Reliability-based Electronics Shielding Design Tools

J.W. Wilson[1], P.M. O'Neill[2], T.A. Zang[1], J.E. Pandolf[1], R.K. Tripathi[1],
Steven L. Koontz[2], P. Boeder[3], B. Reddell[3], C. Pankop[3]
[1]NASA Langley Research Center, Hampton, Virginia 23681
[2]NASA Johnson Space Center, Houston, Texas 77058
[3]The Boeing Company, Houston, Texas 77058
POC: john.w.wilson@nasa.gov

Abstract

Shielding design on large human-rated systems allows minimization of radiation impact on electronic systems. Shielding design tools require adequate methods for evaluation of design layouts, guiding qualification testing, and adequate follow-up on final design evaluation.

Introduction

It is well established that space radiation shielding provided by large-scale human-rated spacecraft is an important consideration for single event upsets (SEU) in avionics systems (Shinn et al. 1995, 1998). Furthermore, provision of appropriate design methods is critical to the use of low-cost commercial-off-the-shelf (COTS) electronic devices with their, often, high-radiation sensitivity and manufacture variability. A similar shield design tool development activity for human protection under the Constellation Program already includes evaluation of the natural and induced environments mapped throughout the modeled vehicle to assure astronaut safety, thus providing most of the software framework required for electronics shield design and evaluation. The present project would prepare modified software tools for use in electronics shield design with appropriate National Aeronautical and Space Administration (NASA) mandated verification and validation processes using the Space Shuttle and the International Space Station (ISS) flight data (Wilson et al. 2006a). This development provides a well-validated tool for use in the Crew Exploration Vehicle (CEV) design with first design validation in low Earth orbit (LEO). User-friendly design engineering interfaces to follow preliminary design concepts to final engineering design are being developed (Wilson et al 2004). Provision for multidisciplinary optimization (MDO) processes (Qualls et al. 2003) and reliability design methods (Wilson et al. 2004) supported by high-speed computational procedures will be discussed. Currently, only the NASA-developed HZETRN code has been identified for this purpose within the NASA design standard STD-3000. As a result, Wilson et al. (2005) have prepared a review of past HZETRN code development, verification, and validation activity. This design tool is of utmost importance for electronics placement in future large-scale human rated systems.

Design Tool Development

A schematic overview of the design tool functionality being developed under NASA's Constellation Program is shown in Fig. 1. Spacecraft shield geometry specification is a central part of model development but the response of sensitive systems (such as human tissue, materials, or electronics) is an integral part of the design process as indicated in the top tier of the figure. The analysis/interface tools imply interaction with other non-radiation related tools shown on the bottom tier of the figure. Current interest is integration of flight data as shown on the middle tier of the figure. This requires interfacing with ISS models and detector response functions, and comparing with flight measurements to validate the galactic cosmic ray (GCR) and South Atlantic Anomaly (SAA) tool functionality. Present application focus is on web-based analysis tools with on-the-fly model building for Constellation development teams.

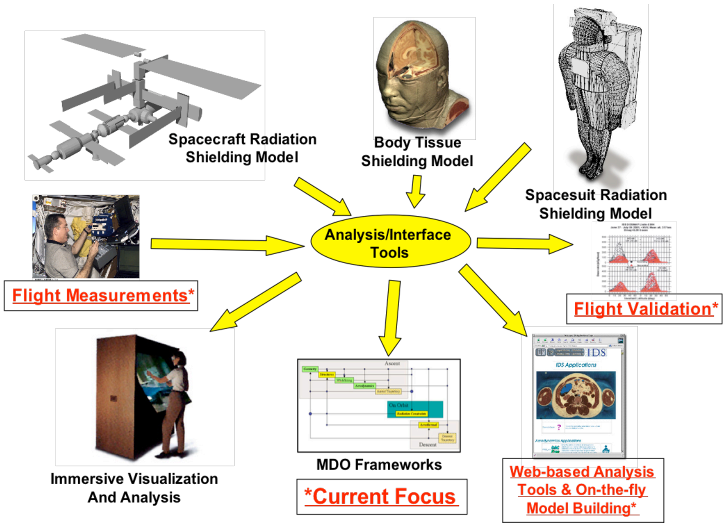

Fig. 1. Schematic overview of radiation analysis and design tools. Current focus denoted by *.

Enabling Technology

The development of such a tool is enabled by high-performance computational methods based on direct solution of the Boltzmann transport equation. This multi-dimensional system of partial-differential-integral equations defined over three position variables $\boldsymbol{x}$ and three motion variables $\boldsymbol{\Omega}, E$ describe all of the processes by which ionizing radiation interacts with bulk materials including molecular, atomic, and nuclear processes. The Boltzmann equation describes the radiation flux of type j particles $\phi_j(\boldsymbol{x},\boldsymbol{\Omega},E)$ (including photons) as

$$\boldsymbol{\Omega}\bullet\nabla\phi_j(\boldsymbol{x},\boldsymbol{\Omega},E) = \sum_k\int \sigma_{jk}(\boldsymbol{\Omega},\boldsymbol{\Omega}',E,E')\ \phi_k(\boldsymbol{x},\boldsymbol{\Omega}',E')\ d\boldsymbol{\Omega}'\ dE' - \sigma_j(E)\ \phi_j(\boldsymbol{x},\boldsymbol{\Omega},E)$$

where $\sigma_j(E)$ and $\sigma_{jk}(\boldsymbol{\Omega},\boldsymbol{\Omega}',E,E')$ are the shield media macroscopic cross sections, and incoming flux is specified at the material boundary. The $\sigma_{jk}(\boldsymbol{\Omega},\boldsymbol{\Omega}',E,E')$ represent all those processes by which type k particles moving in direction $\boldsymbol{\Omega}'$ with energy E' produce type j particles in direction $\boldsymbol{\Omega}$ with energy E *(including decay processes)*. The solution methods are based on combinations of physical perturbation, asymptotic expansions, and numerical procedures (Wilson et 2005). Monte Carlo codes (HETC and TIGER) have played an important role in verification of the combination of analytical and numerical procedures as shown in Figs. 2 and 3.

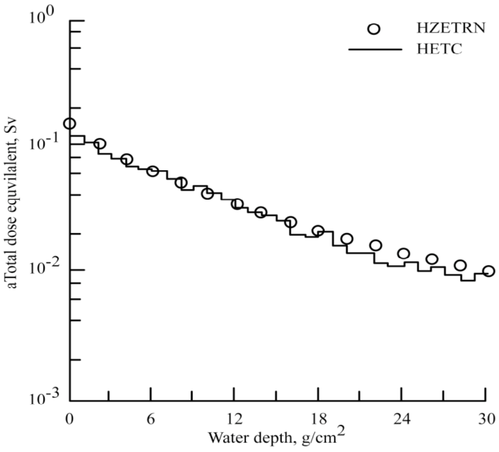

Fig. 2. Verification using dose equivalent evaluation with HZETRN and HETC in 30-cm water shielded by iron at 20 g/cm^2 from the Webber model solar particle event.

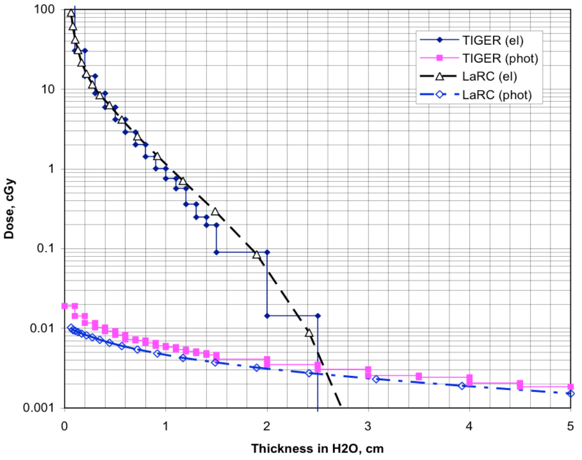

Fig. 3. Verification using dose in water for incident electrons according to LaRC ELTRN and the Air Force TIGER code.

Validation follows two tracks. The first track is the validation of basic computational procedures and databases (molecular/atomic and nuclear) using well-defined particle beams and detailed experimental characterization of the resulting fields produced in materials (Wilson et al. 2005, 2006b). The second validation method is through flight measurements involving specific flight platforms. Unlike the laboratory validation where the radiation source and material geometry is simple and well understood, flight validation is often limited by uncertainty in environmental models, uncertainty in material arrangement, and properties of complicated spacecraft. Otherwise, flight validation represents more accurately the engineering design problem. An example flight validation using the Liulin-094 detector system in the forward compartment of the US Laboratory of ISS during 27 June-4 July 2001 (Dachev et al. 2006) is shown as a single pass through the SAA along a descending phase trajectory in Fig. 4 in comparison to the current modeled values (Wilson et al. 2007). Improved definition of the SAA is required.

Electronic Response Models

The computational models with verification and validation processes discussed to this point are common to any shield design problem whether it is for protection astronauts, various materials, or electronic devices. Specific shield design applications is through the specification of responses and mission design requirements. Similar to the case of human protection, response functions are driven by basic physical processes through which energy is transferred to sensitive materials or tissues. There are two main processes by which energy is transferred to sensitive materials. The first process is the transfer to the orbital electrons leading to direct ionization, and the second process is the displacement of atoms from well ordered lattice sites on which the device function depends. The transfer of energy from a passing energetic ion to orbital electrons provides a local electron flux propagating from the ion path into the material producing additional ionization and excitation. Aside from the addition of dose to the bulk material, these electrons produce a current (if local electric fields are present) and additionally initiate chemical change in materials through ionization and excitation processes. The high-energy density in electronic devices provide high electron-hole pair densities near the central track of the ion path resulting in Auger recombination effects limiting the response of electronic devices depending on the exact nature of the energy deposit and the charge collection time of the device.

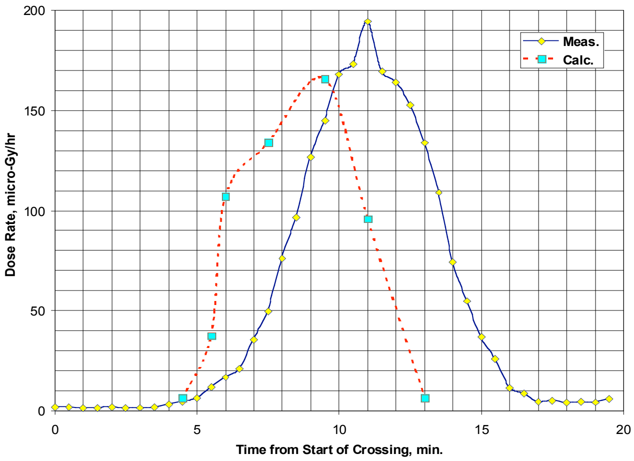

Fig. 4. Dose rate measured on a single descending passage through the heart of the SAA compared to computational model results.

Auger recombination effects for low-energy target fragments within electronic devices is demonstrated in the Shuttle computers (Shinn et al. 1995) with results of SEU rate (SEU/computer-day) for STS-51 at low orbit inclination and STS-56 at high inclination shown in Table 1. The SEU from target fragments produced mainly by protons and neutrons colliding with the Si nuclei of the memory chips is grossly overestimated if the Auger processes are ignored (Shinn et al. 1995, 1998). With Auger recombination, reasonable agreement is obtained with computational models as seen in the table.

Table 1. Shuttle shield and memory SEU model validation (SEU/computer-day).

Mission	Flight data	Model
STS-51	2.13	1.52
STS-56	6.05	5.85

Spacecraft Analysis Method

It is instructive to go through a specific design process to see how the above tool elements are integrated to accomplish an end design product. The SAGE-III instrument (Fig. 5) samples light from the Earth's atmosphere and passes it down an optical bench to a quartz grating which is focused on a charged-coupled device (CCD) array to quantify the optical frequency distribution. The CCD is sensitive to displacement damage in its active layers. It was anticipated that energetic trapped electrons would be a major limiting factor in the performance of the device, and a tantalum shield was planned because of the efficient multiple scattering limiting electron penetration. A detailed shielding model was developed as shown in Fig. 5 for the analysis. Although the electron induced displacements were indeed the major contributor to CCD degradation as expected, neutrons produced in the tantalum shield that also contributed to driving the CCD beyond requirements. An aluminum detector shield was designed to adequately limit electron penetration and reduce the neutron component as shown in Fig. 6.

Concluding Remarks

The Constellation Program requires verified/validated/standardized analysis, design, and testing procedures for quality assurance of future hardware. This involves the improvement and validation of environmental models and computational procedures for Constellation design teams. From a hardware perspective, environment and shielding design tools will be coupled to hardware specific damage functions of which the first level is evaluation of basic physics models for total ionization, displacement damage, and linear energy transfer spectra. These basic quantities then couple to specific device response models with shielding analysis and shield materials optimization. The output of such analysis would include design specific testing protocols for qualification that assures the proper mix of basic physical processes (dose, dose rate, displacement damage, and LET spectral contributions) to be matched to available accelerator capabilities (electrons, protons, high energy heavy ions). The design tool software can then be run in a design validation to qualify with test-flight data in low Earth orbit for design prediction validation mode for Lunar and Mars mission design validation. Developing design tools plays a central role in the above processes and at minimum added costs when leveraged out of the human protection program.

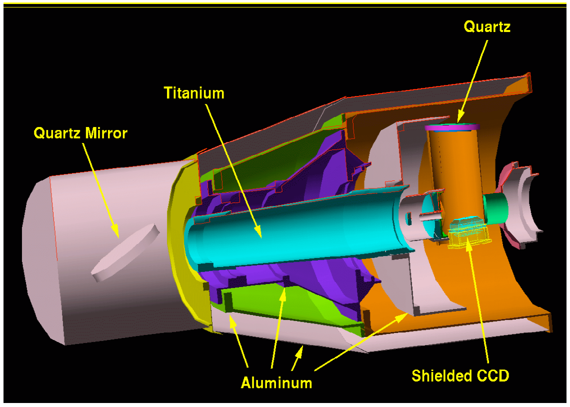

Fig. 5. SAGE-III shielding model used in CCD shield design.

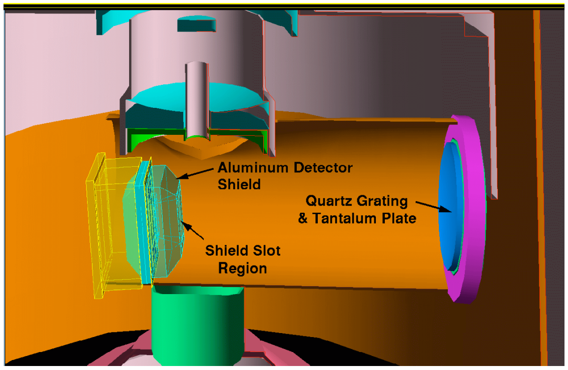

Fig. 6. Final SAGE-III detector shield with aluminum alloy.

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