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Radiation Transport and Shielding Challenges at NASA Marshall Space Flight Center

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Introduction

Several unique radiation transport and shielding challenges for various spacecraft and ground test facilities have recently been explored at NASA Marshall Space Flight Center (MSFC). Many radiation transport methods and code packages have been utilized during this effort, and some additional analytical tools have been developed to support this work. This includes the development of a nuclear thermal propulsion stage, in which radiation damage to hardware, radiation heating, and crew dose must be assessed for a large spacecraft. Radiation shielding for such a stage must be optimized to minimize weight, and additional dose consequences are expected from cosmic sources. Development of a nuclear engine requires ground test facilities, which themselves require significant development effort that includes deep-penetration shielding analysis for facility design and site selection. Additional radiation transport analysis has been performed in support of a notional lander mission to Europa, the icy moon of Jupiter. The radiation burden to spacecraft has been analyzed, and charged particle radiation transport methods have been utilized to apply correct doses to material samples in ground test facilities.

Nuclear Thermal Propulsion

Nuclear thermal propulsion (NTP) is among the leading candidates of in-space propulsion for a crewed Mars mission, due to its high specific impulse, or I_{sp} (analogous to 'fuel economy'), as well as its high thrust capability. This permits the shortest transit times and the most robust set of launch opportunities compared to other viable alternatives. The basic premise is that a compact (~1m L by ~1m D), high-power (>500 MWth) nuclear reactor acts as a flow-through heater for a propellant gas, which is then ejected from the nozzle at high velocity and yields thrust to the spacecraft through conservation of momentum. Hydrogen is an ideal candidate due to its low molecular mass, but it must be kept at cryogenic temperatures to maintain liquid state, and even then it is of such low density that it requires multiple large storage tanks to carry the amount needed for a round-trip to Mars. The storage tanks reside between the engine(s) and crew habitat, affording shielding during nearly all of the engine operation. Shielding analysis for this architecture presents several challenges, including a mixed neutron-gamma field during operation, transient gamma field after shutdown, transient thickness of propellant, and extremely deep penetration through propellant. Shielding must be optimized using multiple materials across multiple dimensions to reduce total mass and balance crew dose burden and thermal effects to propellant. To accomplish this task, a workflow has been developed that utilizes MCNP6[1], ADVANTG[2], and a variety of custom scripts and methods, including a multiobjective evolutionary optimization algorithm.[3]

Ground test facility analysis has been marginally less complex, and requires more traditional nuclear shielding techniques. Many of the same tools and techniques used above still apply, but optimization of shielding deals more with dose through thick structures and at large distances through air.

Space environment radiation analysis for a Europa mission primarily deals with the dose consequence of the extreme charged particle flux trapped by the magnetic field of Jupiter. Equipment exposed to this environment for even a short period (hours) can receive total ionizing dose (TID) in the range of several hundred Mrad. Much of that dose burden is due to sulfur, oxygen, and protons with minimal penetration. However, a significant fraction is due to high energy electrons, and material with only modest shielding (several mm Al equivalent) may encounter several Mrads TID. Test articles irradiated in the electron beam at MSFC's Combined Environmental Effects Facility (CEEF) must be modeled using charged particle Monte Carlo analysis to ensure a proper dose profile. Dose uniformity (or proper dose gradients) are targeted using electron transport codes, and the beam energy and sample manipulation procedures are modified to meet those targets. Many of these test articles include energetic or explosive material, limiting the availability of irradiation facilities. Alternative methods, including irradiation using high power X-ray devices, are also being explored for feasibility.

References

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