Space System Verification Approach Based on MEAL and Mission Risk Posture

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ABSTRACT

There is no "one size fits all" solution for verifying space avionics systems to ensure safety and mission success. This paper presents a verification approach based on MEAL and risk posture for space systems. MEAL refers to Mission, mission Environment, Application, and Lifetime of the application. In addition to the description of the verification approach, the paper also provides the awareness of the different levels of risks associated with verification tests and inspections when performed at part-, board- and box-level, and discusses the applications of the approach for flight heritage verification, commercial off the shelf (COTS) verification and radiation-effects verification.

KEY WORDS: space system, verification, risk, MEAL

1. BACKGROUND

There is a trend of sacrificing rigor in verification testing to meet mission cost and schedule constraints, and this trend can place projects at high-risk. Current and emerging aerospace, space scientific and human exploration projects continue to face new performance demands and new technological challenges. These technological challenges combined with finite budgets and limited schedules are forcing designers, scientists, engineers, and managers to push technologies to their physical limits. At the same time, budget and schedule pressures challenge how those technologies/missions are verified.

A clear understanding of verification processes is needed to ensure proper verification of the technology for the mission (i.e., capabilities, advantages, and limitations). The goal of verification is to prove through test, analysis, inspection, and/or demonstration that a product provides its required *function* and meets performance requirements. It is important that verification yield understanding of representative performance under worst-case conditions so that margins to failure can be evaluated for proposed applications. The capabilities, advantages, and limitations of the testing and inspection performed at each integration level are different, and the risk incurred by omitting a verification step depends on the level of integration as well as Mission, Environment, Application and Lifetime (MEAL) [1].

This paper focuses on verification processes, with the goal of ensuring safe implementation of avionics technologies, giving proper consideration to a project's MEAL and project risk posture.

2. MEAL AND RISK POSTURE

MEAL refers to Mission, mission Environment, Application, and Lifetime of the application. Risk posture is the position project management is willing to take based on the MEAL and identified risks.

2.1 MEAL

MEAL is defined as below:

Mission: The ultimate science goal or objective of the overall effort. The "mission" in the MEAL acronym identifies what type/kind of mission: human or robotic mission, mission category and payload classifications, and level of risk is the mission willing to take. Different types of missions often have different sets of requirements, standards, and test criteria.

Understanding the mission helps define the requirements associated with the environment, the applications to meet the mission goals, and the expected progression of the mission from development to decommissioning. The mission also defines the risk posture, which is the position the mission is willing to take based on the identified MEAL risks. There is no single, uniform standard for risk posture, and depending on the mission, risk posture is often tailored to mission applications and needs.

Environment: The relevant ambient conditions the system would experience during its life cycle to accomplish the mission (e.g., thermal effects, electromagnetics effects, electrostatic effects, radiation effects, etc.).

The mission environment is critical for avionics technologies as it defines the stresses experienced and ensures an understanding of the required operating environment, non-operating conditions and performance thresholds and margins. Environmental performance specifications relative to the mission environment must be defined to maintain required design margins.

Application: Specific function(s) to be executed to meet the goals of the mission. The mission application includes the architecture, its redundancy requirements and parts technologies. This enables proper use of parts for the application/function and gives designers an understanding of how the parts function and interact at all levels, from the individual part up through the system level.

Lifetime: The total time during which the system must perform its intended functions, including subcomponent manufacturing, systems development, system implementation, system execution/operations, and retiring of the system to accomplish the mission.

The mission lifetime defines the criteria for avionics technologies including EEE parts to be selected, applied, and tested for missions, so that premature failures do not affect the mission outcome and wear-out effects do not shorten its duration. These considerations help designers understand of how to size the lifespan of parts and use them in a given architecture.

The understanding of the MEAL requires a complete synchronous picture of effective use of avionics technologies. The MEAL suggests appropriate strategies for mission design, development, implementation, and even defines end-of-mission conditions. It also informs/bounds the verification approach and processes through all stages. The selected verification processes must ensure the adequacy of the design is commensurate with the risk the project is willing to accept.

2.2 Risk Matrix and Risk Posture

For a NASA spaceflight project, the risk matrix is a management tool for communicating how individual issues (e.g., schedule, cost, and technical) related to a given mission are classified and prioritized to one another. The risk matrix main components are: 1) the probability/likelihood of failing to achieve a particular outcome, and 2) the consequence/impact of failing to achieve that outcome. NASA does not have a specific risk matrix for all missions, but has allowed each project to develop their own matrix to fit their given mission requirements based on the respective MEAL. As one example, the NASA Engineering and Safety Center (NESC) defined "Risk" as a measure of the potential inability to achieve overall project objectives within defined constraints. Figure 1 presents the NESC risk matrix and related definitions of the matrix elements [2].

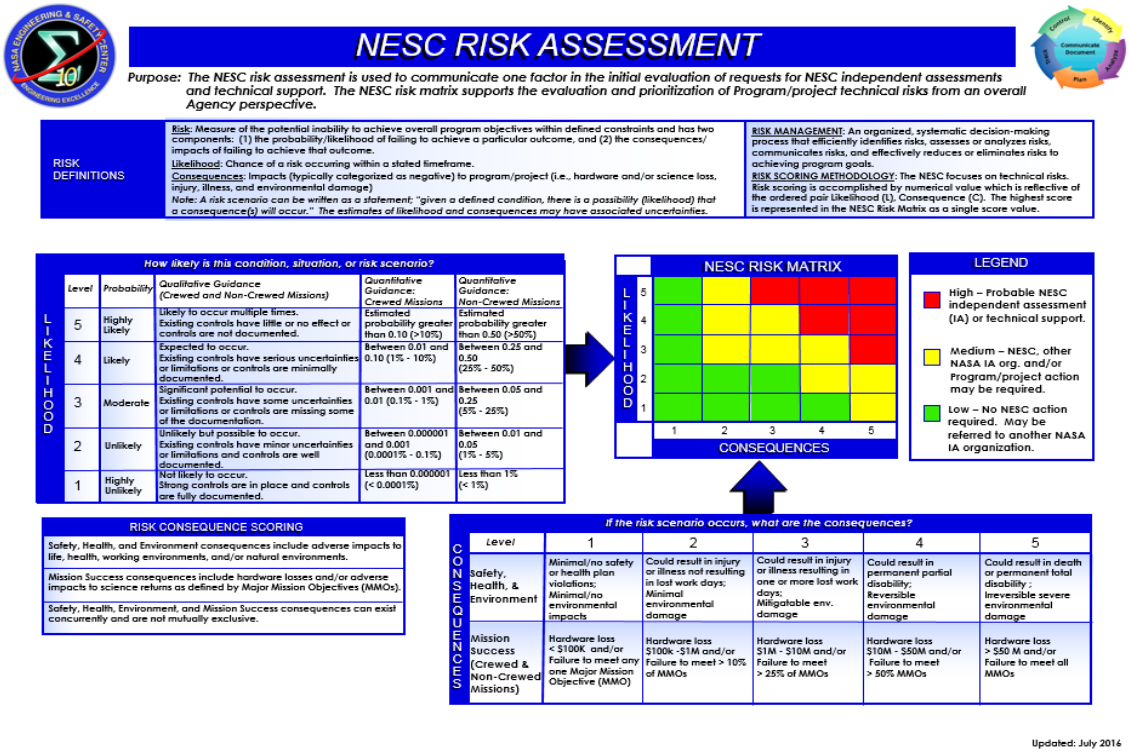

Figure 1. NESC Risk Matrix and Related Definitions of the Matrix Element Definitions [2]

The primary risk impact/consequence areas considered in this paper are crew safety and health, mission success or technical performance, and programmatic as listed in the Table 1.

Table 1. Elements of Mission Risk Posture Impact/Consequence Areas

Mission Type	Risk Impact/Consequence		
	Safety & Health	Mission Success or Technical Performance	Programmatic
Human-rated Exploration	LOC	LOM	COST/SCHEDULE
Robotic Exploration	LOM	LOM	COST/SCHEDULE

Programmatic risk impact/consequence includes cost and schedule for human-rated and robotic explorations. Risk impact/consequence for human exploration missions include loss of crew (LOC) and loss of mission (LOM) in Safety & Health, and Mission Success or Technical Performance, while robotic exploration missions focus primarily on LOM impact/consequence.

Risk posture is the position project management is willing to take based on the MEAL and identified risks. There is no standard for risk posture, and depending on the mission, the approach taken is often tailored based on the mission applications and needs (e.g., human-rated versus robotic, launch vehicle versus spacecraft).

3. Verification based on MEAL and Risk Posture

The MEAL and risk posture based verification process applies to any avionics technology system verification. There is no "one size fits all" solution for the selection and verification of the avionics system and technology to ensure safety and mission success.

The verification of the avionics system and technology in spaceflight projects should begin with the mission definition and its related MEAL, along with the acceptable risk associated with the mission category and/or payload class. These factors influence the design, development, integration, implementation, end-of-mission conditions, and verification process throughout all these stages. The purpose of verification is to show by analysis, demonstration, inspection, and/or test [3] that hardware will perform satisfactorily in the expected MEAL and that minimum workmanship standards have been met in accordance with the project risk posture.

Verification processes should show that the end product conforms to its specified requirements at **all** levels, i.e., part-, board-, box-, subsystem-, and system-level.

A list of common verification tests and inspections performed at different integration levels, i.e., the part-, board- and box-level, is summarized in reference [1], along with the purpose of the procedures, capabilities, advantages, and limitations if performed at part-, board-, and box-level. When properly implemented, these tests ensure that the given technology can be safely used on the given flight project with acceptable risks even in safety critical spaceflight applications.

While reference [1] has all details regarding the verification tests and inspection at different integration levels and the associated risks, typically the "cost to test" decreases and "cost and schedule impact to fix" increases as the test is performed higher levels of integration. This is partly because of the number of independent tests required decreases when moving to higher levels of testing. The test cost can be lower, but the cost and schedule consequences of experiencing a failure increase dramatically. Cost savings will be realized only if ***no*** failures are detected during testing at the higher integration level, assuming this higher integration level testing is sufficient to catch individual parts that could fail during a mission. If there were any failures detected at a higher level, then it would negatively impact cost and schedule. Moreover, vulnerabilities not detected during verification process may lead to adverse consequences ranging from degraded performance to catastrophic failure.

Improper verification of the avionics system and technology can occur due to lack of understanding the project's MEAL, risk posture, or avionics technology, skipping verification testing at different integration level(s), or taking vendor technical and/or qualification data at face value without sufficient evidence or understanding. This can expose projects to unknown risks arising from the implementation/use of these technologies. At the same time, the more

complex the avionics system, the more MEAL-dependent will be the conclusion of the analysis of verification data.

The MEAL suggests appropriate strategies for mission design, development, implementation, and defines end-of-mission conditions. It also informs/bounds the verification approach and processes through all stages. The understanding of the MEAL requires a complete synchronous picture of the effective use of the avionics technologies. Emphasizing one of the MEAL elements without understanding the others can compromise system integrity and performance and impact mission success.

4. Applications of MEAL-based Verification

The MEAL and risk posture based verification process applies to any avionics technology and system verification. As examples, applications of flight heritage verification, COTS verification and radiation effect verification are discussed below.

4.1 Application #1: MEAL-based Verification for Flight Heritage

The following two notional scenarios illustrate the MEAL-based verification to assess heritage. A successfully flown technology is considered to have achieved TRL 6 or higher (TRL refers to Technology Readiness Level [4]). Each figure represents the respective MEAL boundaries.

Scenario 1: The Blue Round Mission was successfully flown. The Orange Star Mission wants to use the same technology. Since the Orange Star Mission characteristics (i.e., Environment, Application and Lifetime) are bounded within the Blue Round mission, the technology would be considered at TRL 6 or higher.

Figure 4. MEAL-based Verification for Flight Heritage Scenario 1.

Scenario 2: The Grey Square Mission was successfully flown. The Purple Triangle Mission wants to use the same technology. Although the Application and expected Lifetime characteristics of the Purple Triangle Mission are bounded within the Gray Square Mission, the Environment is not. Therefore, for the Purple Triangle Program, the technology would revert to the appropriate TRL.

Figure 5. MEAL-based Verification for Flight Heritage Scenario 2.

Table 3 illustrates MEAL-based verification step-by-step process to assess flight heritage technology by using four examples, (b), (c), (d) and (e).

Example (b): although heritage is often taken to apply to any previous successful flight experience, in reality the environment, application, and lifetime of the heritage mission must be equivalent or exceed the mission severity under consideration.

Example (c): in the event that the application and lifetime are bounding, but the new mission is in a more severe environment, the assumed TRL is 4 because the technology has been established at the prototype or breadboard/experimental level.

Example (d): if the new application is more severe than that for the heritage mission, then the assumed TRL is 3 because while the mission represents proof of concept, the technology requires validation for the intended application.

Example (e): if the environment, application, and mission life of the new mission exceed those of the heritage mission, then the assumed TRL is 1.

There are some scenarios not shown in Table 3. For example, if the environment and application are bounding, but the mission life is longer for the new mission, then the assumed TRL is 4 because while the technology is validated in principle, the success of the technology for the new cumulative stresses and failure probabilities have not been.

In summary, MEAL-based verification provides the steps required to qualify any design and could help assess whether the "heritage design" is or is not suitable for the given mission. To claim "heritage", the previous mission's characteristics must bound those of the new mission in terms of environment, application, and lifetime. If these bounds are not realized, then the new system would regress to the appropriate TRL and be certified/verified to the predicted conditions of new mission.

Table 2. MEAL-based Verification Step-by-Step Process to Assess Flight Heritage Technology.

		Description	Mission Examples											
			(a)	Environment	Application (b)	Lifetime	Environment	Application (c)	Lifetime	Environment	Application (d)	Lifetime	Environment	Application (e)	Lifetime
			New Technology	Proposed New Mission MEAL (mission environment, application and expected lifetime) is equal or a subset of the previously flown mission MEAL, including identical concept, form fit, design, interfaces, etc.			Proposed New Mission application and expected lifetime is equal or a subset of the previously flown mission, including identical concept, form fit, design, interfaces, etc., but with an environment outside the previously flown mission			Proposed New Mission MEAL is equal or a subset of the previously flown mission MEAL, but with different application implementation (i.e. different design outside the previously flown like mechanical, thermal &/or electrical)			Design previously flown but different application, environment and lifetime (where the original application does not envelope the new application)		
	TRL #	Description as stated on 7120.5C													
Concept	1	Basic principles observed and reported	V&V	Previous Data Available			Previous Data Available			Previous Data Available			Previous Data Available		
Concept	2	Technology concept and/or application formulated	V&V	Previous Data Available			Previous Data Available			Previous Data Available			V&V		
Concept	3	Analytical and experimental critical function and/or characteristic proof-of-concept	V&V	Previous Data Available			Previous Data Available			Previous Data Available			V&V		
Implementation – Ground	4	Component and/or breadboard validation in laboratory environment	V&V	Previous Data Available			Previous Data Available			V&V			V&V		
Implementation – Ground	5	Component and/or breadboard validation in relevant environment	V&V	Previous Data Available			V&V			V&V			V&V		
Implementation – Ground	6	System/subsystem model or prototype demonstration in a relevant environment	V&V	Previous Data Available			V&V			V&V			V&V		
Implementation – Space	7	System prototype demonstration in the real environment	V&V	V&V			V&V			V&V			V&V		
Implementation – Space	8	Actual system completed and "flight qualified" through test and demonstration	V&V	V&V			V&V			V&V			V&V		
Implementation – Space	9	Actual system "flight proven" through successful mission operations	V&V	V&V			V&V			V&V			V&V		
		Comments:	Must undergo through the entire TRL process	Must verify system/subsystem under relevant environment (acceptance verification test)			Must validate component &/or Breadboard under relevant environment.			Must validate component &/or Breadboard under laboratory environment.			Must be treated as the new technology		

Notes:

V&V	Must be validated and verified as per TRL Definitions and descriptions.
Previous Data Available	Validation data available from previously flown/validated system. Requires Verification at all levels of implementation.

4.2 Application #2: MEAL-based Verification for COTS Use in Spaceflight Projects

Spaceflight projects are driven to use COTS avionics technologies to reduce design, development, test, and evaluation (DDT&E) costs, to meet programmatic schedules, and increase

system performance. Meanwhile, with continued pressure to minimize DDT&E costs and undertake more complex spaceflight mission designs and interfaces (i.e., advanced architectures and more complicated parts), the potential for increased/unrecognized risk increases.

In an Aerospace Corporation study [5], several dozen missions were reviewed and the evidence of a "No Fly" zone, characterized by increased failure rates, was found to exist when pressures to reduce Design Development Test and Evaluation (DDT&E) cost and programmatic schedule meet increased system complexity, as shown in Figure 6. The Aerospace team developed a "complexity index" based on considerations of mission characteristics, spacecraft size, power consumption, number of payloads, GN&C demands and data processing and throughput. This normalized index correlated with mission success and failure, giving strong indications of a no-fly zone where complexity drove mission cost and schedule and where attempts to drive down these constraints tended to lead to mission failures [6].

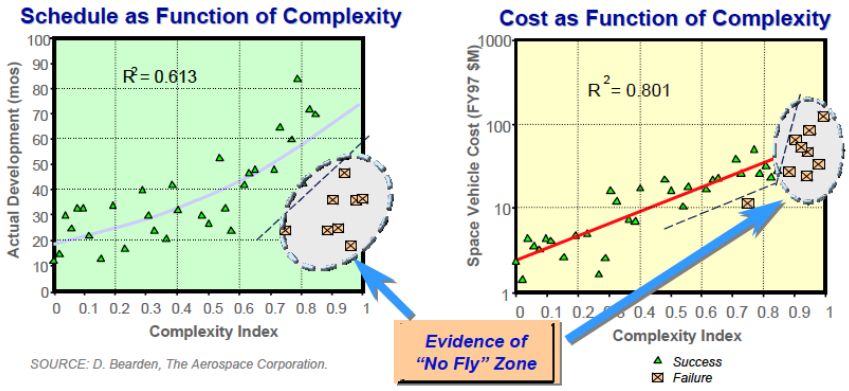

Figure 6. Evidence of "No Fly" Zone [5].

As demands for improved performance in spaceflight projects increase, the temptation has increased to implement new avionics technologies, including commercial off the shelf (COTS) technologies, into human-rated and robotic spaceflight projects. In addition, it is likely that the pressures will increase. Using complementary metal-oxide-semiconductor (CMOS) technology as one example, the performance (e.g., speed, density, power, etc.) differences between CMOS COTS parts and radiation-hardened parts continues to expand. While commercial CMOS doubles in density roughly every 18 months, radiation hardened CMOS doubles in density every 24 months, which means that radiation-hardened CMOS performance lags even further behind commercial technology, dropping another generation behind roughly every decade, shown in Figure 7.

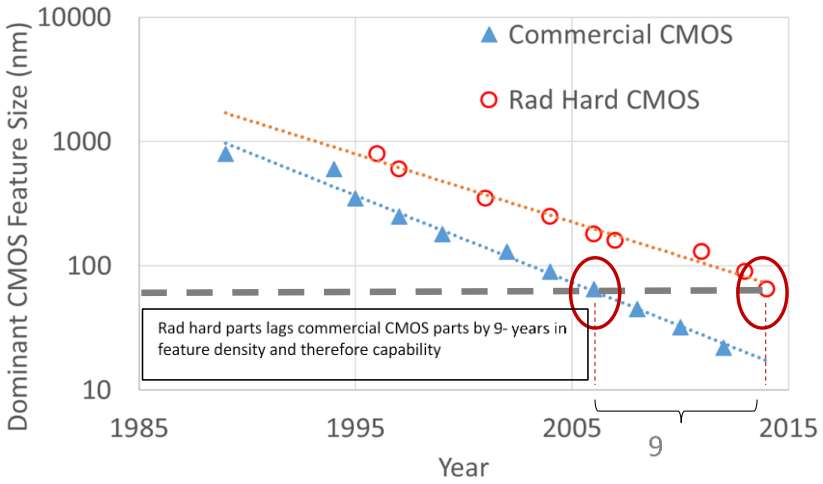

Figure 7. Comparison between Commercial and Radiation-Hardened CMOS Technologies [6].

While state-of-the-art COTS parts can increase system performance and capabilities, they also can dramatically increase system complexity to the point where characterization of the part, let alone the system, for all logical and operating states become practically impossible. The system state space complexity increases exponentially with the part complexity, and access to information about individual part performance and margins to failure decreases. This makes full characterization for board- or box-level testing with complex parts a daunting problem.

Limited understanding of COTS technology and how they perform in the mission environment over the design lifetime may lead to incomplete verification processes. NASA has successfully used COTS parts in mission critical applications throughout the Agency's history. This has been achieved by careful selection, qualification, and screening of the parts to meet the missions' requirements as well as careful system design to capitalize on the strengths of the COTS part while mitigating its weaknesses. The level at which part performance must be verified to ensure it will work successfully is highly dependent on MEAL, the avionics architecture, and the part technology [8].

4.3 Application #3: MEAL-based Verification for Radiation Effects

Threats that the space radiation environment poses to semiconductor devices in space missions can be divided into two broad categories: dose effects and single event effects (SEE). Dose effects, i.e., TID and displacement damage dose (DDD), result from cumulative exposure to the space radiation environment. As such, they behave like wear-out effects with failure rate increasing as the dose increases. In contrast, single-event effects (SEE) are the parts' prompt responses to the passage of a single ionizing particle through a volume in the part sensitive to that SEE mode.

4.3.1 TID, DDD, and SEE

Radiation tests for TID, DDD, and SEE are all at least potentially destructive. Therefore, such testing is done during qualification testing on a sample of parts representative of the flight parts. For TID and DDD, this usually means the test parts must belong to the same wafer diffusion lot as the flight parts. For SEE, lot-to-lot differences in performance are not usually as significant as those for TID or DDD. As long as the test parts are fabricated in the same process and with the same mask set as the flight parts, the test is likely to be valid. Note that in some cases, lot-to-lot

and even part-to-part variation is significant for SEE and these situations require greater fidelity between test and flight parts.

Radiation testing for SEE has different goals than that for TID or DDD. TID and DDD are cumulative effects, and failures are usually preceded by gradual parametric and functional degradation. Thus, the goals of TID and DDD testing are to determine which parameters/ functions degrade and the part-to-part variation in that degradation at each dose step. If parts are tested to failure (either parametric or functional), then the part-to-part variation in the failure dose is also of interest. Mitigation of TID and DDD involves adding shielding or taking other steps (e.g., selecting operating conditions) to ensure that the dose on the part remains low enough that the probability of failure or degradation affecting the part's ability meet requirements is negligible.

In contrast, SEE can occur at any time in the device with equal probability (per ion). As such, the primary goal of SEE testing is to identify all the SEE modes to which the part may be susceptible. Thus, independent of whether the radiation environment is severe or benign, the test will irradiate the part to ion fluences much higher than will be seen during the mission. SEE test methods are specifically tailored to include conditions where a given SEE mode is likely to occur if the device under test is susceptible. For example, if the device under test includes CMOS (which can be susceptible to single event latch-up — SEL), some test runs will be performed with high fluences (i.e., greater than 10^7 ions per cm^2) of highly ionizing (i.e., high-linear energy transfer (LET)) ions. These runs would be performed with the worst-case conditions for causing SEL in the DUT. Once this susceptibility is detected, then it is measured for a variety of ion species, energies, LETs, and angles of incidence. These data are used to estimate the probability of each SEE mode occurring in the mission radiation environment application and lifetime.

4.3.2 Radiation Testing at Different Configuration Levels

Whether parts are tested at the part-, board-, or box-level affects the extent to which the goals outlined in the previous section can be met by testing. First, board- and box-level studies are often performed with a single sample of the board or box. This makes it impossible to assess how part-to-part variation would affect flight board/box performance unless there is high confidence part-to-part variation is negligible for all parts on the board. Even if multiple test units are irradiated, the interactions between parts with different variability on the boards makes it difficult to interpret the results and bound flight unit performance.

Radiation of higher-level assemblies also precludes optimizing the test to detect particular susceptibilities in any given technology. Moreover, parts on a board may only be susceptible to some failures for a fraction of the boards' operating conditions. For example, if any part on a test board is bipolar, it is potentially susceptible to enhanced low dose rate sensitivity, in which parts degrade more severely at low dose rates (e.g., in space) than at high dose rates (e.g., in an accelerated TID test). This means that the entire test must be conducted at a low dose rate. Similarly, increasing board temperature and voltage may not be possible, and SEL testing would likely have to be done for realistic missions rather than bounding conditions. Test conditions and levels will be driven by the weakest parts in the test unit rather than by the level of hardness designers desire for the system.

Nondestructive SEE modes and parametric degradation may also remain hidden in tests at the board- and box-level. While it can be argued that such modes are not significant at the system level, they could have consequences if the hardware is in another logical or operating state when

they occur. In general, the more complicated the test unit, the less likely it is that the tester will be able to cover the full state space of operations in an accelerated test.

Not every radiation test can be performed at all integration levels. TID tests with gamma rays could be performed even for complex boxes as long as the beam is large enough to expose the entire test unit. X-rays have less penetrating power than gamma rays, but are similarly suitable for part-, board- and box-level testing as long as the penetrating range of the radiation is much longer than the system size. A concern for multi-board systems is that a gamma ray or X-ray beam can be degraded as it passes through the forward boards, resulting in higher doses for the rear boards than the forward boards. Proton TID, DDD, and SEE tests can also be performed on integrated systems although the range of the protons must be considered (the range of a 200-MeV is about 13.7 cm in Si).

Heavy-ion SEE testing at levels of integration higher than the part level is problematic. Preparing parts on the board to ensure ions from conventional accelerators reach device sensitive volumes can compromise their structural integrity, making them unreliable and vulnerable to mechanical failures. In principle, a sufficiently broad, high-energy heavy-ion beam (e.g., like that at the NASA Space Radiation Laboratory (NSRL)) could effectively test parts at the board-level without modification, albeit with significant amounts of analysis required to account for beam degradation as it traverses various parts. However, heavy-ion SEE testing at the multi-board or box-level is generally not feasible due to limited penetration ranges of the ions and the difficulty of modeling transport of the ions through complicated structures in the test unit.

Board- and box-level tests must be designed around the limitations of the weakest part(s) in the system, which creates challenges for radiation testing. This is especially true for board-level SEE tests, which are usually performed with high-energy protons due to their greater penetrating range, eliminating the difficulties with part/board preparation for heavy ion tests. Such a proton test cannot detect SEE modes caused only by moderately to highly ionizing particles (Z>14). However, even for modes that occur at low LET, only 1 of ~289000 protons creates a recoil ion (i.e., the secondary particle capable of causing the SEE) while every proton contributes to TID. To avoid board- or box-level failures due to TID-susceptible parts, the test will often need to be restricted to a low proton fluence (e.g., 10^{10} to 10^{11} cm^{-2}). Such low-fluence tests usually fail to reveal all, or even a representative sample, of the SEE susceptibilities in the system under test and on-orbit experience can differ dramatically from the test results, as seen in Figure 8.

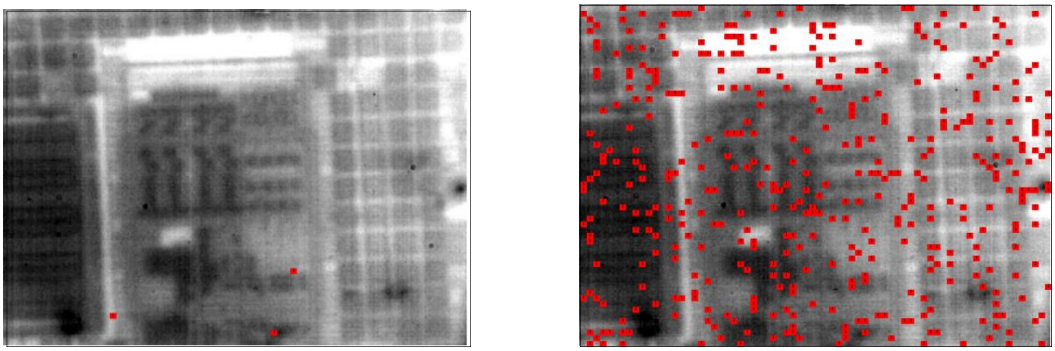

Figure 8. Simulated strikes of ions (red dots) overlaid on a photomicrograph 60 x 70 μm^2 section of an Elpida 512 Mbit SDRAM. Left: Recoil Ions due to 10^{10} Protons/cm^2. Right: 10^7 ions/cm^2 typical of heavy ion SEE test.

Often, the softest parts to TID in the test unit that drive the low fluence requirements are linear bipolar components fabricated in large-dimension, older technologies. These simple parts do not

usually require high ion fluences to characterize their SEE response. In contrast, complex parts that require high fluences for SEE characterization are fabricated in more advanced microelectronic technologies that are usually much more tolerant to TID and remain functional at the high proton fluences required to provide adequate coverage of SEE modes.

In general, the fluence required to adequately test a device scales with its complexity and the transistor count is often a good guide to device complexity. Transistor count scales roughly as the inverse square of the minimum feature size of the technology.

However, there are other factors to consider (e.g., number of functions or operating modes). A quad core processor with a given transistor count is likely less complicated than a single processor with the same transistor count. Similarly, a static random access memory (SRAM) may be fabricated in an advanced CMOS process with high transistor density, but its architecture will be highly repetitive and, as such, it will not require as high a fluence to characterize its SEE response as would a less repetitive part with similar transistor count. In contrast, although the memory array of a synchronous dynamic random-access memory (SDRAM) is highly repetitive, the part exhibits complex SEE behavior due to upsets in its control logic.

Even if the testing is performed with ultra-high-energy heavy ions rather than protons, differential performance in the parts on the board (box-level testing is not possible with heavy ions currently available at any accelerator) can still complicate the task of thoroughly characterizing the board. If one or more of the components on the board is susceptible to destructive or highly disruptive SEE modes, it may prevent the test from accumulating sufficient fluence or probing all of the full state space of the test unit.

5.0 Summary

This paper presents a verification approach based on MEAL and risk posture for space systems, provides the awareness of the different levels of risks associated with verification when performed at part-, board- and box-level, and discusses the applications on flight heritage verification, commercial off the shelf (COTS) verification and radiation effect verification.

The MEAL and risk posture based verification process applies to any avionics technology system verification, including COTS technology and previously flown technology. There is no "one size fits all" solution for the selection and verification of the avionics system and technology to ensure safety and mission success.

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