsets and then a discussion of proton interactions with device materials. Then we discuss how proton testing can increase what is known about SEE response beyond the case of no testing. Then we review the PBTM, providing details about how it works. We then discuss alternate uses of proton board level testing. Key limitations of the approach are discussed in detail in Section 3.

2.1 Review of Available Materials

This section discusses key materials and information available that form the basis of PBTM. We focus on environment, testing, proton generation of upsets and secondary particles, material specifically on PBTM, and the expected benefit achievable with PBTM.

2.1.1 Environment Discussion

SEE sensitivity is critically important for space missions. The SEEs occur because of individual particles in the space environment that can cause circuits to perform incorrectly or become damaged. We begin this section by reviewing the environments of interest for spacecraft and explaining our focus on the ISS orbit. In general we must know the number of particles that pass through the components in a spacecraft during a given time period. In practice, we require the estimated fluence of particles in two different forms—the number of protons, with their energy spectrum; and the number of heavy ions, with their LET spectrum. This information is specific to the orbit or trajectory of a spacecraft and is generally time dependent. In addition, natural environments also include a chance of particle contribution from solar flares. For this work we focus on the environment of the ISS to keep the document focused and enable direct use of most of the relevant reference material.

The ISS orbit is at 51.6° inclination with varying altitude, generally taken to be about 400 km. The environment is composed primarily of low- to moderate-energy protons and heavy ions. The protons are due to a combination of galactic cosmic rays and Earth's inner trapped particle (Van Allen) belt, with a significant portion coming in a region known as the South Atlantic Anomaly (SAA) where the inner belt dips into the ISS orbit. There is also a small component of high energy galactic cosmic rays (GCRs), but they primarily have low LETs and are only important when the question of shielding is considered because shielding increases their LETs. The proton spectrum is given in **Figure 2-1**, and the heavy ion LET spectrum is given in **Figure 2-2**.

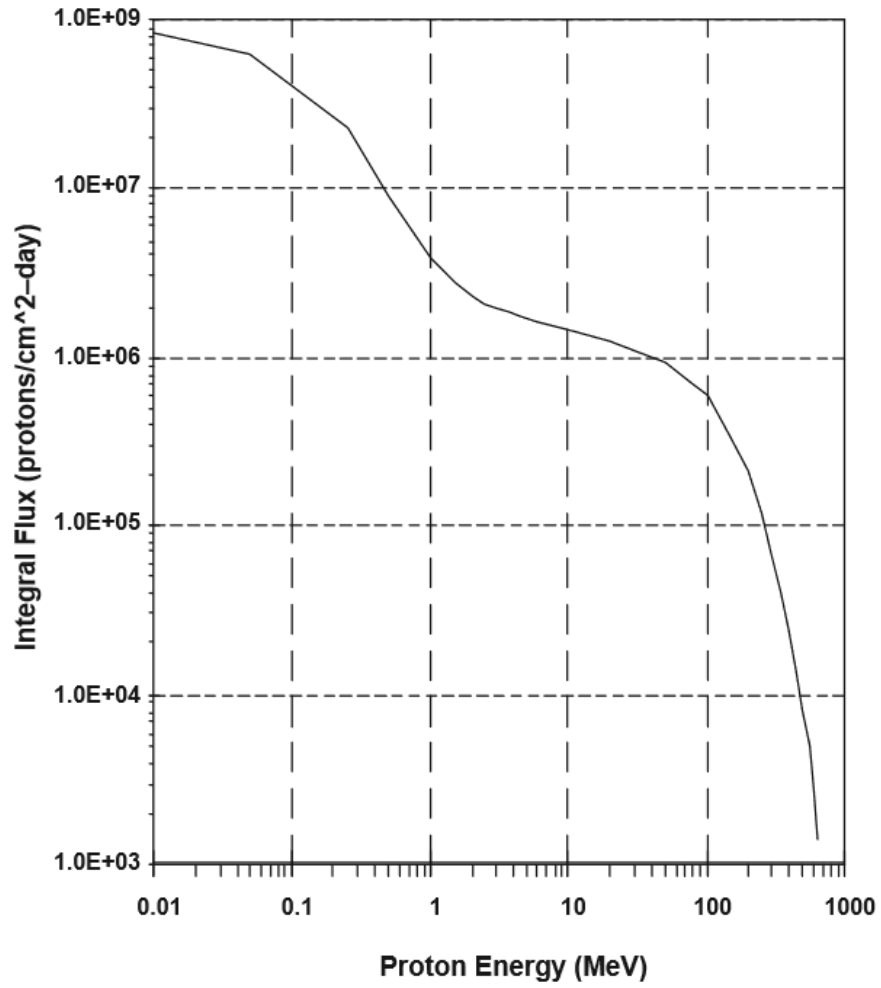


Figure 2-1. The integral proton flux spectrum for the ISS orbit , excluding flares Boeder 1994 [3]). Note that by 200 MeV the spectrum is falling off very quickly.

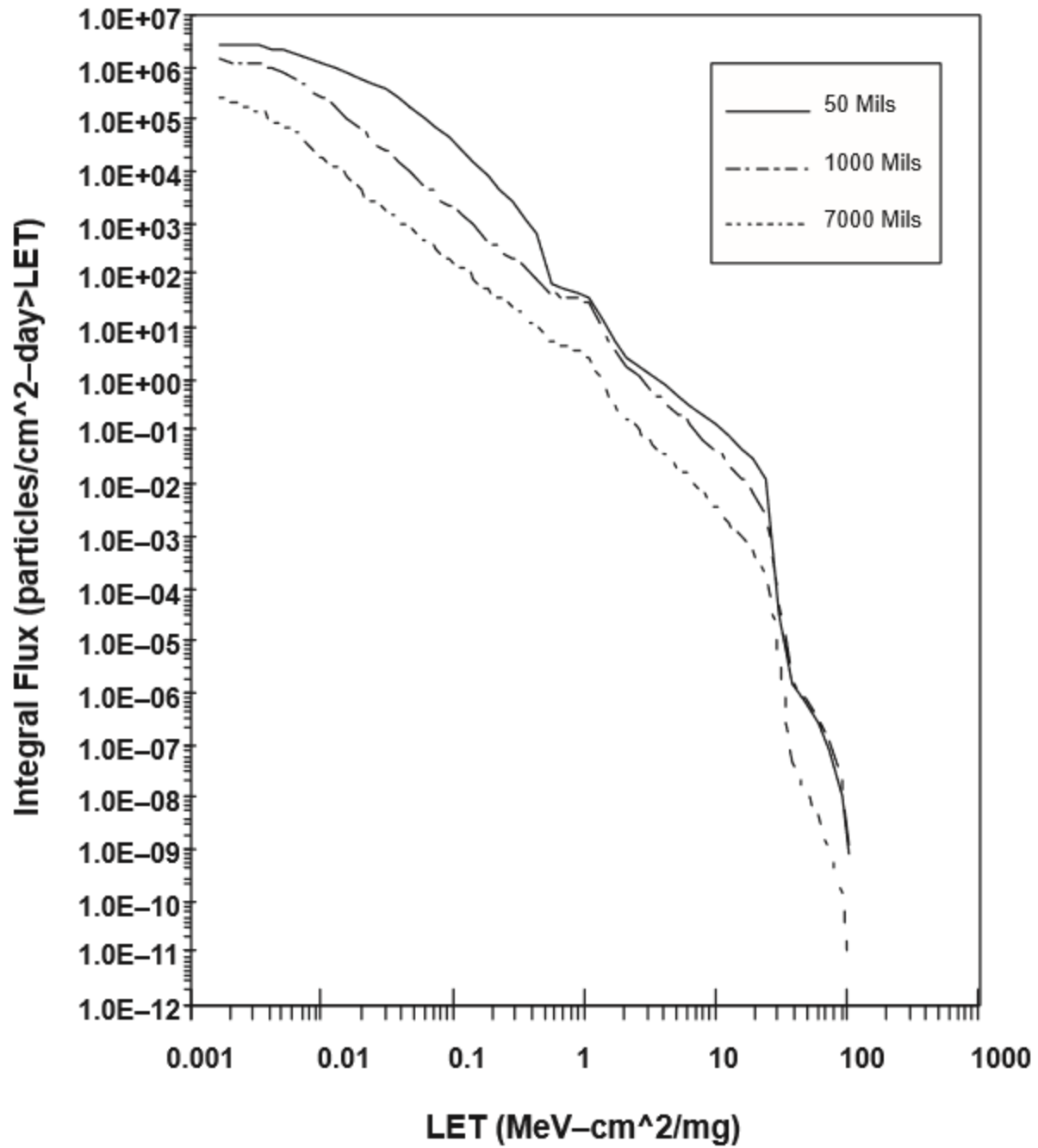


Figure 2-2: Integral LET spectrum for the ISS orbit behind various amounts of aluminum shielding (Boeder 1994 [3]).

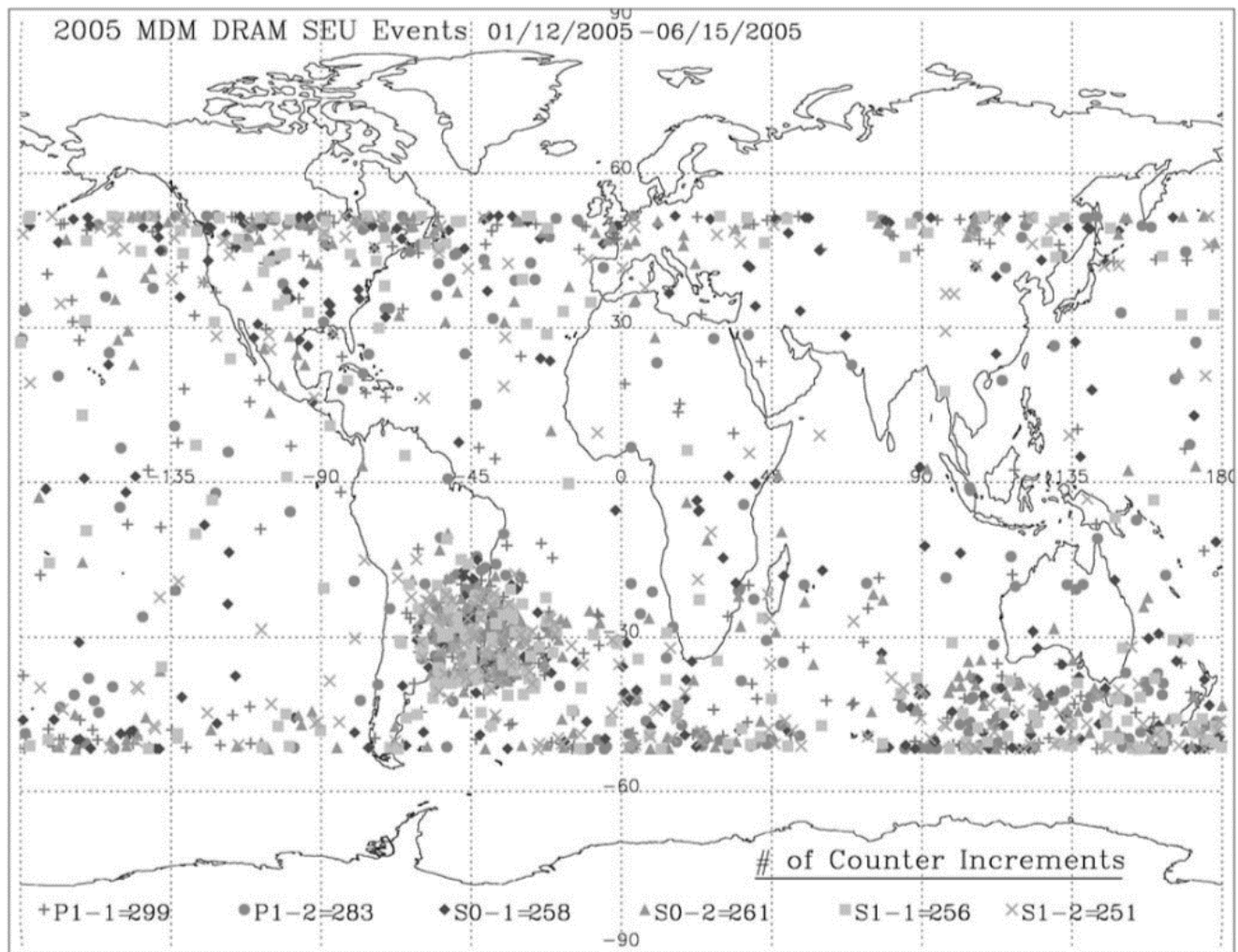


Figure 2-3: Example of upsets in DRAMs - showing correlation with higher latitudes and the SAA (koontz2005 [4]). © 2005 IEEE

An example of the distribution of particle interactions in the ISS environment can be seen in the DRAM upsets reported by Koontz and shown in **Figure 2-3** [4]. The increasing GCR contribution at the higher latitudes can be seen by the increase in the density of errors there. Also, the SAA is obvious by the clustering of errors near Brazil, Argentina, and Uruguay.

As stated above, this document is limited to the case of the ISS environment, in order to keep the material focused. The arguments do apply to other environments with the general understanding that the greater the GCR component in the environment (and therefore reduced geomagnetic shielding), the less effective PBTM will be. This occurs because PBTM works best when the majority of the environment consists of particles with LETs below $15 \text{ MeV-cm}^2/\text{mg}$, and protons with low- to moderate energies. The two environments where PBTM may work better than for the ISS (for determining SEE sensitivity) are low-inclination low Earth orbit (LEO), and middle Earth orbit (MEO). They are both expected to have very little GCR component, but MEO missions are expected to have much stronger parts-level radiation requirements due to total ionizing dose (TID).

Solar flares are a component of the ISS orbit. When they occur they may or may not affect satellites near Earth because individual flares do not cover the entire orbit of the Earth. Generally, if a flare is likely to hit Earth, satellites are intentionally commanded into a low vulnerability mode, because a large portion of the SEU-sensitive components in the satellite will likely upset. This upset sensitivity is especially true for

COTS. When a flare hits, systems have to expect a very high number of upsets will occur. The ISS environment during a solar flare is augmented by both protons and heavy ions, with proton energies possibly well over 1 GeV, and heavy ion LETs similar to the GCR spectrum. The heavy ion solar flare spectrum is given in **Figure 2-4** from [3]. In the case of solar flares, shielding does help significantly. At 50 mils of aluminum shielding, however, the solar flare orbit-averaged maximum heavy ion fluence for LETs below 20 is increased more than 1000 times that of normal. Because spacecraft that have been planned to survive a solar flare must have a known TID response of components, solar flares are essentially outside of the planning of any mission utilizing PBTM. For this reason, and the expectation that the spacecraft is largely powered down during a flare, we do not discuss them further.

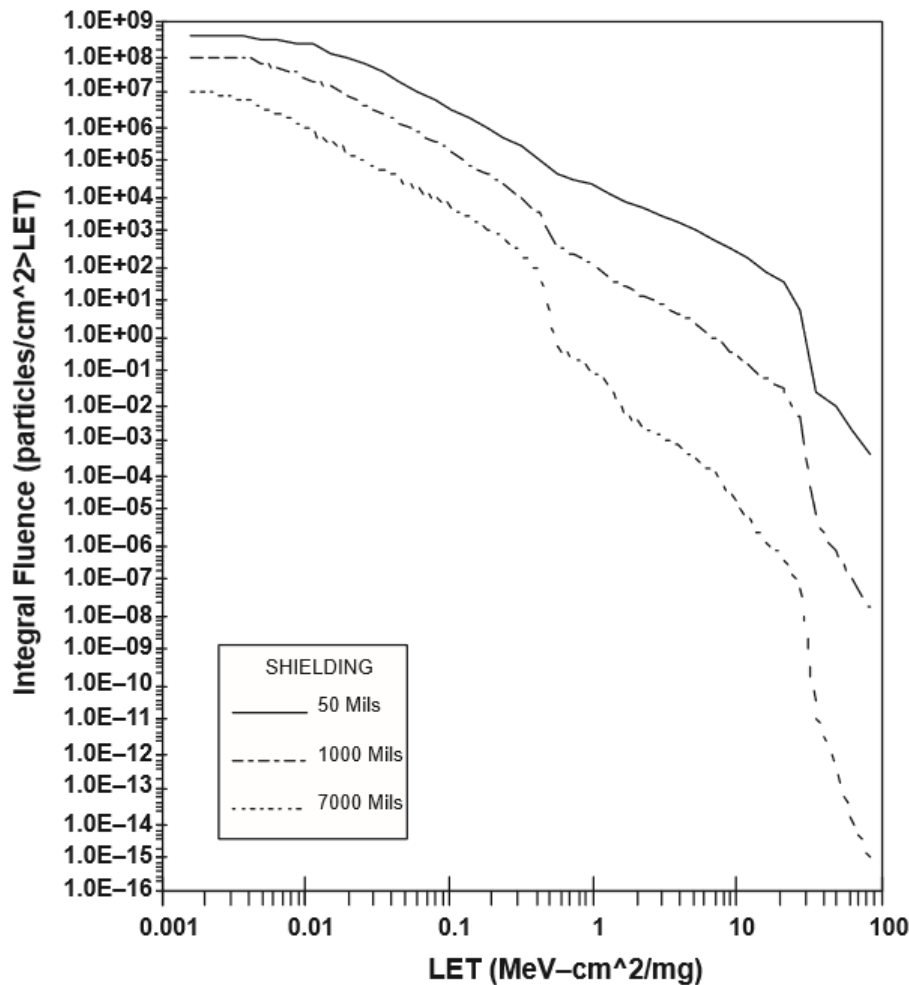


Figure 2-4: Maximum solar flare orbit-averaged integral heavy ion fluence [3].

2.1.2 Shielding

Generally it is expected that shielding will significantly reduce radiation effects with a “workable” increase in mass. This is not true for SEE. The reason is that shielding is most effective at reducing TID, by stopping particles that are moving very slowly. But those particles do not cause significant SEE risk. Instead, SEE is primarily caused by high energy particles that require at least inches of material to significantly attenuate. Furthermore, protons are most effectively shielded by low atomic number (Z) material, while heavy ions are most effectively shielded by high-Z material. So there is no mass-efficient shielding material to stop all SEE-causing particles in the space environment. As a practical example of this, **Figure 2-4**, above, shows the difference between 50, 1000, and 7000 mils of aluminum shielding on the LET spectrum experienced

in electronics in the ISS orbit (without flares) [3]. The difference between one and seven inches is about a factor of ten decrease in particles across the entire spectrum. In contrast, usually at least 50 μm of Aluminum is used to shield spacecraft in the ISS environment because this clearly reduces the TID below 1 krad/year – but the difference between 50, and 1000 μm is not significant above 1 $\text{MeV}\cdot\text{cm}^2/\text{mg}$, except for a reduction of perhaps a factor of 3 between 3 and 15 $\text{MeV}\cdot\text{cm}^2/\text{mg}$.

2.1.3 Normal EEE Parts Testing for Critical Applications

EEE parts must have known or bounded radiation response, within the mission parameter envelope. It is important to highlight that this document is focused on SEE only, and that issues regarding appropriateness of proton testing for TID or displacement damage are not relevant here. Under a full program for evaluating the SEE risk of EEE components, often a full evaluation of single-event latchup (SEL) and SEE performance is performed over a full range of simulated environmental particles. This means that a device is either tested for both heavy ion sensitivity as a function of LET and proton sensitivity as a function of energy; or it is tested for one of these two, and the results are then used to provide a limit for the response of the system to the other.

The main issue at question in this BoK is the suitability of protons to be used in ground testing intended to simulate the space environment. SEEs are often taken to occur when a threshold of generated charge, called the critical charge [Q_{crit}], is exceeded during the passage of a charged ion through a sensitive volume (SV) [5,6]. The general picture is shown in **Figure 2-5**.

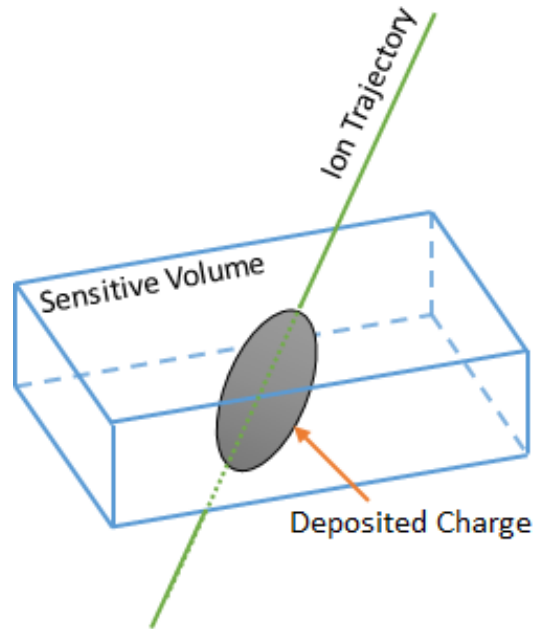


Figure 2-5: Ions passing through matter leave an ionization trail. When the charge is released in a sensitive volume it can result in an upset if it exceeds the critical charge.

The ionization produced per unit path length by the ion in the SV, the LET, is dependent on the ion's atomic number, energy, and the material it is going through. This is given by the Bethe-Bloch equation given below. (1) is relativistic, (2) is non-relativistic.

$$-\frac{dE}{dx} = \frac{4\pi n z^2}{m_e \beta^2 c^2} \left(\frac{e^2}{4\pi \epsilon_0} \right)^2 \left(\ln \left[\frac{2m_e \beta^2 c^2}{I(1-\beta^2)} \right] - \beta^2 \right), \quad (1)$$

$$-\frac{dE}{dx} = \frac{4\pi n z^2}{m_e v^2} \left(\frac{e^2}{4\pi\epsilon_0} \right)^2 \left(\ln \left[\frac{2m_e v^2}{I} \right] \right), \quad (2)$$

In these equations z is the charge of the moving ion, E is its energy, n is the electron number density in the target, I is the mean excitation potential, c is the speed of light, β is the speed of the particle divided by c , v is the velocity of the particle, ϵ_0 is the permittivity of the vacuum, e is the electron charge, and m_e is the mass of the electron. LET is dE/dx normalized to the density of the target material. The charge deposited is proportional to the product of the LET and the distance the ion travels through the SV (the chord length).

A key element of the theory of equivalence of terrestrial and space SEE is that this LET is constant throughout the SV, which is the case when the energy is not changing significantly. When determining a mission's expected environment, the distribution of ions as a function of LET is based on ions that have, on average, the LET observed. If the LET is changing during ground testing, then the correct LET to assign is not obvious.

Ground-based proton testing can cover the entire range of proton energies observed in LEO due to trapped particle belts [3]. When being used to explore the sensitivity of devices to heavy ions, however, proton secondaries lack some key properties. The secondaries are key to the approach as the incident proton has a maximum LET of 0.01 [TRIM/SRIM]. We will discuss this in more detail in section 3. The key for now is to point out that nuclear reaction secondaries produced from 200 MeV proton interactions have relatively short range, and during their transit of the SV their LET may be changing significantly.

In practice, several efforts to find ways to use heavy ion data to predict proton rates, and vice-versa, have been pursued [7,8,9]. Aside from rare proton situations, such as tungsten plugs [10], using heavy ions to provide rough estimates for the worst case proton sensitivity has been relatively successful. Alternately, for some classes of parts and representative technologies (i.e., those with a small charge collection volume), protons provide a good estimate of heavy ion sensitivity [11,12]. In some important cases, however, proton test results are not good for predicting heavy ion sensitivity [13], especially in cases where no events are observed. This is particularly true when the effect is dependent on long ion ranges, such as for SEL [14].

Although proton testing is not necessarily good for predicting heavy ion sensitivity. It is possible that a proton test can enable a relatively inexpensive bound on total radiation sensitivity. A proton test of an entire board can be less expensive than a heavy ion test on a single type of device on the same board. Thus, the PBTM is an effort to bound the possible response of a system for which very little SEE information is known. The relevant issue, however, is the following. If PBTM can establish an upper bound for system SEE sensitivity, how does this bound differ from what must be assumed if no SEE test data exists on some or all of the components in the system. Both of these bounds are discussed later in Sections 2.3 and 2.4.

There are two situations that can arise from proton testing. Either upsets are not seen, or they are seen. In the former case, the previous paragraph applies. But in the case where upsets are observed, proton testing can often provide useful rate estimates for environments with both heavy ion and proton contributions. This happens because an SEE that is observed with protons is likely to have sensitivity to heavy ions with LETs in the range of 2–12 MeV-cm²/mg, with the effect largely saturated by LETs above 10 MeV-cm²/mg, and in this range proton secondaries do provide a good distribution of injected ion LETs.

2.1.4 Proton Interactions in Materials

Protons can produce low-energy secondary ions with relatively large atomic number (Z). These particles then have fairly large LET because of the z^2 dependence in the stopping power (see equation 1). But these secondary ions have low energy in terrestrial testing because of kinematic limitations. Low energy means that the ions are depositing energy very quickly and about to stop. In this range, the ion's LET is changing rapidly. In order to establish the appropriateness of proton secondaries to simulate the space environment for high LET particles, it is important to have the two following pieces of information in mind: (1) the rough

size of sensitive volumes for SEE; and (2) the range over which the particle has a slowly-varying LET. In this section we discuss material that establishes these.

As a specific example, relatively high energy transfer can occur in the proton + Si elastic collision where the collision is head-on with the Si nucleus starting at rest and having final momentum in the direction the proton had initially. In this case, the non-relativistic version of conservation of momentum results in the following equation (3) for the energy of the outgoing Si nucleus.

$$E_{Si} = E_p \frac{4m_p m_{Si}}{(m_p + m_{Si})^2}, \quad (3)$$

where m_p is the mass of the proton, m_{Si} the mass of the silicon nucleus, and E_p is the initial kinetic energy of the proton. In the case of 200-MeV protons, the outgoing energy of the silicon nucleus is 26.6 MeV. This corresponds to an LET of approximately 14 MeV-cm²/mg, but a very short range.

Significant studies of the reaction products of protons in a primarily Si target have been performed by Heimstra (2003) [15] and Schwank et al. (2005) [10]. In particular, Heimstra is a detailed study of the energies and LETs that are produced as proton secondaries. A plot of LET versus range is given in **Figure 2-6** for reaction products from 500-MeV protons, which is evidenced by the maximum range of Si given as about 25 μm— corresponding to an energy of about 65 MeV. Note that many ions other than Si can be produced. A more detailed discussion of reactions is available in Messenger and Ash (1997) [5].

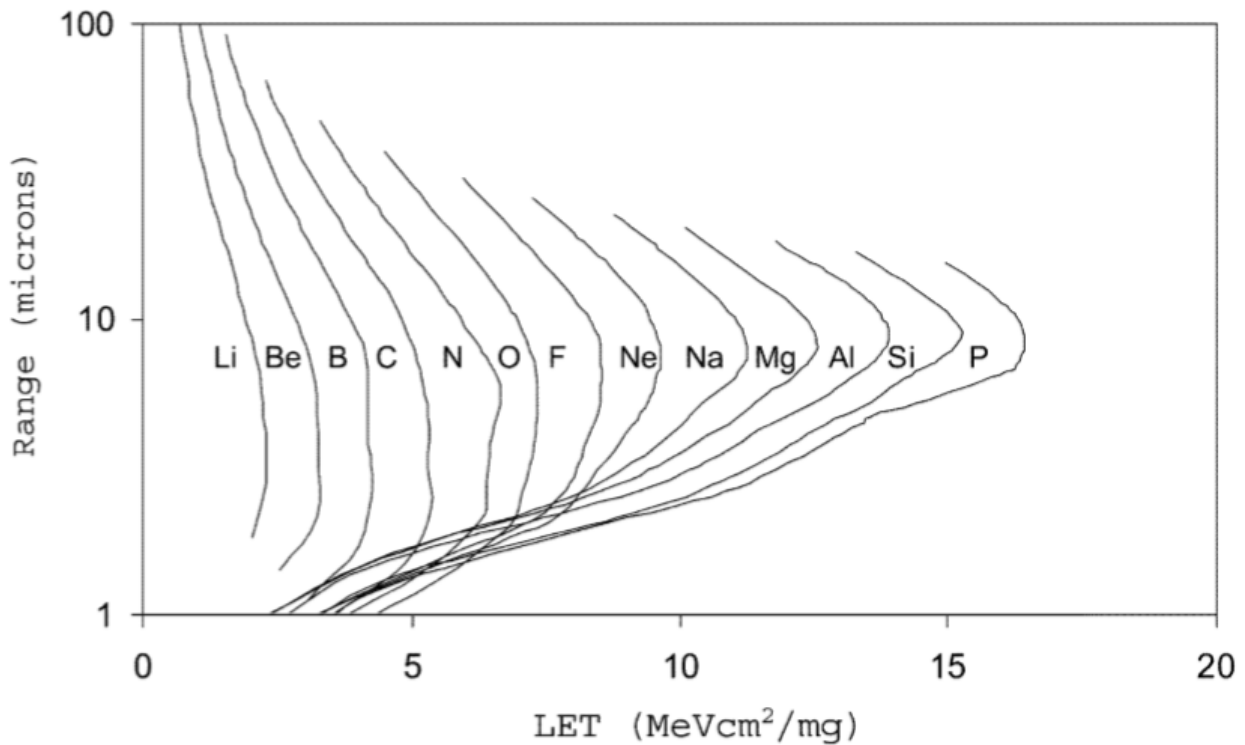


Figure 2-6: Range versus LET for ions generated in 500 MeV proton interactions in Si devices (Heimstra 2003 [15]). © 2003 IEEE

The most important considerations relative to these reaction products are the ranges and relative abundances produced at a given range as a result of $1 \times 10^{10}/\text{cm}^2$ of 200-MeV protons. This is discussed as a difficulty with PBTM in Section 3.

Another issue to cover is that protons can interact with atoms other than silicon in a target device. There are also dopant atoms and metals used in bonding the device to the external pins. If these atoms are involved

in the process of creating secondaries, the LET of the secondaries can be considerably higher than the phosphorus limit in **Figure 2-6**. This is explicitly explored in the case of tungsten (W) plugs [Schwank 2005].

2.1.5 Review of PBTM Materials

This section briefly lays the groundwork for the current situation regarding PBTM. More detail is developed later in this section. The key elements of the approach discussed here were developed by the Johnson Space Center (JSC) in an effort to improve the situation of electronics with no known evaluation of radiation sensitivity. The first relevant paper that discusses this test method is O’Niell (1997 [8]). This paper draws from two other important predecessors. Specifically, in Petersen (1992) [7] the relationship between proton energy threshold and heavy ion LET threshold is drawn, allowing calculation of proton rates from heavy ion data and vice versa, but acknowledging the idea is to estimate rates generally, but not catch outlier cases. Second, in McNulty (1994) [16], a careful study of the spallation reaction spectrum resulting from protons impinging on a silicon device was performed.

After the initial discussion of the method, a few supporting papers were made available. In O’Niell (1998) [17] the applicability of PBTM is extended, indicating a very low chance that any SEE with a rate higher than 1 per 10 years would not be observed during $1 \times 10^{10}/\text{cm}^2$ irradiation with 200 MeV protons. The method was reviewed using a Monte Carlo simulator to explore more of the stages of the nuclear interactions. In Foster (2008) [18] the method of calculating LEO MTBF is examined from the perspective of energy deposition.

The most significant problem with using proton testing to estimate heavy ion upset contributions in various orbits is the relationship between the spectrum produced by proton exposures and the natural spectrum which includes high LET particles. O’Niell (1997) [8] pointed out that the test method necessarily does not determine sensitivity to part of the natural spectrum, with about twenty particles per year having no effective simulation by the proton recoil spectrum. This was studied in Heimstra (2003 [15] with an evaluation of all ions produced during the exposure as discussed in Section 2.1.4. The specific findings regarding how many particles are not simulated is not well agreed upon. This is one of the key difficulties discussed in section 3.

In addition to the issues with mismatching range and changing ion LET, there are also modern device questions. The initial work was based on earlier technologies, and did not focus on SEL and SET in more modern devices. Koga et al. (2002 [19] performed a detailed exploration of this problem. It should be noted that the general concern of unknown, possibly very complex, interaction between proton and heavy ion upset sensitivities was found to be worse for new technologies. Additional counterexamples of the comparison were provided in Edmonds (2002) [20] and [Normand 2004]. It can only be inferred that technologies in the last decade continue to have the risk of not having well-defined relationships between proton and heavy ion SEE sensitivity.

The key material reviewed above relates to events with deep SVs where no upsets were observed during testing. However, many upsets will be observed during testing. But the majority of these will result in misbehavior of the system with no permanent failures. Of course, depending on the system architecture, a simple microprocessor hang can be mission ending. Based on O’Niell (1998) [17] and several papers that discuss predicted proton and heavy ion event rates in the many different types of devices [Normand (2004) [21],[Koga et al. (2002) [19], [Allums (2012)[1]], and others, it is clear that devices that upset during PBTM will have largely predictable on-orbit rates because the ISS orbit includes a significant proton fluence. and additional GCR proton and heavy ion exposure will also contribute to the error rate. Foster et al. (2008) [18] provides specific information regarding how to calculate the LEO MTBF by first measuring the device proton cross section at 200 MeV, then apply the energy deposition distribution method (EDEPDIST) to develop a modified cross section that takes into account how well the proton 200-MeV energy deposition spectrum matches that of the ISS environment particles. Examples from [Foster 2008] are provided in **Table**

2-1 below. Note that the corrected cross section is derived from the EDEPDIST method. Also, Weibull parameters are developed to enable calculation of the LEO MTBF. It is clear, from the table, that some devices will have upsets more than once per day. Note that this list of example devices is several years old, and modern systems are expected to have even higher potential ISS-orbit upset rates (e.g. tens of SEUs/SEFIs per day).

Table 2-1: Cross sections from proton testing, EDEPDIST, and Peterson FOM, are compared. Predicted MTBF is developed using the NASA Johnson Space Center code HIZ Badhwar (1996) [22]. The HIZ MTBF is given, as is the multiplication factor for the case of no upsets is also given. Weibull parameters based on the EDEPDIST method are available in (Foster et al. (2008)) [18]. This table is from Foster et al. (2008) [18]. © 2008 IEEE

Part #	Part ID	Measured Device P Xsection (cm ² /Device)	EDEPDIST Calculated P Xsection (cm ² /Device)	Petersen FOM P Xsection (cm ² /Device)	LEO HIZ MTBF (Days)	M Multiplier Factor	LEO - 1 SEU in 1E10 p's MTBF (Years)
1	93L422_AMD	3.14E-07	4.31E-08	1.38E-07	5.71	23.68	7.40
2	93L422_Fairchild	1.42E-07	7.98E-08	2.55E-07	3.30	25.10	4.81
3	2164	4.61E-07	2.13E-07	2.99E-07	1.75	23.40	11.14
4	1601_Epi	9.00E-08	6.09E-08	2.74E-08	13.81	7.43	5.49
5	OW62256	8.70E-08	1.01E-07	6.94E-08	12.14	6.70	5.60
6	SMJ44100	7.00E-07	6.92E-07	7.83E-07	0.96	19.33	6.57
7	62256	1.47E-07	1.89E-07	9.23E-08	4.13	12.43	7.95
8	IBM_16MEG	2.12E-08	1.75E-08	9.91E-09	187.55	4.57	27.75
9	MT4C1004C	3.94E-07	6.15E-07	3.91E-07	1.50	15.40	6.48
10	KM41C4000Z-8	3.27E-07	4.78E-07	2.75E-07	1.96	14.75	7.57
11	01G9274	4.19E-09	6.56E-08	3.77E-09	374.81	3.74	33.76
12	MT4C4001	2.94E-07	5.43E-07	3.13E-07	1.40	16.48	6.97
13	HM6116	4.59E-08	2.63E-08	1.38E-08	40.40	4.82	7.63
14	62832H	2.89E-08	1.89E-08	1.15E-08	78.74	4.70	16.92
15	2901B	8.50E-10	9.66E-10	6.65E-10	791.77	2.02	9.74
16	TC514100Z-10	1.00E-06	1.26E-06	7.79E-07	0.37	31.10	6.60
17	HM_65656	2.98E-08	5.63E-08	3.47E-08	16.84	8.98	19.01
18	MB814100_10PSZ	6.90E-07	1.06E-06	1.14E-06	0.56	21.65	5.13
19	HYB514100J-10	1.46E-06	1.68E-06	1.31E-06	0.26	34.70	5.91
20	LUNA_C	2.12E-08	2.99E-08	1.65E-08	119.56	4.84	20.14
21	D424100V-80	1.76E-06	1.59E-06	1.68E-06	0.25	34.06	5.63
22	PowerPC603_Reg	4.59E-10	7.36E-10	4.06E-10	1742.16	2.08	39.51
23	PowerPC603_Cach	3.12E-08	1.65E-08	1.05E-08	57.34	6.96	34.35
24	HM6516	2.46E-09	5.23E-09	3.32E-09	212.77	3.16	15.67
25	Xilinx VII FPGA_CONFIG MEM	8.68E-08	6.54E-08	3.33E-08	4.90	30.50	51.79
26	Xilinx VII FPGA_Blk_RAM	2.98E-08	2.32E-08	1.91E-08	14.66	19.80	51.91

2.1.6 When No Upsets Are Observed

One of the possible observations during PBTM testing is to not observe any upsets. In this case, based on the discussion above, we know that the device has been exposed to a significant number of particles with LETs up to 15 MeV-cm²/mg. However, we do not know what types of upsets the device may be sensitive to and what the appropriate SVs might be. For this reason it is difficult to know exactly what the limiting cross sections might be for various event types. However there are some worst case and most common limits that have been studied. These can be somewhat understood in the context of the energy deposition method of Foster et al. (2008) [18] where the energy deposited in the SV is considered. Under this approach, the primary issue is to understand how much energy may have been deposited in the sensitive volume.

Although other SEE types may be of concern, the most significant SEE type of concern here is SEL. This is because SEL can have a very long charge collection depth. An example of how this can be a problem is shown in Dodd et al. (2007) [14] where the threshold LET for SEL was found to be about two times lower when ions with higher energy (but the same LET) were incident on the DUT.

Rather than establish a theoretical working point for the worst case SEL risk, we take the approach of focusing on devices with known SEL sensitivity that may pass PBTM with no observed proton SEL sensitivity. We consider two devices. The first is the HM65162, discussed in Edmonds (2000) [13] – the 1985 device. This device is known to have a proton cross section of 1.4×10^{-10} cm²/device. Thus it has a

reasonably high chance of being missed during a PBTM test with $1 \times 10^{10}/\text{cm}^2$ exposure. This device has an SEL rate of 0.01/device-day. This is not the only device with this type of SEL rate. Table 2 below can be used to find some alternatives, such as the NEC4464, which has an SEL rate of about 0.005.

For upsets that have relatively shallow charge collection depth, PBTM can be coupled to the method described in O’Niell (1998) [17]. where the expected MTBF is roughly 2000 days/# of SEE observed during testing. But where you take the number of SEEs as 1 (or, alternately, the 2-sigma upper bound for observing 0 SEEs, which would be 3.7). So the MTBF can be taken as 2000 days (or 540 days for the 95% confidence interval). We use the value 0.001/device-day for the remainder of this BoK.

It should be noted that PBTM is known to be of limited value for critical systems because of the fact that protons cannot be guaranteed to behave like heavy ions. Thus there is the clear possibility of unexpected sensitivities being missed during this testing (i.e., PBTM necessarily has known deficiencies that can be tested and should not be left unexplored in critical systems). The use of PBTM is recommended for non-critical systems only [8].

2.1.7 If Upsets Are Observed

For event types that are observed, PBTM provides a more straightforward way of determining event rates in space. This happens because of the abundance of protons in the ISS orbit, and may not apply easily to other orbits. The difficulty is in determining the relationship between proton cross section with 200-MeV protons, and event rates with the full proton spectrum. This, unfortunately, is only approximately correct without detailed information about the SV of the observed event type. The most basic approach is to employ the PROTEST solution (O’Niell, 1998) [17], which is approximated by an MTBF of $2000/N$ days, where N is the number of events observed when exposing the device or system to $1 \times 10^{10} \text{ p/cm}^2$. For more detailed study, it is possible to determine a proton cross section curve and apply the Bendel method (see Bendel and Petersen (1983) [23]).

In the case where upsets are observed, the test system then also becomes a platform for error injection. If useful, engineers can use this test scenario to explore how errors are handled. This is discussed in more detail in Section 2.4.

2.2 Why PBTM Is (Nearly) Optimal

PBTM may be considered as an approach to the multidimensional optimization problem of reducing potential risk of a system through limited testing. Although clearly performing more tests at the device level, deducing the specific device behaviors and expected rates, would yield more complete data, as an approximate approach PBTM sits in a narrow range. We will explore these issues in this section. The first element to the discussion is that PBTM is not likely to result in excessive TID exposure. The second is that ions with LETs in excess of $10 \text{ MeV-cm}^2/\text{mg}$ are produced in the active components. The third is that the beam range used for PBTM is at a relative sweet-spot in terms of availability (or at least was before the closure of IUCF). The final point is that PBTM utilizes beams that are near the cutoff of the energy spectrum in the LEO orbit.

There are two reasons why the $1 \times 10^{10}/\text{cm}^2$ PBTM approach is an optimal (or nearly optimal approach). The first is that $1 \times 10^{10} \text{ p/cm}^2$ at 200 MeV results in about 600 rads of exposure. (In contrast, $1 \times 10^{10} \text{ p/cm}^2$ of 50-MeV protons would result in approximately 2,000 rads of exposure. Although there are some devices that degrade with only 600 rads, they are rather rare. But failures with dose become much more common as the dose increases. The dose is proportional to the dE/dx in Silicon, which is shown in **Figure 2-7**. With this figure it can be seen that increasing proton energy results in decreasing dose for a fixed fluence, up to proton energies around 2–3 GeV.

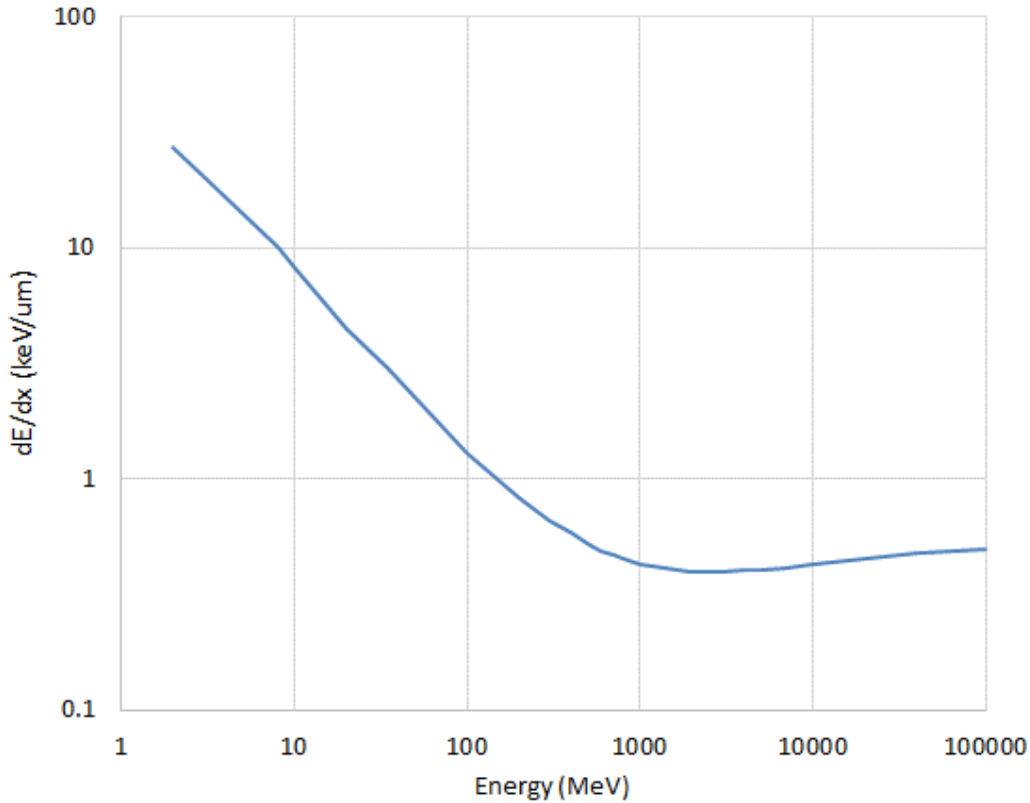


Figure 2-7: dE/dx of protons in Si - calculated from Bethe-Bloch.

As indicated above, the dose would be lower for the same fluence if the energy were increased to 2–3 GeV. However, availability of beams is another important part of the optimization problem. There are some locations, such as the Tri University Meson Facility (TRIUMF) and the Los Alamos Neutron Science Center (LANSCE) that can provide beams above the 200–250 MeV range of typical cyclotrons [24,25]. Realistically, it is currently unknown what facility availability will be in the near future due to the IUCF closure. Higher energies (above 2 GeV) may be available from specialized facilities but are generally much more expensive than the typical rates for cyclotrons producing protons in the 200–250 range. It should be noted that this range is also a standard range for proton medical treatment facilities and may prove to be readily available from many sources [26].

The third reason the PBTM approach is nearly optimal is that 200-MeV protons are capable of producing secondary heavy ions with LETs (at the point of production) above 10 MeV-cm²/mg. The spectrum of produced particles has been explored, primarily through the use of Monte Carlo simulation tools and is reported in [31] and [32]. The spectrum of LETs due to various recoil particles is shown in Figure 6 above [15]. The approximate production of particles with a given LET or higher when a device is exposed to 1×10^{10} p/cm² is shown in **Figure 2-8** [8].

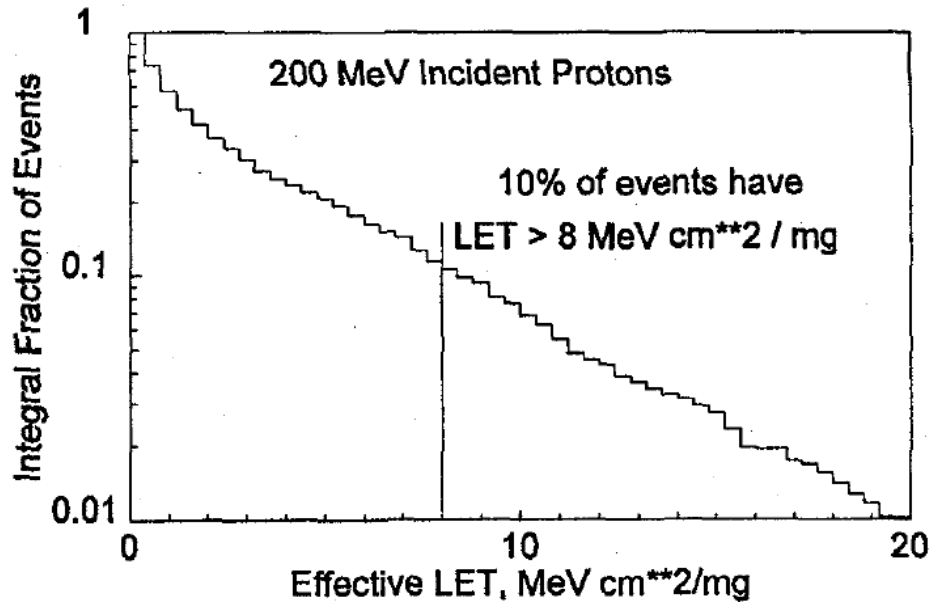


Figure 2-8: Fraction of events that produce at least a given LET, due to exposure to 200 MeV protons (from O’Niell et al. (1997) [8]. © 1997 IEEE

2.3 Where We Are with No Testing

As discussed above, the reason PBTM is used is to reduce the risk of flying a system without comprehensive SEE test data. In the case where there is no SEE testing is performed for a system, there is usually some knowledge of the SEE sensitivity of many of the parts. For the sake of discussion, we focus on a typical system. Without justification, but based on engineering experience, we assume a typical system has approximately 65 components. So the question becomes, about how many of these components can be expected to have some SEE data, and how many may be the critical ones for the worst case SEE estimations. And of the worst case devices, how bad are they? A rough survey of how these devices may be triaged is in order. In a typical system, many of the devices will have no data, but will come from known product lines that have common, or at least bounded behavior. For example, some devices will be known to be constructed on an epitaxial layer or silicon on insulator (SOI) and will therefore exhibit reduced or no sensitivity to SEL (in any case the sensitivity will be below what can be established by the proton test).

Based on experience triaging parts lists, it is expected that 2/3rds of the parts, or about 40 of the 65, will have enough existing data that SEE performance can be bounded to be better than the worst case established by the PBTM. The remaining 25 or so parts, however, may have problems. Most likely the remaining questionable devices will include a handful of unknown logic gates, a handful of power control devices such as metal oxide semiconductor field-effect transistors (MOSFETs), 10–15 or so memory devices – including flash and electrically erasable programmable read-only memory (EEPROM), SRAM, and DRAM, and a handful of special single instance devices. The special, single instance devices include field programmable gate arrays (FPGAs), microprocessors, microcontrollers, and other application-specific ICs (ASICs). There may also be a few devices with SET sensitivity. Generally, it is necessary to analyze these devices in a generic way, but focused on a couple classes of SEEs.

Without testing, there are three primary types of SEEs that the system may be sensitive to which must be considered. The most important SEEs of interest are damaging SEEs. These include single-event gate rupture (SEGR) and single-event burnout (SEB), SEL, and a few other (potentially) permanent failure modes. Second is the single event functionality interrupt (SEFI) which may or may not be possible to recover without a power cycle. And third are single-event upsets (SEU). Many SEUs will manifest as SEFIs,

and for system sensitivity reasons, they will be treated as SEFIs here. So SEUs are specifically those events that manifest as a bit flip that is isolated but may result in a calculation error or similar effect. SETs are often not important by themselves (though they can sometimes cause damage), but they can manifest a system behavior of SEFI or SEU.

Table 2-2 provides SEL information compiled from many sources [21]. In **Table 2-2**, the onset LET is L_0 , the saturated cross section is σ_{HI} limit, the shape parameter is s , and the width parameter is w . Petersen (1998) [12] provides the figure of merit (FOM) and limiting cross section for proton SEL ($\sigma_{SEL}(Ep)$ limiting), along with details about the source of the data in the paper. We take the specific case of the DSP96002, where $\sigma_{HI} = 0.49 \text{ cm}^2$. $L_0 = 0.1 \text{ MeV-cm}^2/\text{mg}$, $S = 4.5$, and $W = 21.4$. Using this, with the Creme 96 rate calculation code Tylka (1997) [27], we obtain a nominal rate for SEL of $1.54 \times 10^{-2}/\text{device-day}$ (assuming a width to depth ratio, L , of 0.2 for the rectangular parallelepiped [RPP]), and a worst-case of $7.14 \times 10^{-2}/\text{device day}$ (for $L \sim 0.01$).

In addition to this, Schwank et al. (2006) [28] provides proton cross section data for several SRAMs, including a 180- μm SRAM with a proton cross section of $2 \times 10^{-8} \text{ cm}^2/\text{device}$. Based on the PROTEST approach (discussed in the next section), this device would have a predicted SEL rate of 0.1/device-day. It should be noted that the cross section for this device increases with angle of incidence, so it is reasonable to predict this device may have an even higher SEL rate.

A similar event rate can be inferred from proton test data on SEGR and/or SEB, where devices experiencing permanent failure due to these mechanisms under protons have inherently high failure rates. With these failure mechanisms, device sensitivity depends significantly on the implementation, so systems not designed for radiation environments are more likely to show these problems. Under some scenarios, devices have been observed to have mean time to failure (MTTF) of 0.1/device-day and exhibit failures in proton testing with cross sections on the order of $1 \times 10^{-8} \text{ cm}^2$.

Certainly there is no guarantee that a device with SEL or SEGR/SEB performance this bad will actually be part of the system. However, without testing and without other information to support robust design arguments, this type of failure rate must be inferred. Thus, a reasonable worst case MTTF for a system not tested with the PBTM would be on the order 0.1/board-day.

Table 2-2: Tabulation of parts susceptible to SEL with information about proton SEL sensitivity (from Normand (2004) [21]). (References cited in the table are to that document.) © 2004 IEEE

Device	σ_{HI} Limit	Lo	W	S	FOM	σ_{SEL} (Ep) Limiting	Ref. for data
Cat. 1 Devices w/ Measured Proton SEL Cross Section							
HM65162-85	0.02	2.30	8.48	3.33	3.0×10^{-4}	4×10^{-10}	10
LCA200K	0.047	3.90	20.9	1.96	2.1×10^{-4}	2.3×10^{-11}	11
NEC 4464-JPL	0.12	1.00	18.5	3.78	5.8×10^{-4}	2×10^{-10}	7, 8
NEC 4464-ESA	0.13	1.00	35	1.3	6.2×10^{-4}	2×10^{-9}	6
K-5	0.29	0.10	54.1	3.34	2.06×10^{-4}	6.6×10^{-9}	8
LSI-64811	0.2	1.40	35.8	4.44	2.49×10^{-4}	1.7×10^{-11}	8
DSP 96002	0.49	0.10	21.4	4.51	1.82×10^{-3}	4.5×10^{-9}	12
32C016	0.05	1.20	42.3	2.51	6.83×10^{-5}	1×10^{-9}	8
TC55VD386	0.012	1	10.8	0.36	6.6×10^{-3}	4×10^{-8}	13, 14
AMD486 §	0.14	2.51	45	4.70	1.1×10^{-4}	3.5×10^{-10}	15, 16
Cat. 2 Devices Exposed to Protons, No Measured Proton SEL							
AD7664†	0.0012	7.0	35.0	3.0	1.56×10^{-6}	N/A	17
87C51FC†	0.014	10.0	80.6	3.3	3.26×10^{-6}	"	18
ADSP2181†	0.0086	1.7	59.6	3.7	4.43×10^{-6}	"	19, 20
EPM5128‡	0.0064	5.6	45.7	2.6	5.55×10^{-6}	"	21,22,23
EPM7256‡	0.0011	7.1	10.0	0.5	1.7×10^{-5}	"	22,23,24
LTC1272£	1.1×10^{-4}	5.1	11.9	8.96	1.36×10^{-6}	"	25,26
XA1ASIC-bulk†	0.0037	6.5	13.7	2.42	1.7×10^{-5}	"	25, 27
XA1 ASIC-epi†	3.1×10^{-4}	5.4	49.3	2.75	2.3×10^{-7}	"	25, 27
Cat. 3 Devices Never Exposed to Protons, thus Proton SEL Unknown							
K7M801825	0.109-	0.8	16.6	2.3	9.98×10^{-4}	N/A	14
AS5SS256K	0.026	6	10.2	0.4	6.1×10^{-4}	"	14
LTC1064	0.028	10.8	40.	1.64	3.2×10^{-5}	"	28
Xilinx3090	0.11	1.1	81	4.33	2.9×10^{-5}	"	29
PACE1750A	0.015	8.1	32.2	1.63	2.8×10^{-5}	"	30
CY7C601	0.014	8.0	28.9	3.7	1.69×10^{-5}	"	31
AT22V10B	0.0013	4.4	46.6	1.55	2.1×10^{-6}	"	32
EPM1810	0.0017	0.9	47.0	3.6	1.48×10^{-6}	"	33
ADSP2187L	0.0017	13.5	48.7	2.4	9.4×10^{-7}	"	34
CY7C265	6×10^{-5}	8.3	10.0	0.4	7.7×10^{-7}	"	35
GAL22V10C	2.3×10^{-4}	10.6	20.0	1.8	5.47×10^{-7}	"	36
A1020B	1.2×10^{-5}	12.9	13.3	3.1	2.4×10^{-8}	"	37

* HI-Heavy ion, σ_{HI} in cm^2 ; FOM-Figure of Merit, Lo, W and S are the Weibull parameters

§ Proton test conducted on the very similar AM5X86

† Proton test conducted, no SEL observed

‡ 3 Altera EPLDs (EPM7160, EPM7032 and EPM9560,[22], [23]) were in proton beam and no SEL was observed; these devices are very similar to EPM7256 and EPM5128 that exhibited HI SEL [21], [24].

£ Proton testing conducted on the very similar 12 bit ADC LTC1298

2.4 Use of Proton Board Level Testing

The specific case of $1 \times 10^{10}/\text{cm}^2$ proton exposures with 200-MeV protons has been used frequently over the last 15 years. It has been used to specifically check and provide related examples for the PBTM method. Also, it has been used to provide data for flight programs. In general, PBTM exposures have been limited to non-critical systems, or performed in combination with other tests that reduce risk after PBTM is used. In the case of critical systems, PBTM usually shows no SEE vulnerability before additional testing is performed. As indicated in Allums et al. (2012) [1], the approach used by JSC is a “Go/No-Go” screen for payload applications, supplemental avionics, and crew support equipment. In this section we review available documents presenting PBTM and PBTM-like data sets.

Using proton upset counts during the 1×10^{10} p/cm² exposure, the space rate for the same event type is obtained by using the PROTEST code, as indicated in [O’Niell 1998,2]. Alternate methods for calculating space rates are presented or used in Foster et al. (2008) [18], Allums et al. (2012) [1], and others. Although there may be some differences in the papers, a reasonable estimate of the predicted rate for an event seen during PBTM testing is approximately an MTBF of 1800/N, where N is the number of upsets observed. This is a simplification and does not include statistical uncertainty in the test sample’s ability to predict the population (i.e., the confidence interval on the population, as a result of the test sample, is not taken into account). Alternately, the EDEPDIST method provides a more technology-specific range of MTBF examination; however, it is clear that the appropriate SV is not always obvious. For the specific case of epitaxial substrates and SOI, the predicted MTBF of 1800/N is probably somewhat conservative, but for other event types there is no good guidance unless heavy ion data is also available (at which point PBTM has limited value).

PBTM data has been reported several times over the years, primarily for parts used for the ISS program [4,29,30]. An example table from Allums et al. (2012) [1] is given in **Table 2-3**. The MTBF is generally based on 6 years divided by the number of observed events, which is consistent with the 1800/N indicated above (the first line is somewhat different, based on the composite nature of the data and the test engineer’s analysis). Similar data is available from several similar sources. It should be noted that all examples indicate that for critical operations additional testing would be performed. Also it should be noted that some of the information in **Table 2-3** comes from composite systems, such as laptop computers that were tested by targeting specific test positions on the test article that would correlate to irradiating memory chips, microprocessors, hard drives, and etc.

Table 2-3: Entries from PBTM testing for ISS programs from Allums (2012) [1].

Test Article Description	Observed Results	Composite MTBF Estimate
Oxigraft Board, CPU Boards, Digital and Serial I/O Boards	37 SEFIs in 1e10	84 days
Dragger Chip Measurement Unit	0 errors in 1e10	> 10 years
Modified Ethernet Hub and Gateway	32 SEFIs in 1e10	57.8 days
COTS Wireless Access Point Bel Air 100n	12 SEFIs in 2.5e10	374 days
MDI DC-DC Converter	0 errors in 1e10	> 10 years
Hynix 2GB SDRAM	8 bit errors in 1e10	223 days
Hynix 2GB SDRAM (2)	28 bit errors in 1e10	63.4 days

There is recent interest in migrating PBTM to be a more comprehensive tool for mission assurance. This includes possibly making PBTM the only assurance test for critical systems, or using systems that are observed to upset during PBTM testing. These efforts are still in development and it is unclear if they will resolve into a viable toolset. The main issue in recent applications of PBTM beyond the non-critical ISS components discussed above is the limited increase in expected MTBF of components. However, some systems are employing FT and redundancy such that small increases in assurance are magnified by powers

of three or more (i.e., a 0.05 probability of failure in a specific unit translates to a 6×10^{-6} (0.05^4) chance of system failure). Because this type of magnification of increased mission assurance may be a good way to handle multiple types of problems (including COTS traceability and outlier concerns), it is possible that PBTM will add enough increase in assurance that it continues to gain traction and PBTM gains wider use. The recent loss of the primary PBTM facility— ISAT (formerly IUCF)—likely means that alternate facilities will be employed, and this is not likely to have a direct impact on the application of PBTM.

2.5 Possible Alternate Uses

Aside from assuring missions by reducing the risk of possible SEE failures in a space environment, proton testing of electronic components can be used for other research. Protons are a relatively inexpensive way to inject errors in devices and systems, enabling testing of fault tolerance [2]. Proton upsets are very similar to neutrons, with the possibility that neutron cross sections may be larger by factors of three to ten [31]. Thus protons provide an alternate source for injecting faults that are similar to expected terrestrial faults.

It should be noted that a proton test can quickly identify if a system will meet its space FT requirements, because flight-like faults will be present. Thus, any unimplemented (or incorrectly implemented) FT systems will be observed. A good example of this is a microprocessor that bypasses FT to meet performance requirements, such as operating a parity-protected cache in a mode where the parity protection causes crashes rather than enabling error correction. As with the case of PBTM, however, a null result (no faults observed) will not provide adequate verification of FT systems.

3.0 A SIMPLE EXAMPLE

In order to illustrate what the available research and applications cases provide us, a simple example may be extremely beneficial. We will discuss the points developed in this BoK using the straw-man mission and design parameters listed below.

- 1) Low-Earth orbit (LEO) (similar to ISS – 450 km 51.6° inclination)
- 2) Single board payload
- 3) Approximately 100 mils of Al shielding
- 4) Power conversion circuits for five power domains (each with a regulator, a few MOSFETs or linear power devices, feedback circuitry, and an analog-to-digital converter (ADC))
- 5) Recharging circuitry – solar
- 6) Communications electronics
- 7) Computer system with one processor, five high speed memories (SRAM), two buffer memories (SRAM), and two storage devices (one NAND flash, one EEPROM)
- 8) Computer interface and isolation
- 9) Four instruments with an average of one microcontroller, one SRAM, and a couple sensor chips
- 10) Pyro system with a few ADCs, DACs, logic devices and a microcontroller

Altogether, this list of subsystems will comprise approximately 65 active components with the following approximate distribution:

- 1) High speed microprocessor – 1
- 2) Microcontrollers – 5
- 3) SRAM memories – 12
- 4) Regulators – 4
- 5) MOSFETs – 12
- 6) NAND flash – 1
- 7) EEPROM – 1
- 8) Oscillators – 4
- 9) Logic devices – 15
- 10) ADCs – 4
- 11) Digital-to-analog converters (DACs) – 1
- 12) Interface or Isolation - 6
- 13) Others – 5

3.1 SEE Evaluation Limited to Analysis Only

If this type of list were available for a system to be used in LEO, with no other information than part numbers/bill of materials, an initial estimate of possible system failures can be determined and generally follows as such: approximately 45 of the 65 devices can be triaged as having SEE rates below 0.1% in 10 years – which is much better than the other 20; so these 45 are removed. Of the remaining 20 devices, the worst-case device can potentially be as bad as 1% chance of failure per day for 1 cm² of device area— with this failure being permanent damage to the device. With no testing, it is necessary to use this number

as an upper bound. Realistically if a device with this high a rate is on the board, there are probably a few of them (i.e., they are likely to be SRAMS), but it is possible there is no device this bad. In the latter case, it is generally necessary to assign a rate of 0.15%/device-day for permanent failure to each remaining device. When considered in the context of 20 devices with unknown radiation risk, the final rate is approximately 3%/system-day for permanent failure. It should also be expected that on the order of 10 SEUs/Gb-day may occur in volatile memory, and on the order of 1 permanent bit flip/Gb-day may occur in non-volatile memory.

3.2 SEE Evaluation Similar to Flagship Missions

A full SEE test campaign is the other extreme. In this case the remaining 20 devices above would require testing for potentially damaging SEEs—damaging SEL and SEGR or other events (including loss of critical memory). Assuming any device found to have a risk of damaging SEE during testing is removed and replaced with an alternate, the individual device rates drop to below 0.0002%/device-year. This is much lower than the initial triage of the remaining 45 devices. So this approach only makes sense if the entire set of devices is reviewed this way, or if devices are only tested to the 0.01%/device-year level. In the most conservative case (all devices tested to below 0.0002%/device-year), the failure probability for the board is below $(1-(1-0.000002)^{65}) \approx 0.013\%$ /system-year. If instead, the triage level of 0.01%/device-year is used, the failure probability for the board is below $(1-(1-0.0001)^{65}) \approx 0.65\%$ /system-year. In both cases, these failure probabilities are upper bounds, and should not be used as expected rates (except for worst-case design efforts).

3.3 SEE Evaluation Using PBTM

The focus of this BoK is neither of the above approaches. Instead, the PBTM lies between the two approaches above (and far closer to the first, high failure probability, case). Using the PBTM, the system would only be tested in a flight operating scenario. Ideally during the test the system would go through all of the states seen during flight with operating time ratios for each state proportional to the amount of space SEE exposure expected; but realistically this is impossible to achieve without already knowing the SEE sensitivity. Because the PBTM includes irradiation of all devices, the system expected failure rate should be based on the number of devices in the test (because the likelihood of a device luckily passing the test increases linearly with the number of devices tested). In some literature and application cases, this linear calculation is not made (likely due to the very similar number of devices in most applications). The predicted system failure rate if no damaging events are seen during PBTM is taken to be 1%/system day in this case (see Section 3). Keep in mind this is for the ISS orbit, which is very similar to the most benign orbit possible. This discussion is roughly consistent with the following interpretation of the proton test.

For the 20 devices with unknown SEE response, the proton test is the only data the mission will have. As discussed above, it is possible for a device to pass the proton test but have an approximately 1%/device-day chance of a catastrophic failure. However, it is unlikely that such a device is on the test board. Thus, we fall back to the alternate rate of 0.1%/device-day for permanent failure – and it is reasonably assigned to 10 of the 20 parts. The other 10, due to technology and other parameters, are assigned failure rate limits of 0.005%/device-day. In this case, the probability of permanent failure can be calculated as $(1-(1-3 \times 10^{-7})^{45}(1-0.001)^{10}(1-0.00005)^{10})) \approx 1.1\%$ /system-day. This is about the same as if the system had the worst-case device. This is about 2 to 3 times better than without testing.

As illustrated here, the key to when the PBTM is useful is when a factor of 2 makes a difference. Because space environments and other parts of a system have margin, it is important to note that this factor of two has to be at the end of the calculation, and be magnified, for it to be much good.

3.4 Other Uses of Proton Data

One other set of data comes from the PBTM. Aside from damaging events, it is also possible to have SEEs such as SEU where the system has an error but is expected to be able to fully recover from the error. The recovery cases range through: self-correction (averaging out of a bad reading), shutdown of some function till commanded to recover from the ground, or on-board fault tolerance detecting and recovering from the SEU.

4.0 CONCLUSION

This book of knowledge has focused on the available information regarding using the proton board-level test method to improve the assurance of systems. The key available materials break down in three ways. First, there are the papers specifically discussing the method and what it provides. These primarily involve how the $1 \times 10^{10}/\text{cm}^2$ 200 MeV test can establish bounds to the performance of systems that pass the test where passing the test generally means the system functions nominally after the test, but may have had errors during the test. When there are errors, the papers provide ways to estimate how often the test observations will likely occur during a space mission. These papers also make it clear that this method, when applied to critical systems, is only a screen that is followed up with a more complete test regimen such as subsequent heavy-ion exposure. The second type of material can generally be considered a set of data and arguments that are fairly consistent with the theory papers in the first set, but it provide a set of counterexamples indicating the potential danger of using the system and how it can fail to accurately predict the failure rates of devices – where this finding is sometimes based on anomalous devices, and other times on modern processes that have different response. The third type of reference material available is papers that provide test data related to performance of PBTM.

The papers reviewed indicate some interesting things about what PBTM can tell us. We reviewed several papers that describe PBTM. These papers range from basic description of the particles produced and how they relate to the ISS/LEO environment, all the way to examples comparing proton and heavy-ion sensitivity at the levels suggested by PBTM.

The key to when the PBTM is useful is when a factor of ten makes a difference. We provided a critical review of available “worst-case” devices that suggests that devices with an MTTF of ten days are possible on a COTS assembly. We also showed how the available literature can be used to argue a resulting MTTF between 100 and 2000 days for systems tested with the PBTM, with the 100-day MTTF being for critical SEL events. Because space environments and other parts of a system have margin, it is important to have a very well-established understanding of what the required performance is, and what performance bounds are achieved without testing. It is also important to determine if design rules and device information can be reviewed which may allow further bounding of the SEE response in a way that may marginalizes the value of the PBTM. That is, it is possible that analysis may provide the majority of the possible benefit of PBTM. However, for a true COTS system, it is likely that enough uncertainty remains that the majority of the factor of ten improvement will require proton testing to achieve.

It should be understood that the past use of PBTM has been entirely for low criticality systems for use in the very benign LEO environment at the ISS. General application to a larger set of environments is likely to be very problematic and at least require significant theoretical development to establish the potential benefit. It is unlikely, however, that the predicted MTTF will improve for any other space environment compared to the LEO/ISS environment.

This BoK has focused on the available information regarding the PBTM. Implementation of PBTM is equally important. At present there are problems with facility availability due to the closure of the IUCF. Further, a best practices guideline for carrying out PBTM may be of significant benefit. Additional development of this topic can include extension of the theory to alternate environments (recall this BoK focuses on available materials, which are currently only developed for the ISS/LEO environment).

5.0 ACRONYMS AND ABBREVIATIONS

ADC	analog-to-digital converter
ASIC	application-specific integrated circuit
BoK	book of knowledge
COTS	commercial-off-the-shelf
DDD	displacement damage dose
DRAM	dynamic random-access memory
EDAC	error detection and correction
EDEPDIST	energy deposition distribution method
EEPROM	electrically erasable programmable read-only memory
FPGA	field programmable gate array
FT	fault tolerance
GCR	galactic cosmic rays
ISAT	Integrated Science and Technology (hall)
ISS	International Space Station
IUCF	Indiana University Cyclotron Facility
JSC	Johnson Space Center
L1	level 1
L2	level 2
LEO	low Earth orbit
LET	linear energy transfer
MEO	middle Earth orbit
MOSFET	metal oxide semiconductor field-effect transistor
MTBF	mean time between failures
MTTF	mean time to failure
NAND	negative and
NEPP	NASA Electronic Parts and Packaging (program)
PBTM	proton board-level test method
RPP	rectangular parallelepiped
SEB	single-event burnout
SEE	single-event effect
SEFI	single event functionality interrupt
SEGR	single-event gate rupture
SEL	single-event latchup
SET	single-event transient
SEU	single-event upset
SOI	silicon on insulator
SRAM	static random-access memory
SV	sensitive volume
TID	total ionizing dose
Z	atomic number

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