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Connecting Mission Profiles and Radiation Vulnerability Assessment

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ABSTRACT

Radiation vulnerability assessment early in spacecraft development is cheaper and faster than in late development phases. RGENTIC and SEAM are two software platforms that can be coupled to provide this type of early assessment. Specifically, RGENTIC is a tool that outputs descriptions of radiation risks based on a selected mission environment and the system's electronic part portfolio, while SEAM models how radiation-induced faults in electronic parts propagate through a system. In this work, we propose a spacecraft evaluation flow where RGENTIC's outputs, which are radiation vulnerabilities of electronic parts for a given mission, become inputs to SEAM, resulting in an automatic part-type template palette presented to users so that they can easily begin modeling the occurrence and propagation of radiation-induced faults in their spacecraft. In this context, fault propagation modeling shows how radiation effects impact the spacecraft's electronics.

The interface between these platforms can be streamlined through the creation of a SEAM global part-type library with templates based on radiation effects in part-type families such as sensors, processors, voltage regulators, and so forth. Several of the part-types defined in RGENTIC have been integrated into SEAM templates. Ultimately, all 66+ part-types from the RGENTIC look-up table will be included in the SEAM global part library. Once accomplished, the part templates can be used to populate each project-specific part library in SEAM, ensuring all RGENTIC's part-types are represented, and the radiation effects are consistent between the two.

The harmonization process between RGENTIC and SEAM begins as follows: designers input a detailed knowledge of their system and mission into RGENTIC, which then outputs a generic part-type list that associates each part-type with potential radiation concerns. The list is then downloaded in a SEAM-readable file, which SEAM uses to populate the initially blank project with the part templates that correspond to RGENTIC's output. The final product is a system fault model using a project-specific radiation effect part library.

The radiation effects considered in the part library are associated with three categories of radiation-environment issues: single event effects (SEE), total ionizing dose (TID), and displacement damage dose (DDD). An example part-type is the discrete LED, which has been functionally decomposed into input power and output light. It has a single possible radiation-induced fault that is associated with DDD, which causes degraded brightness and is observed on the output.

Overall, designers will benefit from a coordination of these two tools because it simplifies the initial definition of the project in SEAM. This is especially the case for new users, since the necessary radiation models for their parts are available before modeling commences. Furthermore, starting from a duplicate of an existing project decreases the amount of time and effort required to develop project-specific models. Incorporating RGENTIC's table of part-types resolves these issues and provides a streamlined process for creating system radiation fault models. Consequently, spacecraft designers can identify radiation problems early in the design cycle and fix them with lower cost and less effort than in later design stages.

INTRODUCTION

Future of Radiation Mission Assurance

The future of mission assurance will benefit from automating the identification of radiation vulnerabilities early in the spacecraft development process. This is because spacecraft designers are increasingly relying on commercial off-the-shelf (COTS) components instead of radiation-hardened components. COTS components are appealing in this respect because they are cheaper and often perform better than available radiation-hardened counterparts.

Furthermore, spacecraft designers may not have radiation effects experts on their teams to provide guidance on using these components. Without such radiation effect guidance, it is difficult to assess radiation vulnerabilities of the spacecraft. Such guidance is important because it provides a degree of reliability assurance for the spacecraft based on its mission profile. Reliability and maintainability (R&M) assurance is a field that requires extensive and meticulous understanding to achieve proficiency. To emphasize this point, NASA and the U.S. Department of Defense (DOD) provide a body of work detailing the technical basis for R&M in projects across their respective departments. For the case of NASA, the NASA-STD-8729.1A is used [1], while the DOD relies on their 2005 'Reliability, Availability, and Maintainability' guide [2]. We begin with a short review of some of the issues faced by design teams and describe how the RGENTIC-SEAM interface helps alleviate these issues. We then describe these platforms in-depth with the help of an example component (an LED). We then conclude with a discussion on how the final output of the RGENTIC-SEAM interface helps provide designers with a degree of awareness regarding potential radiation concerns that may impact their spacecraft design.

Small Satellite Design Teams

Small satellite (e.g., CubeSat, etc.) or academic design teams are most likely to lack radiation effects experts and to forego radiation-hardened components. When compared to larger satellite design teams, they tend to lack the level of funding that government and defense organizations need to afford radiation effects experts and/or acquire radiation-hardened components for small satellite projects. Furthermore, academic organizations are expected to triple their small satellite launches [3]. At the same time, commercial groups are expected to increase sevenfold their satellite launches over the same time period [3].

One solution that can alleviate satellite designers' concerns when using COTS components is an automated and straightforward web-based solution for radiation vulnerability assessment. To this end, NASA and Vanderbilt University have developed and deployed the System Engineering and Assurance Modeling (SEAM) platform to work in conjunction with the RGENTIC platform. SEAM can be found at the following website: https://modelbasedassurance.org/. RGENTIC can be found at https://vanguard.isde.vanderbilt.edu/RGentic/. Both are standalone programs that were designed with non-radiation effects experts in mind. In short, RGENTIC associates a user-provided parts list with their respective radiation concerns, and SEAM outputs a system fault model using that part list. Each has a low barrier to entry and provides rapid analytical results. Combining the two allows RGENTIC's output of a downloadable generic part-type list to be read by SEAM to create a project-specific radiation effect parts library.

MOTIVATION FOR CONNECTING MISSION PROFILES AND RADIATION VULNERABILITY ASSESSMENT

The mission profile refers to the design and launch parameters relevant to achieving the goals set forth for a spacecraft. These parameters include everything from altitude of deployment to date of launch. All data relevant to the mission profile has the potential for being important to radiation vulnerability assessment. For example, date of launch can affect the level of solar radiation due to the number of sunspots, as shown in Figure 1 [4]. Outside of solar radiation, charged particles of concern include protons, electrons, and heavy ions. Depending on the charged particles under consideration, they have the potential to induce single event effects (SEE), total ionizing dose (TID), and/or displacement damage (DDD).

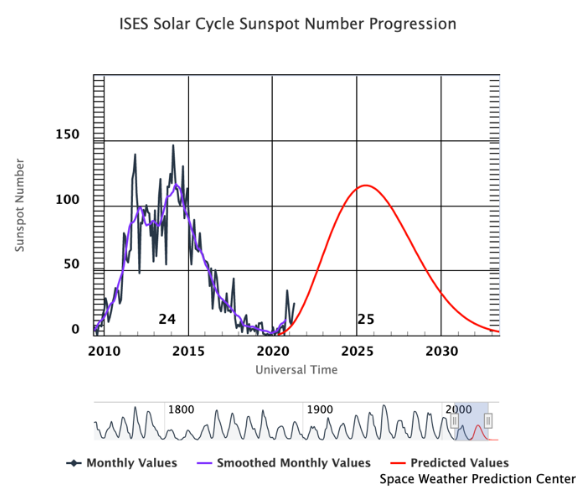

Figure 1: Solar cycle progression and prediction according to the National Oceanic and Atmospheric Administration (NOAA)

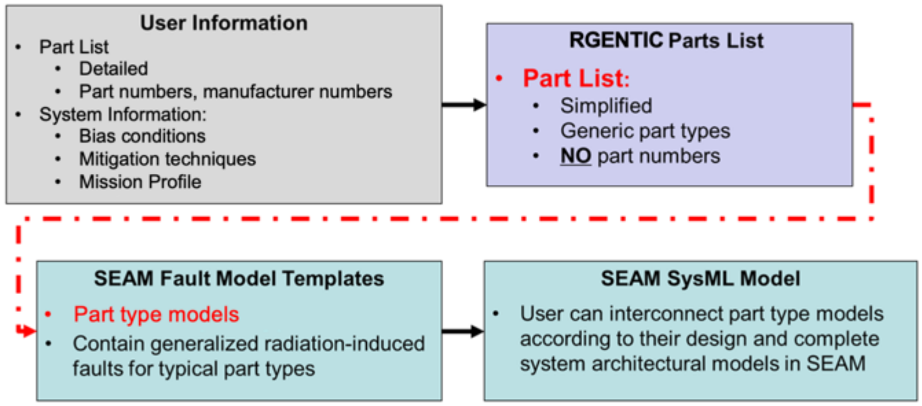

Figure 2: Radiation Fault Propagation Model

Radiation effects can be categorized based on whether they cause transient damage or long-term degradation. An example of a transient effect is a single event upset (SEU), which is an SEE that causes a soft error and is potentially non-destructive. An effect that can potentially cause long-term degradation is a single event latch-up (SEL). An SEL is also an SEE but results in a high current that can permanently destroy a circuit or cause latent damage that may manifest as errors in circuit performance later during the mission. TID is the result of cumulative long term ionizing damage caused by charged particles such as electrons. Examples of long-term effects include increased device leakage and transistor threshold voltage shifts [5]. Displacement damage is the cumulative damage done to a semiconductor lattice. It can degrade minority carrier lifetimes.

Radiation vulnerability assessment is a specific subcategory of risk assessment that refers to radiation-induced faults. Risk assessment itself is the process of pinpointing all faults and their probabilities for occurring within the spacecraft design. As a result, connecting mission profiles to their respective radiation vulnerability assessment is a key requirement for radiation hardness assurance (RHA). RHA is the process of identifying radiation-induced faults and managing their risk.

MOTIVATION FOR RGENTIC-SEAM INTERFACE

The RGENTIC-SEAM interface serves two purposes: 1) it automates the radiation vulnerability assessment process to a point where non-radiation experts can utilize it, and 2) it makes radiation vulnerability assessment user-friendly. Specifically, instead of requiring new users to individually create all the necessary radiation models in SEAM, new users only need to input the spacecraft's components and mission profile into RGENTIC for the relevant radiation models to then appear automatically in SEAM. As a result, in addition to being user-friendly, this process also decreases the amount of time and effort required to develop project-specific models.

Previously, the SEAM platform required an extensive amount of time for creating radiation models. We address this by providing standard radiation fault model templates for an extensive library of EEE part types used in space. Hence, SEAM no longer requires the user to start from either a blank project or to duplicate an existing project for modification purposes. Otherwise, starting from a blank project is time-consuming and requires training for new users. Furthermore, starting from an existing project may result in users having to make unnecessary modifications to the duplicated project. This method also assumes that new users have pre-existing projects for duplication purposes, which cannot be guaranteed. To this end, RGENTIC is useful because it provides a starting point for new projects so that the models in SEAM only contain EEE parts of interest for the particular project the user is interested in. As a result, starting with RGENTIC for radiation model creation reduces the complexity and time-consumption of making new projects in SEAM.

A brief overview of radiation fault propagation using RGENTIC and SEAM can be found in Figure 2. It starts with the user inputting a detailed part list into RGENTIC. This step also requires the user to input bias conditions, mitigation techniques, and the mission profile. RGENTIC then exports the list of EEE part types and possible radiation effects of concern for this mission to SEAM, which creates an initial "canvas" with the appropriate radiation-effect part-type models automatically for the spacecraft mission. The final product is a SEAM System Modeling Language (SysML) model where users can interconnect part-type models according to their design.

RGENTIC

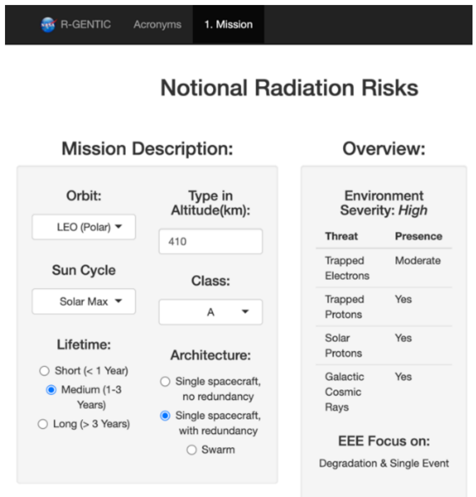

Figure 3: RGENTIC environment page that contains orbital parameters

RGENTIC is a tool that was largely developed at NASA Goddard Space Flight Center (GSFC). It provides guidance on typical radiation risks that may apply to EEE parts based on user input on the mission but does not replace the need for modeling one's own environment [6]. If extensive radiation testing is not possible due to budget constraints and short development cycles, then RGENTIC (in combination with SEAM) can help pinpoint the components of concern that need to be tested or replaced with less vulnerable equivalents.

The RGENTIC user interface involves four sections: 1) user profile; 2) environment comparison; 3) device response, and 4) guidelines. The first section is very similar to mission profile, and it requires the user to input the orbit, mission lifetime, and risk tolerance of the mission. Specifically, the user selects an orbit from a drop-down list consisting of LEO (Polar), LEO (Equatorial), MEO, GEO, Interplanetary, and Sun Synchronous. Altitude is provided by typing in the desired valued in kilometers in the provided box. A sun cycle selection must also be made, and can be chosen from a drop-down list consisting of the options Solar Max or Solar Min. Risk tolerance options include 'Do No Harm', A, B, C, or D. Each refers to a different level of allowable risk. Lifetime can be one of three options: short (which is less than 1 year), medium (which is 1 to 3 years), or long (which is greater than 3 years). Finally, the architecture options are 'single spacecraft with no redundancy,' 'single spacecraft with redundancy,' or a 'swarm configuration' [6]. In Figure 3, the follow parameters were inputted: an LEO (Polar) orbit, an

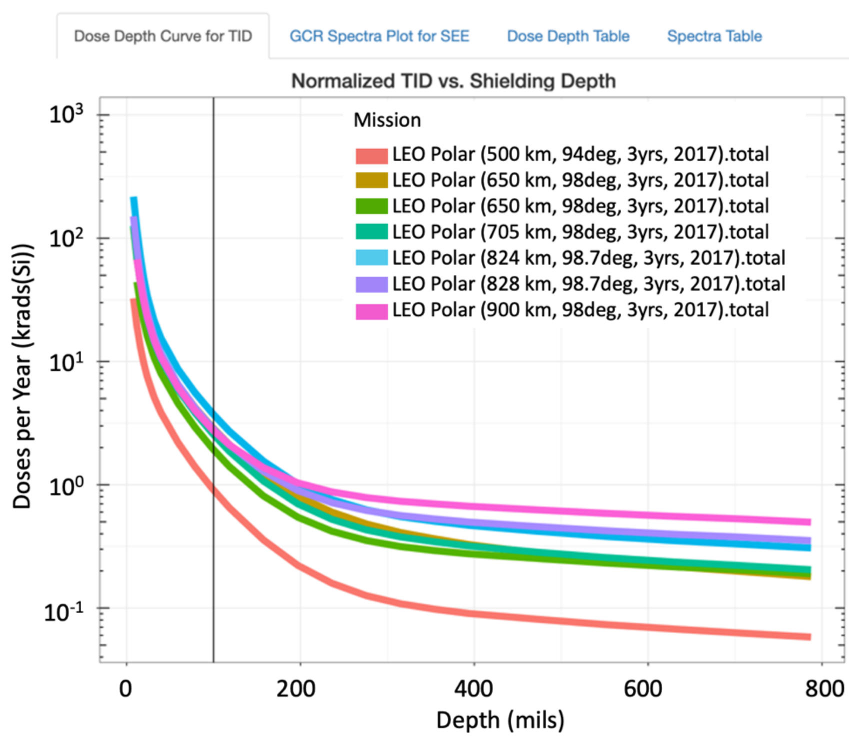

Figure 4: RGENTIC's environment page comparing normalized TID vs. Shielding Depth

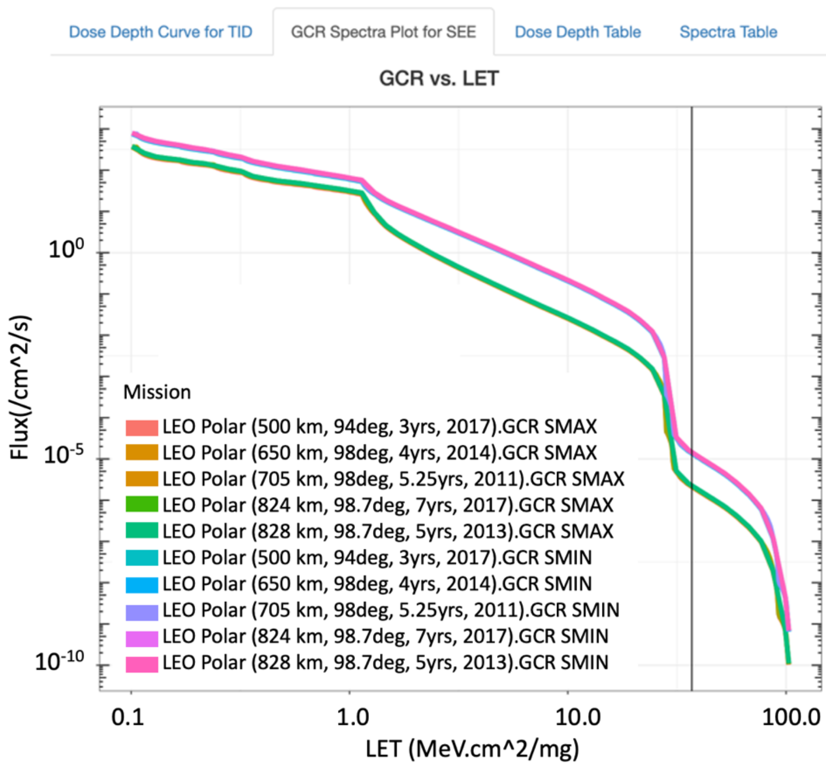

Figure 5: RGENTIC's environment page comparing GCR to LET

altitude of 410 km, a Solar Max sun cycle, Class A risk level, medium lifetime, and single spacecraft with redundancy architecture. These parameters produced an overview showing that the environment severity is high.

The second RGENTIC section takes the output from the first step and displays previous mission modeling efforts for the sake of comparison. Specifically, it finds a mission that has been calculated to be similar to the user's mission after normalized to one year for approximation purposes. The resulting output panel then allows the user to select from multiple missions to compare and explore. It also takes into account the solar cycle because depending on the launch year, the solar cycle determines dose levels.

This section of the tool shows how mission characteristics impact the user's radiation concerns through the display of two curves. They are the TID vs shielding depth curve (Figure 4), and the GCR vs. LET curve (Figure 5). GCR is an abbreviation for galactic cosmic ray and refers to the heavy ions traveling in space at relativistic speeds. They tend to have high linear energy transfers (LETs), which is the average amount of energy that the ions deposit into a material. The thick black line in Figure 4 shows where 100 mils of aluminum shielding is on the curves, in order to make it easy to find that particular common value. Figure 5's black line shows where the iron cutoff of 32 MeV.cm^2/mg is in relation to the flux spectrum. The steep drop in the flux near the LET of iron particles is called the "iron knee," and for many missions this is the maximum LET that needs to be considered in a radiation analysis. Each plot also comes with its respective data table for further analysis.

The third RGENTIC sections allows the user to input device types of interest for the program to then identify the basic radiation concerns. The device susceptibility to various potential radiation concerns are shown once the user inputs the component's information. In return, the tool displays examples of radiation concerns through the use of plots and referencing of similar components [6] (Figure 6).

A table summary for all inputted part is shown in Figure 7, which appears after the user inputs the various components that are incorporated into the spacecraft. The user is required to assign a reference design/unique ID to each part in Figure 6. However, it is not recommended to use the actual part numbers due to proprietary and/or export control purposes.

To choose a part, the user first selects the appropriate Family from the drop-down list and the Function drop-down list will update to provide appropriate choices for generic part-types available in that family. These are very general descriptions of parts; for example, LED,

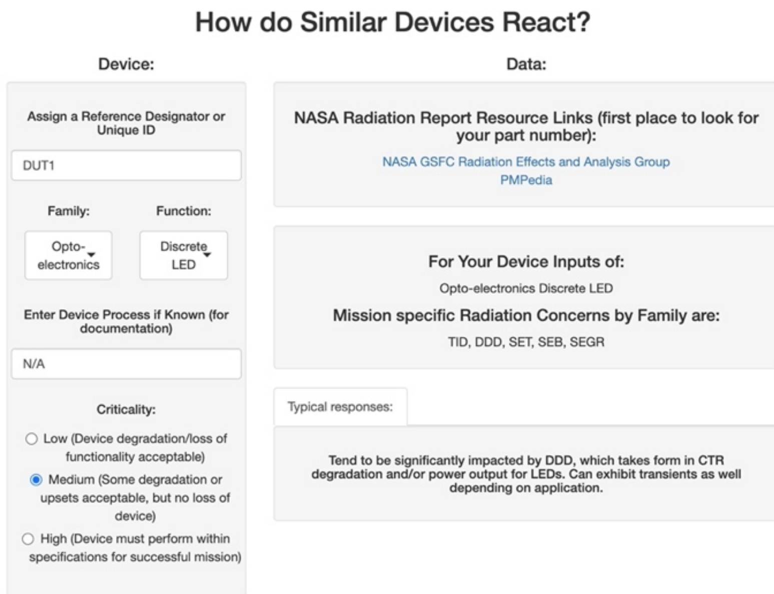

Figure 6: RGENTIC device page, where user answers the question 'How do similar devices react?'

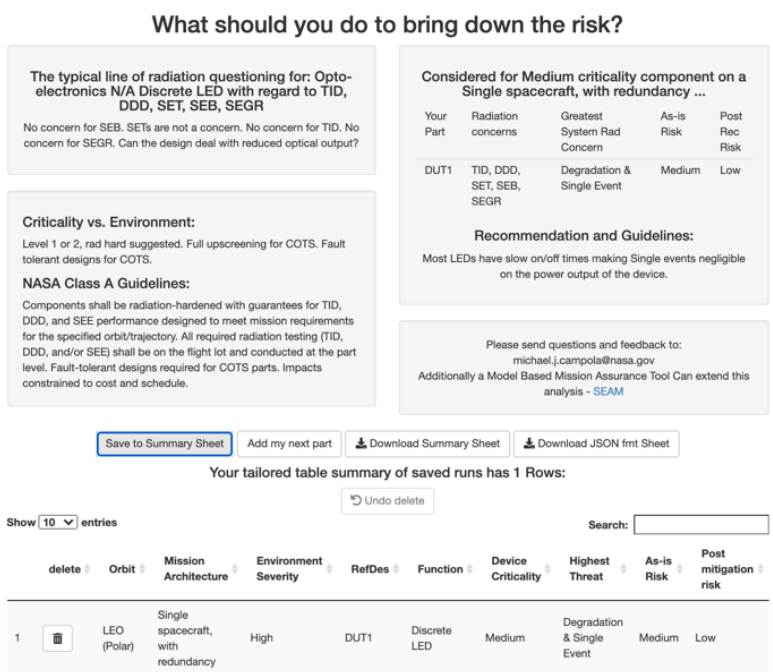

Figure 7: RGENTIC device page, where user answers the question 'What should you do to bring down the risk?'

photodiode, microprocessor, etc. RGENTIC does not consider specific part numbers, or the differences between space grade components as opposed to COTS parts. It only considers generic part-types and then provides standard radiation concerns and responses based on the user's selections.

Finally, the user must specify how critical this part is to the functionality of the system, choosing either Low, Medium, or High. In Figure 6, an LED from the opto-electronics Family is selected. It has a medium criticality for this mission. In the middle right box, generic radiation concerns by family are provided. For example, in the case of opto-electronics, the user should be

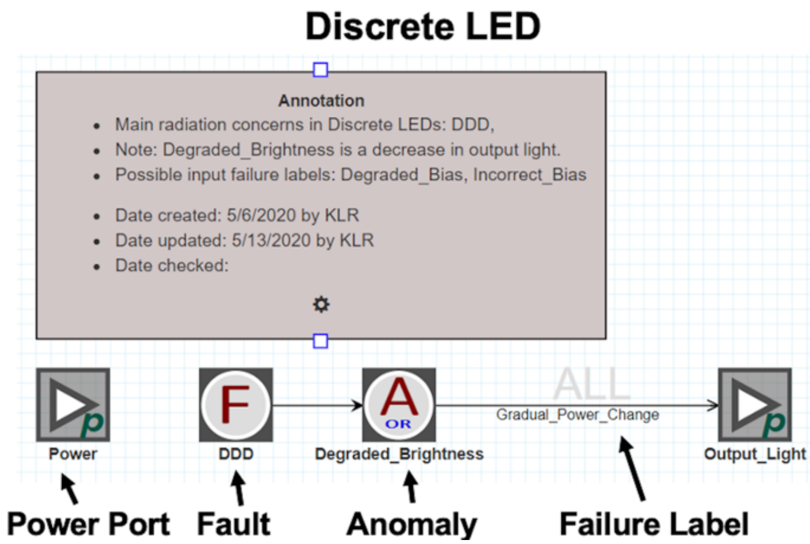

Figure 8: Discrete LED schematic in SEAM

concerned with TID, DDD, single event burnout (SEB) and single event gate-rupture (SEGR).

The fourth RGENTIC section is where major concerns are clarified, and radiation specific class guidelines are given. It presents radiation concerns specific to the user's mission inputs, and the user is given presented with potential strategies for reducing these concerns. This data can then be saved to a table.

In Figure 7, the top-left box gives a typical line of radiation questioning for the Family of the device, with device-specific information given beneath. The lower-left box provides recommendations based on the part's criticality, the environment's severity, and the mission class. NASA Class Guidelines are also shown for the specific mission class. Meanwhile, a summary for the user's part-type can be found in the upper-right box. This summary will be saved to the summary sheet after the user clicks "Save to Summary Sheet."

Overall, this example investigates radiation effects of Discrete LEDs. RGENTIC reveals that the user does not need to be concerned with radiation effects such as single event burnout, TID, or single event gate-rupture. However, the user should be concerned with whether the design can survive reduced optical output due to DDD. Given the criticality of the part and the environment, the user may need to consider replacing the COTS component and using a radiation-hardened component instead. The user can then add this part to a summary sheet and go on to add more parts. Once the user has added all the parts wanted, the user can then download the summary sheet, which saves as a CSV of all the pertinent information.

SEAM

SEAM is a web-based collaborative modeling tool for providing a modeling assurance case that integrates with models of the spacecraft system [6]. The platform is a collaboration between NASA and Vanderbilt University, and is hosted on an Amazon Web Services (AWS) server. SEAM allows for building project-specific libraries, which are called part-library templates. They include commonly used part-types, failure labels, etc. While not intended to duplicate the functionality of a physics-based simulator like SPICE, SEAM provides a means for creating a logical, descriptive modeling of the user's systems [6]. Overall, the platform provides rapid analysis results compatible with the CubeSat development environment and workstyle.

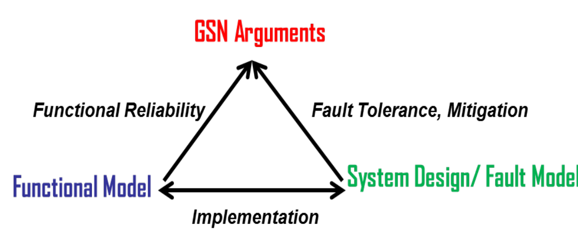

Figure 9: Representation of relationships between GSN Argument, Function Model, and System Design/ Fault Model

The SEAM platform can be used to evaluate any spacecraft system. However, it is especially useful for small satellite applications with short development timeframes and significant utilization of COTS components. It incorporates SysML internal block diagrams to represent the spacecraft system architecture model to demonstrate radiation fault propagation through the system. Its capabilities allow users to assessment the radiation performance of their spacecraft design without relying on intensive radiation testing, or even extensive knowledge of the electronic components themselves. As a result, the SEAM capabilities allow assessment of the radiation performance of a spacecraft without relying on intensive radiation testing campaigns, or extensive physical knowledge of the electronic components.

Goal Structuring Notation (GSN) provides a framework for setting radiation concern requirements. It is a visual that allows the system to operate correctly within the specified (radiation) environment. GSN is very useful in being able to track the reasoning behind radiation hardness assurance decisions, such as justifications and supporting data. These types of analyses are extended using SEAM.

An image of a SEAM model for a Discrete LED can be found in Figure 8. It shows a GSN model in the editor canvas. Engineers can choose modeling elements from the model parts panel on the same page as Figure 8. Specifically, SEAM allows users to create project libraries for both components and failure labels. These libraries reduce the overall creation time of the models, thereby making modeling easier for new users.

An instance of a component in SEAM is created when such a component is added into the editor. The elements of a component can then be modified in the attributes panel on the bottom right. They can also be modified by double-clicking on the elements in the model editor canvas.

If changes need to be made to all the instances of a component, the template in the library can be modified and all instances will be updated. This makes it easy to update the models as components change. Failure labels are all defined in the project definitions used throughout the SysML model.

COMPONENTS SHARED BETWEEN SEAM & RGENTIC

As mentioned previously, RGENTIC has 66 total part types, which are categorized in 14 families:

- Clocks/Timing (4 part-types)
- Digital (5 part-types)
- Discrete (4 part-types)
- Discrete Power (7 part-types)
- Discrete RF (8 part-types)
- Embedded Devices (4 part-types)
- Interfaces (6 part-types)
- Linear (5 part-types)
- Logic (2 part-types)
- Memory (4 part-types)
- Logic (2 part-types)
- Memory (4 part-types)
- Mixed Signal (5 part-types)

Vanderbilt is at work creating radiation model templates corresponding to those in RGENTIC, with the same nomenclature. In addition, the following list shows all the radiation concerns in RGENTIC:

- Single Event Latch-up
- Single Event Burnout
- Single Event Transients
- Single Event Function Interrupt
- Single Event Gate-Rupture
- Multiple Bit Upset
- Total Ionizing Dose
- Displacement Damage Dose

Currently, families for Discrete Power, Discrete RF, Discrete Signal, Embedded Devices, Memory, Opto-Electronics, and Sensors have been completed.

EXAMPLE OF INTERFACING RGENTIC & SEAM

Let's use the LED template as the example for interfacing RGENTIC & SEAM. First, we begin by looking at the LED's intrinsic functionality, which is that an LED takes in power and outputs light. DDD is the only applicable radiation effect in this respect, which leads to the anomaly "Degraded Brightness." This is associated with the generic failure label "Gradual Power Change." This failure label is what propagates outside the part and into the rest of the system. This is representative of a generic LED. RGENTIC then outputs a JSON file with this information.

The goal for this interface is to have RGENTIC's JSON file automatically upload into SEAM and create a secondary family library that contains the parts identified in RGENTIC. The interface between these platforms can be streamlined through the creation of a SEAM global part-type library with templates based on radiation effects in part-type families such as sensors, processors, voltage regulators, etc. 7 of the 14 part-type families defined in RGENTIC have been integrated into SEAM templates. Ultimately, all 66+ part-types from the RGENTIC look-up table will be included in the SEAM global part library.

The part templates can be used to populate each project-specific part library in SEAM, ensuring all RGENTIC's part-types are represented, and the radiation effects are consistent between the two. The harmonization process between RGENTIC and SEAM begins as follows: designers input a detailed knowledge of their system and mission into RGENTIC, which then outputs a generic part-type list that associates each part-type with potential radiation concerns.

The RGENTIC part-type list is then downloaded in a SEAM-readable file, which SEAM uses to populate the initially blank project with the part templates that correspond to RGENTIC's output. The final product is a system fault model using a project-specific radiation effect part library.

CONCLUSION

Connecting mission profiles to the radiation vulnerability assessment process enables the creation of an easy-to-use tool for satellite designers (and especially CubeSat teams) to identify radiation problems early in the design cycle. As mentioned, RGENTIC outputs descriptions of radiation risks based on a selected mission environment. SEAM evaluates radiation vulnerabilities to develop an assurance approach for electronic parts in space systems. Table 1 provides a concise overview of how the two tools can have established relationships with each other.

Table 1: Establishing Relationships between Tools

RGENTIC	SEAM
• Look-up table of parts and effects	• Global part library
• Generic parts list	• Project-specific part library
• Information is descriptive, provides guidance	• Information is Boolean, yes/no does an effect occur
• No connection between components	• Shows connections between components

This paper describes how RGENTIC and SEAM have been combined to simplify the radiation classification and identification process in SEAM for mission profile analysis. The paper also gives examples of radiation part-type model for electronic part families that can be used as starting points for user analysis in SEAM. Each user-created final product is a system fault model using a project-specific radiation effect part library. Currently, 7 of the 14 part-type families in RGENTIC have been incorporated into SEAM. Next steps are to complete incorporating all the part-type families, as well as enable SEAM to seamlessly accept RGENTIC output upon completion.

Acknowledgments

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