Analyses and Methods of Solid Rocket Motor Material Irradiation at Marshall Space Flight Center

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I. Introduction

The search for life on other worlds is among humanity's greatest endeavors. Europa represents the most probable location to discover extraterrestrial life in our solar system, owing to its surface composition of ice covering a liquid water ocean, warmed by the tidal forces of its orbit around Jupiter. Unfortunately, the Jovian system hosts the most intense planetary radiation environment in the solar system due to the charged particles, namely electrons and protons, trapped by Jupiter's immense magnetic field. Any mission that attempts to approach or land on Europa must survive this radiation environment [Hand et al, 2017].

Radiation effects were identified as a priority risk to the successful development of a deorbit stage and solid rocket motor (SRM) early in the Europa Lander De-orbit Stage project concept. The effects of primary concern tend to occur very near the outer surface of the SRM. The charged particles deposit their energy quickly and are mostly stopped in the outer metallic case, but a significant portion of radiation penetrates through the bondline and outer propellant regions. High doses of ionizing radiation are known to cause significant changes to mechanical properties of many materials, especially polymers. For polymers such as the rubber-like materials (elastomers) in a solid rocket motor, the primary damage mechanism is known as cross-linking, in which ionization causes the restructuring of the matrix of long polymer chains. Ionization energy breaks the long polymer chains and allows formation of new cross-linked bonding sites. This hardens and often strengthens the polymer, but at the cost of decreased flexibility (or modulus).

Propellant, insulation, liner, and pyrotechnic materials were identified as higher risk items, and so were irradiated at Marshall Space Flight Center (MSFC) for investigation of changes in mechanical and ballistic properties. This process required significant levels of analysis to evaluate how the radiation environment evolves within the spacecraft during the mission, and also to evaluate how dose is delivered into test articles within the irradiating facilities.

II. Radiation Analysis – Environment Evaluation

A. Density corrections

Radiation dose levels were initially provided to MSFC by JPL's radiation analysis group in the form of tabulated 1D dose-depth charts. These tables give an estimate of total ionizing dose (TID) behind various thicknesses of aluminum. Dose levels are driven primarily by the density-thickness (or areal mass) of any material that separates the region of interest from free space, and so it is a reasonable approximation to scale the material thickness as a ratio of densities for other materials. For example, a 100 mils of aluminum approximately carries the same mass as 1.58 mm titanium. Those tables and approximations were also applied to estimate dose to pyrotechnic initiators and hardware, as shown in Figure 1.

B. MONSOL Monte Carlo Radiation Transport

Improved analyses of radiation depth dose were performed using other tools. A visiting faculty collaborator, Prof. Miloshevsky, produced one such depth-dose profile using an independently produced and validated Monte Carlo code named MONSOL. The input for analyses were based off the particle fluence spectra shown in Figure 2. Results were in good

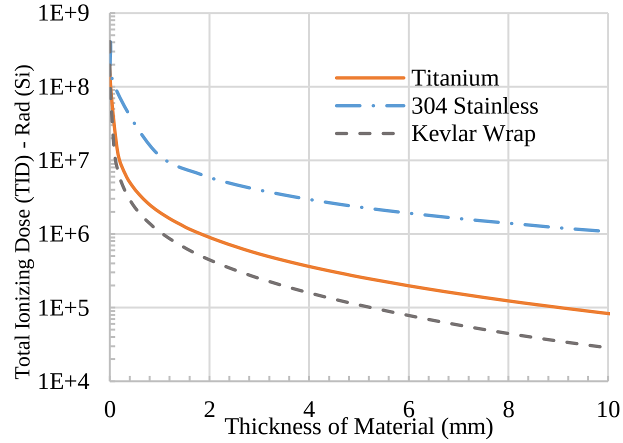

Figure 1. Density corrections were used for initial rough estimates of dose behind varying layer thicknesses of materials exposed to the Europa Lander mission radiation environment.

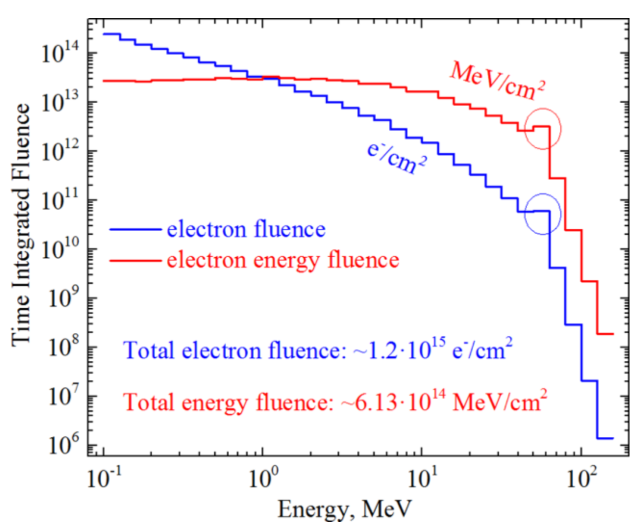

Figure 2. Total time-integrated electron energy spectrum provided for Europa lander mission.

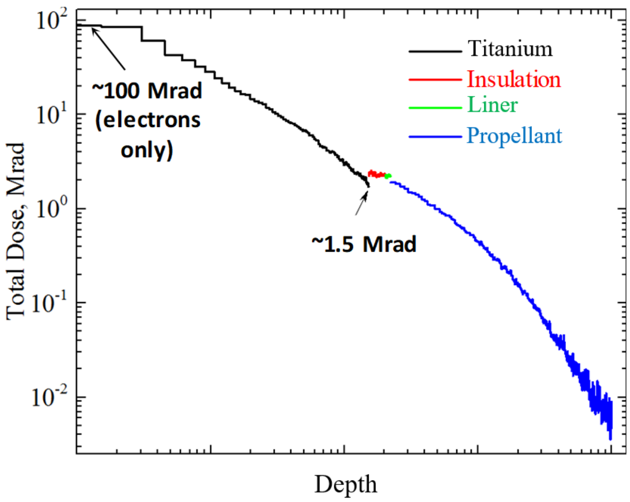

Figure 3. MONSOL simulation of depth-dose from electrons in a notional solid rocket motor used for braking stage of a Europa lander mission.

agreement with the approximations made from the JPL-provided dose estimates, shown in Figure 3. This data was also used at that time to develop a method of analysis for radiolysis of ammonium perchlorate [Miloshevsky et al, 2017].

C. *Geant4 Monte Carlo Radiation Transport*

A more detailed radiation transport analysis was conducted with contracted help from a researcher, John Watts, at the University of Alabama Huntsville. Considerable effort was put towards developing a functional model that supported evaluation of depth-dose profiles from the environment, and to explore gamma irradiation options at external facilities. Work on this model is ongoing and will be used to better assess the radiation dose burden to specific locations on the spacecraft.

III. Irradiation Experiments and Supporting Analyses

A. *MSFC Irradiation Facilities*

A variety of materials expected to be used for a deorbit stage were irradiated for early determination of their risk posture, including live propellant, inert simulated propellant, insulating materials, and pyrotechnics. The results of those experiments are discussed elsewhere [Soler-Luna et al, 2019]. MSFC facilities were used for these experiments, primarily from the Combined Environmental Effects Facility (CEEF), a Pelletron capable of delivering electrons at energies up to 2.5 MeV over a 38 cm diameter target area with flux of 0.1-12 nA/cm^2. It can also deliver protons over the same area with energies up to 700 keV and flux of 1-9 nA/cm^2. Samples in this facility must be pumped down in a hard vacuum and mounted to a sample plate as in Figure 4.

A high-power X-ray system is also used for irradiating hardware in atmosphere. It features a 320 kVp, 4000W max power beam head that can deliver approximately 1 Mrad/hour of ionizing dose to an area of about 10 cm diameter, or proportionately decreased rates across larger areas. X-rays permit greater penetration of dose than those provided by the Pelletron. A high dose rate ion chamber is used to calibrate dose delivery to samples, and can be embedded within material phantoms to account for attenuation.

B. *Experiment methodology*

Neither of the MSFC irradiation facilities described above is able to exactly replicate the Europa radiation environment, which includes electrons with energies extending beyond 100 MeV (though with decreasing frequency as energy increases). Nor can it replicate the high energy proton radiation spectrum, however most experiments have so far focused on the more deeply penetrating electron radiation component.

Experiments have therefore only sought to recreate the estimated total ionizing dose anticipated for a given material in a specific location. To that end, two reasonable assumptions must be made at this phase of risk reduction: First, dose evaluated at a given point delivered through electron radiation has the same relative effect as dose delivered by high energy electrons or by X-rays/photons (in which secondary electrons are the main contributor of energy deposition). Second, that dose rate is not a significant factor in material degradation for the selected materials.

C. *EGSnrc Monte Carlo Radiation Transport*

Irradiation experiments were carefully designed such that the sample received a dose that was uniform across the entire region of interest. In some cases, this required considerable effort to model the experiment computationally. For the electron beam, it was possible to flatten the dose profile through the depth of material by prescribing a set of multiple particle energies with varying irradiation times, and then irradiating both sides of the sample such that the 'straggling' tails of electron range intersect one another at the sample's centerline. See Figure 5.

D. *MCNP6 Monte Carlo Radiation Transport*

3D radiation deposition analysis was performed to examine uniformity of dose delivered by electron beam to samples of non-uniform depth, as shown in Figure 6. It was determined that

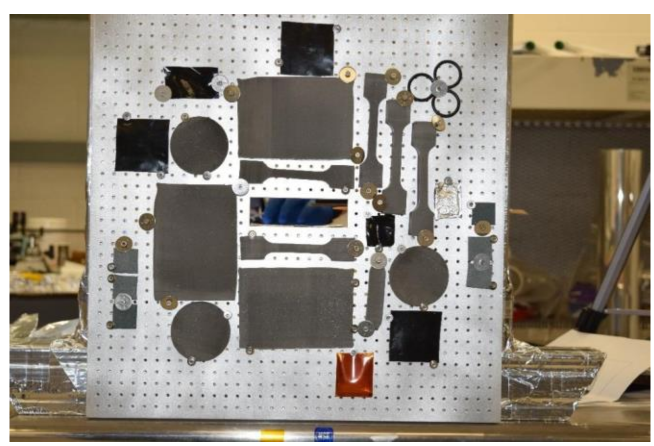

Figure 4. Various in-house solid rocket motor material samples prepared for electron beam irradiation as a pathfinder experiment.

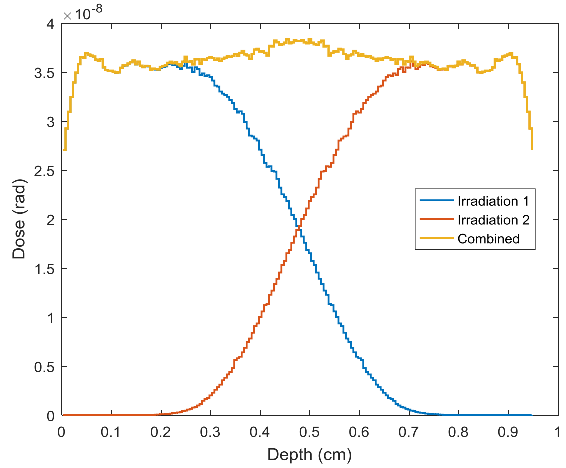

Figure 5. EGSnrc simulation of dose distribution through a sample irradiated on both sides (blue is incident from left, orange from right), also applying multiple beam energies (note three faint peaks on each side). The combined dose profile (yellow) is then relatively flat through the depth of the sample.

samples such as those shown in the figure would be best irradiated while embedded within a holding block that approximately matches the density of the sample. The sample can then be irradiated as if it were a simple slab geometry, and dose can be distributed uniformly as in Figure 5. MCNP6 was also used to model an X-ray beam head and evaluate dose delivered at depth for pyrotechnic hardware, and to evaluate options for full-scale motor irradiation.

E. *NUMIT Charging Analysis*

Deposition of charged particles within an insulating material yields a charge imbalance (deep dielectric charging) that has the potential to result in dielectric breakdown, also referred to as

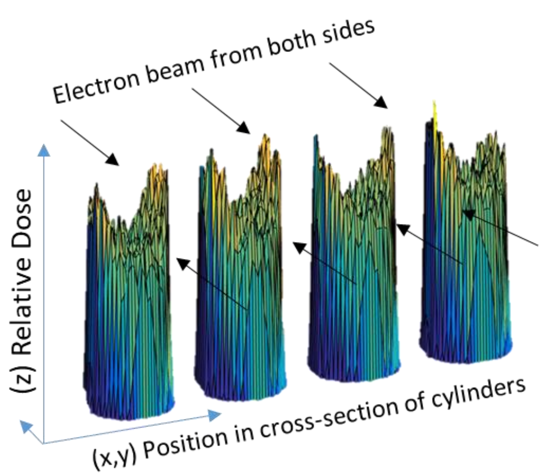

Figure 6. MCNP6 simulation demonstrates highly non-uniform dose distribution in cylindrical samples irradiated by an electron beam.

'internal electrostatic discharge' (iESD). This phenomenon can

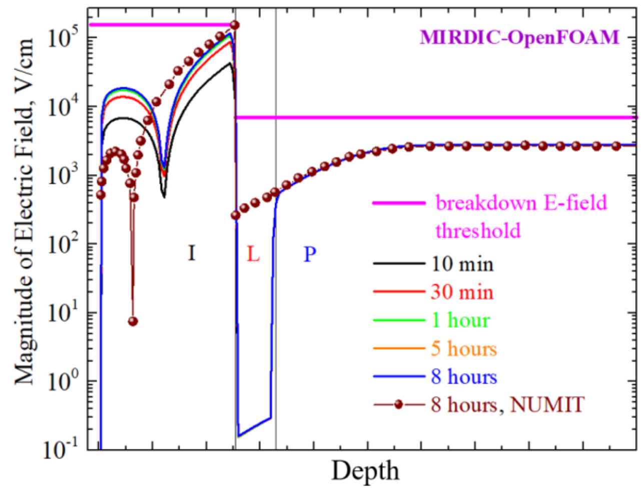

Figure 7. Coupled transport and charging analysis simulation for propellant/liner/insulation samples irradiated in the MSFC electron beam

occur in the space environment, but can also occur while irradiating insulating materials with an electron beam [Schneider et al, 2019], and so is also of interest for the purpose of safety while evaluating energetic materials. 1D analysis of this effect was performed using the NUMIT code [Kim, 2012], the results of which affected the selection of electron flux that could be applied to live propellant samples during irradiation.

F. *Geant4 and OpenFoam coupled charging analysis*

An experimental code was developed by Prof. Miloshevsky in collaboration with MSFC that coupled Geant4 with the OpenFoam general finite volume 3D solver. This could then track deposition of charge through radiation transport (Geant4) and then evaluate propagation and buildup of that charge within a dielectric material (OpenFoam). An example of that analysis is shown in Figure 7. [Miloshevsky and Caffrey, 2018]

IV. CONCLUSION

MSFC support of the Europa lander deorbit stage risk reduction has involved a significant degree of unique analysis and experimental work. The intense radiation environment of this mission concept has provided the opportunity to use and improve upon MSFC capabilities, many of which carry over directly to other project and customer needs.

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