ANS NETS 2018 – Nuclear and Emerging Technologies for Space
Las Vegas, NV, February 26 – March 1, 2018, on CD-ROM, American Nuclear Society, LaGrange Park, IL (2018)

INTEGRATED NTP VEHICLE RADIATION DESIGN

Jarvis A. Caffrey[1]
Mitchell A. Rodriguez[2]
[1]*NASA Marshall Space Flight Center, Huntsville, AL 35811, 256-544-8464, jarvis.a.caffrey@nasa.gov*
[2]*Jacobs Space Exploration Group, Huntsville, AL 35806, Mitchell.a.rodriguez@nasa.gov*

The development of a nuclear thermal propulsion stage requires consideration for radiation emitted from the nuclear reactor core. Applying shielding mass is an effective mitigating solution, but a better alternative is to incorporate some mitigation strategies into the propulsion stage and crew habitat. In this way, the required additional mass is minimized and the mass that must be applied may in some cases be able to serve multiple purposes. Strategies for crew compartment shielding are discussed that reduce dose from both engine and cosmic sources, and in some cases may also serve to reduce life support risks by permitting abundant water reserves. Early consideration for integrated mitigation solutions in a crewed nuclear thermal propulsion (NTP) vehicle will enable reduced radiation burden from both cosmic and nuclear sources, improved thrust-to-weight ratio or payload capacity by reducing 'dead mass' of shielding, and generally support a more robust risk posture for a NTP-powered Mars mission by permitting shorter trip times and increased water reserves.

I. INTRODUCTION

Radiation exposure is among the most prominent challenges for crew health and safety associated with a crewed mission to Mars. There is a large degree of uncertainty for the health consequences associated with the space radiation environment, as well as general public unease to the concept of radiation exposure. Thus it will be prudent to minimize the radiation burden received from all sources of radiation. The general practice of minimizing dose is known by the acronym "ALARA", or "As Low As Reasonably Achievable", and such a philosophy may also be implemented in the design and operations of an interplanetary mission. Specific dose limits will also likely be prescribed, based on the limited available data for health effects in the cosmic radiation environment.[1] For the purposes of early planning, it is assumed that such limits would need to account for radiation received from all sources, including galactic cosmic rays (GCR), solar energetic particles (SEP), and nuclear sources in the case of a Nuclear Thermal Propulsion (NTP) vehicle. An integrated design that accounts for mitigation of all radiation hazards will therefore benefit by sharing mass allocations, thereby reducing all radiation-related risks.

I.A. Cosmic Radiation Sources

There are two distinct sources of space radiation for any interplanetary mission addressed in this paper, GCR and SEP, each with a unique risk profile and mitigation strategy.

I.A.1. Galactic Cosmic Rays (GCR)

GCR are a form of radiation originating outside of the solar system, assumed to be produced from distant extreme events (i.e. supernovae), and are comprised of a large variety of charged particles with a range of kinetic energies. This can include lower mass ions such as Helium, but the most concerning particles in this classification are those with high energy and high mass or proton number (Z), typically referred to as HZE particles. These include heavy nuclei (such as iron) with kinetic energies exceeding GeV levels, but the flux of particles is inversely proportional to their kinetic energy.

The main characteristics of GCR are described briefly with relation to dose effects. They arrive from all directions in space (isotropic). GCR are modulated by the solar wind, such that the inner planets experience higher GCR flux during periods of solar minimum. They are also partly shielded by the magnetic field of the Earth, such that GCR-induced dose is reduced in Low-Earth Orbit (LEO), but GCR becomes the primary dose contributor outside of LEO. They cannot be shielded effectively using traditional methods. In fact, heavy particles incident upon high-Z materials tend to produce a 'spallation' event, or a cascading shower of secondary particles that yields a higher dose consequence than if no shielding was present at all. Any shielding must utilize low-Z materials, especially those rich in hydrogen such as polymers or water. Due to mass requirements, it is generally considered unpractical to fully shield a crew from the GCR environment with current available technology, but consideration for use of existing mass may curtail a significant fraction of the GCR dose hazard.

I.A.1I. Solar Energetic Particles (SEP)

Solar activity can occasionally result in the expulsion of energetic particles such as protons, helium, and electrons. These are difficult to predict, and can arrive as an intense 'radiation storm', in which the flux could potentially be severe enough to cause near-term health effects. Fortunately, these forms of radiation are more easily shielded, but a crew habitat will need to incorporate a more densely shielded 'storm shelter' in the event of an imminent solar particle event.

I.B. Nuclear Radiation Sources

Two primary types of radiation are emitted from a reactor core during and after operation.

I.B.1. Neutrons

Neutrons are produced during fission of nuclear fuel, and are also the sustaining force that continues the fission process. Shutdown of a nuclear reactor is initiated by consuming the net excess of neutrons, forcing the power level to drop. Neutrons are generated at high energy levels, deemed 'fast', then slow primarily through elastic collision with low-mass nuclei. When a neutron is absorbed, it often produces a secondary emission of gamma radiation.

I.B.I1. Gammas

Gamma radiation is produced during nuclear reactor operation, and continues to be produced after shutdown to a much lesser degree. During operation these are generated directly in the fission process, from capture and inelastic scatter of neutrons (especially in hydrogen), as well as from the buildup of radioactive fission products and (to a much lesser extent) activation products. After shutdown, fission and neutron interactions cease quickly, but radioactive fission products and activated material remain for a longer period. These mostly decay rapidly, and will reduce intensity by several orders of magnitude within hours of shutdown. The inventory of delayed sources are determined as a function of the power output and duration of the engine operation.

II. RADIATION EFFECTS

There are three categories of radiation limits with respect to a nuclear thermal propulsion stage. Each can be considered independent in terms of risk profile, but they may share mitigation strategies and therefore mass allocations.

II.A. Material Damage of Components

Ionizing radiation can produce damage in materials through several mechanisms. Metallic and ceramic properties may be modified through dislocation damage from neutron and heavy ion collisions, but not likely to any substantial effect for the relatively short total exposure life cycle of a NTP stage. More concerning would be ionization damage in organics and polymers, especially sealing materials, in which the covalent molecular bonds are disrupted by direct ionization and production of free radicals. Most of these issues can be resolved by strategic placement of sensitive components, proper selection of materials, and spot shielding as needed.

II.B. Nuclear Heating of Propellant

Cryogenic propellant must be pumped out of the storage tanks, and most turbopumps are incapable of handling two-phase flow. If left unshielded or unmitigated, nuclear heating of propellant can result in thermal stratification and large spikes of propellant temperature as the tank is drained. Proper mitigation, such as mixing or flow redirection could allow heated propellant to perform work, possibly even with minimal shielding. This effect is likely to be the primary driver of shield design in the propulsion stage, but is highly system-dependent.

II.C. Health Effects in Crew

Interactions of ionizing radiation in living organisms are very complex and still rather poorly understood. Statistical models permit some prediction of health effects based primarily on historical cohort studies from large doses of gamma radiation. Extrapolation of those predictors down to low levels and to other radiation types (such as space radiation) is an ongoing field of research.

Radiation health effects are divided into two categories. First are stochastic (or probabilistic) effects in which radiation exposure increases the risk of cancer later in life due to damage and misrepair of DNA. This risk is assumed to be linearly proportional to the dose received, even at very low levels, but there remains significant uncertainty of actual low-dose radiation risks due to the high natural occurrence of cancer. This is the primary concern with respect to GCR exposure. Second are deterministic effects that tend to occur from acute high-dose exposures exceeding certain thresholds. These effects can include skin reddening (erythema), or cataracts, while extreme doses can result in damage to bone marrow, stomach lining, and the central nervous system.[2]

III. MITIGATION STRATEGIES

The strategies for radiation mitigation can be essentially reduced into three categories: material, geometry, and time. For terrestrial radiation protection, there is a similar breakdown of mitigation strategies: 'Time, distance, and shielding'.

III.A. Material

III.A.1. Dedicated Shielding

Ideal shield materials vary depending upon the incident radiation of concern. In the case of a mixed field, such as the neutron/gamma environment produced in a nuclear reactor, a laminated system that cycles layers of neutron shield and gamma shield is generally the preferred approach.

Neutrons are best absorbed by materials that feature a combination of two properties. First is low atomic mass, such that elastic collisions rapidly disperse (or 'moderate') the incident kinetic energy. Second is high cross-section of absorption, which is higher for lower energy neutrons than for the high energy state in which they are produced. Additional preference is given for materials that produce minimal secondary radiation or excessive heat during absorption. This narrows the list to only a handful of competitive candidates. For a low-Z moderator, hydrogen is ideal and can be in the form of pure liquid hydrogen, water, or a metal hydride. Other elements such as carbon and beryllium are also relatively effective. For absorption, boron and lithium each have components with very high cross section, and benefit in that they are relatively light atoms as well. Taken together, this generally reduces the ideal candidates to the following: Lithium hydride, which is the most effective per unit mass, but which has little operational history and has numerous operational constraints and technical challenges in manufacturing; or Boron carbide, which offers the greatest effectiveness per unit volume, has extensive operational history in nuclear applications and robust thermal and mechanical characteristics, but comes at the cost of up to 25% increase in required mass.[3,4]

Gammas are stopped through interaction with the electrons and electromagnetic field surrounding the nucleus of the atom, and are therefore most efficiently absorbed by materials with higher electron density per unit mass. These are all high-Z materials, and tungsten is generally the preferred candidate for space applications, with the main drawbacks being cost and difficulty in manufacture. Depleted uranium also works very well, but absorption of neutrons can cause excessive heating.

With respect to cosmic radiation, higher-Z materials should be avoided in the crew compartment to avoid production of secondary radiation. This applies to both solar particles and trapped particles, where electrons can produce secondary bremsstrahlung x-ray radiation, as well as to the HZE components of GCR which can produce a shower of secondary charged particles and neutrons. Those materials suited to neutron shielding also tend to be good crew shielding candidates.

Implementing those dedicated materials comes at the obvious cost of mass, and so the innate shielding capability of other materials must also be considered. Dedicated shield mass is still likely to be required for the purpose of protecting components or propellant near the engine, but minimization of this dedicated mass is a critical aspect of integrated vehicle design.

III.A.II. Propellant

Cryogenic liquid hydrogen is the assumed propellant for a NTP stage, and baseline vehicle architecture typically places the propellant in a series of elongated cylindrical tanks between the crew habitat and engines. Liquid hydrogen is an extremely effective neutron moderator, and does also capture neutrons. Unfortunately, gammas from the engine and from secondary production are poorly shielded by the liquid hydrogen, which has extremely low density, but it is still effective thanks only to the sheer volume inherent in the design of the full stage. Propellant is expended during engine operation, though, such that the vast majority of crew dose delivered by the engine will occur in the final minutes of the last burn of the mission.

III.A.II1. Supplies

A long duration crewed mission will require many tons of supplies and expendable materials, including food and water. Both of these, along with the resulting waste products, tend to be comprised mostly of lower-Z components that can function reasonably well as all-purpose radiation shields. If packaged and organized with this purpose in mind, namely by eliminating streaming paths and gaps, then it may be possible to entirely eliminate the need to add dedicated shield mass in the crew compartment.

III.B. Geometry

III.B.1. Distance

For any source that emits radiation isotropically and is of small size relative to the distance between emitter and absorber, it can be approximated that the flux is reduced as a function of distance squared. A nuclear propulsion stage lends itself to an obvious use of distance to separate crew from the engine by use of traditional rocket architecture. That is a stack of engine(s), propellant, payload/crew, in that order. Due to the very low density of hydrogen and large propellant requirements for a Mars mission, the resulting architecture is likely to incorporate at least 50 meters of separation between the propulsion units and crew habitat.

Application of increased distance can also be used in the placement of the engine with respect to the aft face of the propellant tank. In this case, increasing standoff distance inherently reduces flux through geometric attenuation, as above, but also reduces the required diameter of shadow shielding used to obscure the lines-of-sight between the reactor source and the propellant tanks. Such shielding is likely required to reduce propellant heat loads and scattering/secondary source terms to the crew habitat.

III.B.I1. Shadowing and scattering

A nuclear propulsion stage is an ideal candidate for the use of shadow shielding, in which a shield system resides near the source and blocks only the radiation emitted toward a conical region surrounding the spacecraft. This works well in the vacuum of space, where no scattering medium (such as air) is present to reflect the unshielded component of emitted radiation. Shadowing is also provided by the propellant with respect to crew dose, but this depletes through the mission and is practically eliminated at the end of the final burn. A shadow shield that casts a narrow shadow between engine and crew compartment (ignoring propellant and intermediate scatterers) will only mitigate a fraction of the dose contributors. The substantial fraction of particles that emit at more oblique angles and then scatter at the outer-aft corners of the propellant tank quickly overwhelm and dominate the source term. A conical tank design is beneficial in minimizing this effect and also reduces the required solid angle covered by the shadow shield. Additionally, the narrowed tank profile increases the optical thickness of propellant between engine and crew compartment for equivalent propellant volume, reducing crew dose levels accumulated in the final engine burn.

Ideal shadow shield configurations should utilize mass only in those regions that intersect the line-of-sight between an emitter and a sensitive absorber or scattering body. Optimization of a shadow shield system requires consideration for the relative merit of extending a shield to block a scattering body versus the consequence of generating additional scattering media in the shield itself.

Shadowing in the crew compartment can be used for all forms of radiation, including cosmic sources. During nuclear engine operation, especially those near the end of mission when less propellant is available as innate shield, supplies can be positioned to serve as supplemental shielding for crew dose. This can be fixed permanently, but a better option is to create a reconfigurable system. For all other times, the same shield material can be used to surround a crew sleeping quarters or storm shelter that effectively provides 4π shielding (from all angles), or can provide nearly 2π shielding for individuals working very near the external surface.

III.C. Time

Time of exposure to the space and nuclear radiation environment is primarily driven by mission architecture, for which the concern of radiation dose may serve as one design input among a myriad of others. There are several other drivers that encourage minimizing time in extraplanetary space, including effects of microgravity and long-term operation of life support systems, so that aspect of the mitigation strategy is left for separate discussion.

More pertinent to the present discussion is the manner in which a crew may spend their time within the vehicle over the duration of the mission. For instance, significant dose reductions could be realized if a crew sleeps within a well-shielded cavity, works against a large shielded surface, or shelters during solar particle activity and engine operations.

IV. INTEGRATED DESIGN

Considering all of the factors addressed so far, a method for an efficiently integrated radiation design of a crewed nuclear thermal propulsion mission may be realized. This proceeds as follows:

1) Determine radiation limits to propellant and cryogenic storage hardware, primarily associated with thermal conditioning of propellant during operation. Dedicate primary shield mass in the form of large-form internal or external (to the engine) shields to meet this requirement.

2) Determine radiation limits to components within and adjacent to the engine. Dedicate shield mass for any component not sufficiently protected by the primary shield system. This can involve either reallocating mass from an external shield ‘upstream’ to an internal shield, or inclusion of additional mass from spot-shielding individual components.

3) Determine the profile of radiation penetrating beyond the shielding prescribed above, and define the quantity of material required to adequately protect the crew (primarily in regards to the final burn of the mission). Use only material that can also be configured for protection against the space radiation environment within or near the crew habitat. Ideally, limit the material selection to supplies for which mass is already budgeted elsewhere (i.e., food or waste), or which have other benefits for mission risk reduction (large water supply).

V. CONCLUSIONS

The pervasive and highly penetrating nature of radiation, both from nuclear and cosmic sources, results in a shared environment that impacts nearly all systems of a crewed interplanetary mission. Development of a crewed nuclear thermal propulsion vehicle must include some degree of integrated mitigation for radiation hazards in order to eliminate wasted mass and wasted efforts. The most effective solutions will require early collaboration and communication between crew habitat and propulsion stage designers. The information and recommendations provided here are intended to aid and encourage that collaboration, and ultimately yield a more efficient and robust system architecture.

ACKNOWLEDGMENTS

Many thanks to Mike Houts and Harold Gerrish of Marshall Space Flight Center, for their insight and continuing support.

REFERENCES

1. NASA Space Flight Human-System Standard Volume 1, Revision A: Crew Health (NASA-STD-3001).
2. Cucinotta, F.A., et al., “Predictions of space radiation fatality risk for exploration missions”, Life Sciences in Space Research 13 (2017)
3. Lee, L.W., “Shielding analysis of a small compact space nuclear reactor” AFWL-TR-87-94 (1987).
4. Barattino, W.J., et al., “Review of previous shield analysis for space reactors” Space Nuclear Power Systems Symposium, Albuquerque NM (1984).