RADIATION DOSE ESTIMATES FOR TYPICAL PILOTED NTR LUNAR AND MARS MISSION ENGINE OPERATIONS

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Abstract

The natural and manmade radiation environments to be encountered during lunar and Mars missions are qualitatively summarized. The computational methods available to characterize the radiation environment produced by an operating nuclear propulsion system are discussed. Mission profiles and vehicle configurations are presented for a typical all-propulsive, fully reusable lunar mission and for a typical all-propulsive Mars mission. Estimates of crew location biological doses are developed for all propulsive maneuvers. Post-shutdown dose rates near the nuclear engine are estimated at selected mission times.

Introduction

Nuclear thermal propulsion systems offer a number of advantages both for fast piloted missions to Mars and for nearer term lunar missions. For all missions it is essential to protect the crew and payload from both the natural and the man-made radiation environments. Biologically significant natural radiation sources include the trapped particle belts, solar contributions, and galactic cosmic

rays. The man-made radiation source is the nuclear thermal reactor (NTR) powering the propulsion system. An operating propulsion engine is a potent source of neutron and gamma radiation. Fortunately, engine operating times are relatively short and large quantities of propellant are available for shielding during most of the time the engine is operating.

Natural Radiation Environment

The important components of the natural radiation environment encountered during lunar and Mars missions are galactic cosmic rays (GCR), solar contributions (solar wind, storms, and flares), and the geomagnetically trapped charged particle belts. The GCR particle background consists primarily of protons with some alphas and a small fraction of heavier ions. The high Z-number, high energy (HZE) particles are the primary contributors to the GCR biological dose even though they comprise only a very small fraction of the total particle population. High energy particles interacting in the vehicle structure and shielding are capable of producing substantial showers of secondary particles. The highly penetrating GCR presents a particularly difficult space shielding problem since biological doses decrease very slowly with shield thickness. Water shielding equivalent to about 25 g/cm² is required to reduce the GCR unshielded dose by a factor of two.¹ The galactic cosmic background is essentially isotropic. The maximum GCR biological doses occur at the minimum of the 11-year solar cycle and are typically a factor of two higher than at the peak of the solar cycle.²

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Energetic particles from solar flares also represent a significant threat to operations outside the Earth's magnetosphere. Even though solar flare frequency can be directly correlated with the 11-year solar cycle, the occurrence, intensity, and duration of individual events cannot be predicted. Numerous "ordinary" flares and one or more anomalously large events can be expected during a typical Mars mission. The anomalously large events result in potentially lethal doses for unshielded crew locations. Fortunately, solar flare biological doses are more responsive to shield thickness than GCR doses. Water shielding equivalent to 25 g/cm^2 reduces solar flare doses by about a factor of forty.¹

Round trip lunar and Mars missions must make a minimum of two transits through the Van Allen belts. Additional passages must be considered for missions utilizing multiple perigee propulsion maneuvers for Earth departure and/or highly elliptic capture orbits on Earth return.

Propulsion System Radiation Environment

An operating propulsion engine is an intense source of both gamma and neutron radiation. Important primary photon sources include prompt fission gammas, photons resulting from fission product decay, and photons produced by radiative capture and inelastic scattering events. Prompt fission and fission product decay gammas can originate only from the fueled regions of the reactor. Radiative capture and inelastic scattering events from other locations in the engine make significant contributions to the radiation environment. In particular, the radiation shield itself can be one of the most important contributing sources of gamma radiation at crew and/or payload locations. Another important photon source is scattering of primary gammas from major engine components external to the reactor core. Important scattering sources include the nozzle, tanks, and propellant lines. The operating engine provides a significant flux of both fast and thermalized neutrons.

After engine shutdown, fission product decay continues to provide a significant radiation source. The dominant fission product decay mode is by beta decay with emission of both photons and beta particles. A portion of the beta particle kinetic energy also appears as primarily low energy photons due to bremsstrahlung. The fission product decay source decreases rapidly after shutdown. The mag-

nitude of the time-dependent source strength depends on the engine operating history and decay time. The neutron source strengths from fission product decay, spontaneous fission, and photo-neutron production in moderators such as beryllium are minimal.

Prior studies^{3,4,5,6,7} have examined propulsion system generated radiation environments for a variety of NERVA-type engines and tank configurations. The gamma and neutron energy deposition rates in tissue are of the same order of magnitude in the vicinity of an operating engine. Because of the greater biological effectiveness of neutrons, the neutron contribution to dose will usually dominate for the unshielded engine. Dose rates decrease with distance approaching $1/r^2$ behavior at distances that are large compared to the reactor dimensions. Dose rates around the engine show little directional dependence except in a small cone about the forward axis. Doses along the forward axis are reduced by the shadow shielding provided by an internal shield in the engine, optional external disk shield, and propellant.

Based on the results reported in Reference 3, the NERVA internal shield and core support plate reduce the gamma leakage along the forward axis by about a factor of thirty. For the NERVA-class engines, an external disk shield mass of 4.5 MT (10,000 lb_m) typically reduces the forward gamma leakage by a factor of fifteen to twenty. The dose reductions provided by the propellant depend on the particular tank configuration and the quantity of propellant remaining.

The dose at crew and/or payload locations is dominated by the gamma component. The liquid hydrogen propellant serves as an excellent neutron shield. Even with only the small quantity of hydrogen (required for post-shutdown cooling) remaining at engine shutdown, the neutron dose remains insignificant compared to the gamma dose. The gamma dose rate during engine operation is a function of propellant level. The instantaneous dose rate may vary by three orders of magnitude or more from the tank full to tank empty conditions. The total dose for a particular engine operation must be assessed by integrating the instantaneous dose rate over the entire period of engine operation.

A number of resources may be employed to reduce crew location radiation exposures. These include shielding internal to the reactor, external

reactor shielding, vehicle stage configuration, propellant tank configuration, crew radiation shelters, and engine operational considerations such as total propellant residuals (cooldown plus margins) at engine shutdown.

Computational Methods

Three fundamentally different computation methods are typically employed in the analysis of nuclear propulsion system radiation environments. Monte Carlo analysis enables complex geometries to be accommodated in uncompromising detail. Disadvantages include high computational costs and the inevitable statistical uncertainty associated with all calculated quantities. One problem of particular interest, dose rates at crew locations, is a classic "deep penetration" problem and poorly suited to Monte Carlo analysis. Deterministic neutron transport methods may be applied in one-, two-, and three-dimensional representations of the actual geometry. Complete coupled neutron-gamma solutions may be obtained over the entire geometry. Computational costs increase with the number of spatial dimensions considered and can become prohibitive. Even with three-dimensional capability, some geometric modelling compromises are usually required. Point kernel techniques require the least computational resources and typically allow the same geometric detail as the Monte Carlo methods. Point kernel techniques are suitable only for photon transport problems. Photon source distributions in space and energy must be supplied to the point kernel calculation. Correction of the explicitly calculated uncollided photon fluxes to account for multiple scattering contributions usually involves some approximations.

Analysis of mature propulsion system designs usually involves some combination of all three methods. A typical approach might include two- or three-dimensional S_N analysis of the reactor including all components inside the pressure vessel. The calculated neutron and photon leakage from the pressure vessel can then be used as the source for Monte Carlo calculations of the entire region outside the reactor pressure vessel. The expense of the Monte Carlo calculations usually limit their application to a few carefully selected configurations to serve as calculational "benchmarks". Photon source distributions needed for point kernel analyses can be obtained from the deterministic solutions inside the pressure vessel and from the Monte Carlo solu-

tions exterior to the pressure vessel. Crew location dose rates can then be calculated as a function of propellant level using point kernel methods benchmarked against selected Monte Carlo solutions. Point kernel methods can also be used for scoping calculations of similar configurations.

The above methodology requires a significant investment of both modelling and computer resources. Calculated dose rates are probably no better than a factor of two. Scoping calculations for less mature propulsion system designs involve considerable assumptions and approximations and the calculated radiation environments inherently have even higher uncertainty.

A wealth of radiation environment data were developed during the NERVA program. The crew location dose assessments reported here were performed using data for a NERVA-class engine with performance similar to that being considered for lunar and Mars applications. Reference 3 reported crew location dose rate data as a function of residual mass for a 1575 MW_{th} engine and a particular propellant tank configuration. The dependent variable for the reported instantaneous dose rate data was converted from propellant mass to propellant depth using the appropriate tank configuration and propellant mass flow rate data. Tank drainage histories (propellant level as a function of time) were developed for the new tank configurations and engine operating profiles to be examined. Total tank-top dose rates were estimated by integrating over the tank drainage history for each maneuver. A simple geometric correction was applied to account for differences in reactor source - dose point geometries. Crew location dose rate reductions provided by an external disk shield were obtained from Reference 8.

Lunar Mission Scenario

The Space Exploration Initiative (SEI) outlined by President Bush on July 20, 1989, the 20th anniversary of Apollo 11, calls for a return to the Moon "to stay" early in the next century, followed by a journey to Mars using systems "space-tested" in the lunar environment. During the "90-Day Study",⁹ conducted by the National Aeronautics and Space Administration (NASA), liquid oxygen/liquid hydrogen fueled chemical rockets were baselined for the lunar space transportation system (LTS). Aerodynamic braking at Earth return was also assumed to

keep the initial starting masses in low Earth orbit (IMLEO) below the 275 - 300 metric ton range (1 t = 1000 kg) required for the "all-propulsive" LTS. The chemical systems were also operated in a largely expendable mission mode with significant jettisoning of expendable propellant tanks and/or stages.

Because of its high engine thrust-to-weight ratio and specific impulse characteristics, the NTR is well-suited to performing both piloted and cargo lunar missions. In FY'90, a "fully reusable", all propulsive NTR lunar scenario was proposed by NASA's Lewis Research Center¹⁰ and preliminary stage characterization was initiated. Details of the scenario and a relative size comparison of the aerobraked chemical (chem/AB) and NTR vehicles are shown in Figures 1 and 2, respectively. The NTR-powered LTS is capable of transporting a fully-fueled, cargo-laden, lunar excursion vehicle (LEV) to the Moon, and returning it to low Earth orbit (LEO) after mission completion, for less IMLEO than chem/AB systems carrying comparable outbound and inbound payloads. The all-propulsive NTR LTS would also be "fully reusable" and would have a return payload mass-fraction of ~23 percent — twice that of the "partially reusable" aerobraked chemical systems. After returning to LEO, the crew would transfer to the LEV and return to Space Station Freedom (SSF) while the "radioactive" NTR and its stage would remain at an appropriate "stand-off" distance from Space Station Freedom between missions.

The lunar NTR vehicle contains two distinct modules which will be assembled in orbit via a simple docking maneuver. The main propellant tank uses aluminum alloy 2219-T87 for its construction and is surrounded by multi-layer insulation and a micrometeoroid shield to reduce LH₂ boiloff and particle impact damage, respectively. The tank has a diameter of 10 m, a root 2 ellipsoidal forward dome, and a 10-degree conical aft section with an ~3.6 m spherical end cap radius. The tank's tapered end reduces forward radiation scattering to the crew and helps to reduce stage shielding requirements.

The "propulsion module" contains the NTR engine, an external 4.5 t disk shield, and a small run tank. The NTR operates at 2700 K using a uranium carbide - zirconium carbide "composite" fuel, generates 75,000 lbf of thrust, and has an estimated specific impulse of ~915 s. The run tank has hemispherical forward and aft domes, a cylindrical barrel section, and a LH₂ capacity of 3.9 t. The "wet"

propulsion module has been sized, both in dimensions and total mass, for deployment from the "Space Shuttle" cargo bay as a single autonomous unit. The run tank can be used for engine startup and cooldown, and for short duration burns.

Mars Mission Scenario

Over the last several years, NASA has been examining a variety of mission opportunities, trajectory types, propulsion technologies, and vehicle configurations for its first piloted mission to Mars. From these studies the NTR has emerged as the leading candidate technology for primary space propulsion. This lead role is attributed to both its maturity (a large experimental database was accumulated during the Rover/NERVA programs¹¹) and its ability to leverage a given propellant loading to reduce trip times.

In FY'90 and '91, NASA's reference Mars mission was a 2016 opposition class mission with a 30-day surface stay and an inbound Venus swingby.¹² For this particular opportunity, the overall mission duration is also attractive — on the order of 434 days. Schematics of both the Mars mission scenario and vehicle configuration are shown in Figures 3 and 4, respectively. The "all-propulsive" NTR vehicle features expendable trans-Mars injection (TMI) and Mars orbital capture (MOC) tanks attached to a central truss structure. The TMI and MOC tank sets are jettisoned after their respective maneuvers to reduce overall vehicle mass thus improving performance. Trans-Earth injection (TEI) and Earth orbital capture (EOC) propellant is contained in a common core propellant tank. A propulsion module, similar to that described in the lunar mission scenario, is attached to the core tank. An alternative to propulsive capture at Earth would be an "expendable" vehicle mode. Here the crew would return to Earth utilizing an Earth crew capsule vehicle (ECCV) or capsule similar to that used in the Apollo program while the NTR vehicle would be jettisoned for disposal into deep space.

A "composite" fuel NERVA-derivative engine generating 75,000 lbf of thrust at a specific impulse of 925 s has been assumed as the baseline engine for the Mars mission. A triple-perigee burn Earth departure scenario was also adopted for the reference mission. With the perigee propulsion technique, propulsive energy can be imparted to the spacecraft more effectively thereby reducing the

gravity losses associated with finite burn duration accompanying lower thrust-to-weight vehicle designs.

Results

As illustrated in Figure 1, the lunar mission scenario involves four NTR propulsion system maneuvers. The engine operating times are listed in Table 1. Also listed are the propellant loadings immediately before and immediately after each engine operation. The post-maneuver loadings include cooldown and reserve allowances for the maneuver

and boiloff losses until the following maneuver. The propellant cooldown and reserve allowances are 3% and 2%, respectively, of the impulse propellant required for the maneuver. Boiloff allowances are based on a liquid hydrogen loss rate of $\sim 2.23 \text{ kg/m}^2\text{-mth}$. The fully reusable lunar transportation vehicle configuration shown in Figure 2 is 60 m long. The crew location dose point is 10.5 m from the forward end of the vehicle. The dose point is located 46.8 m from the center of the reactor core.

Calculated crew location integral doses are summarized in Table 2 for each maneuver. The

Table 1. Maneuver Propellant Inventories for Lunar Mission Scenario.

	Trans-Lunar Injection	Lunar Orbital Capture	Trans-Earth Injection	Earth Orbital Capture
Maneuver Duration (min)	28.4	7.2	4.3	9.2
Pre-Maneuver Propellant Loading (MT)	117.503	50.757	31.846	21.550
Nominal Propellant for Maneuver (MT)	63.354	16.062	9.592	20.523
Post-Maneuver Propellant Loading (MT)	54.149	34.695	22.254	1.027

Table 2. Crew Location Integral Doses for Reference Lunar Mission Scenario.

	Crew Location Integral Dose (Rem)			
	No External Shield	4.5 MT External Disk Shield	Factor of 2 Habitat Shielding	Equivalent 25 g/cm ² Storm Shelter
Trans-Lunar Injection	6.83	0.394	0.197	0.098
Lunar Orbital Capture	10.2	0.586	0.293	0.147
Trans-Earth Injection	14.4	0.830	0.415	0.208
Earth Orbital Capture	159.	9.14	4.57	2.28
Total For All Maneuvers	190.	11.0	5.48	2.74

baseline configuration includes the reactor and pressure vessel with internal shield, run tank, and main propellant tank. The column headed "No External Shield" contains calculated integral doses for the baseline configuration. The next column reflects a dose reduction of approximately 17.3 that can be expected from a typical 4.5 MT (10,000 lb_m) external disk shield.⁸ An additional dose reduction can be expected from the habitat module itself. Two representative cases were considered for these analyses. A factor of two dose reduction is typical for an Apollo-like command module⁶ and an additional factor of 2 representative of storm shelters being considered for longer duration missions. The storm shelter dose reduction factor was estimated for an equivalent 25 g/cm² of water using QAD point kernel analyses.

Integral doses could be reduced by external disk shield modifications, by increasing the propellant reserve remaining at the end of the final (Earth orbital capture) maneuver, and by optimization of propellant tank geometry. The additional disk shield or propellant mass imposes an equivalent propellant penalty for each propulsive maneuver. Additional disk shield provides greater dose reduction per unit mass; additional propellant offers greater mission flexibility in that the "shield" can be used for propulsion in an emergency or off-normal situation.

Larger reductions in total dose can be achieved by optimization of propellant tank geometry. Integral doses decrease with decreasing conic section half-angle and with decreasing end cap radius. Dose reductions result primarily from the increased shielding worth of small propellant quantities in configurations where greater propellant depths can be maintained during the last portion of the tank drainage history. Lower doses can result in lower external disk shield masses at the cost of lower propellant tank structural efficiency. Optimization is required to minimize the total mass subject to propellant requirements and other constraints such as maximum tank envelope.

Estimated crew location integral doses are summarized in Table 3 for several alternate lunar vehicle configurations. Propellant reserves at the conclusion of the Earth orbital capture maneuver were increased from 0.41 MT (2% of nominal impulse propellant) to 1.41 MT and to 2.41 MT. The initial mass in low Earth orbit increased by about 2.67 MT and 5.36 MT, respectively, reflecting the additional propellant and tankage required. Crew location doses are reduced by about 16% and 28%, respectively. For comparison, an additional metric ton of external disk shield can be expected⁸ to reduce the dose by about 35%.

Table 3. Crew Location Integral Doses for Modified Lunar Mission Configurations.

	No External Shield	4.5 MT External Disk Shield	Factor of 2 Habitat Shielding	Equivalent 25 g/cm ² Storm Shelter
Base Case	190	11.0	5.48	2.74
Base Case + 1 MT Additional Propellant at EOC Maneuver	159	9.20	4.60	2.30
Base Case + 2 MT Additional Propellant at EOC Maneuver	137	7.90	3.95	1.98
Base Case + Run Tank Mods	124	7.13	3.57	1.78
Base Case + Run Tank Mods and 1 MT Additional Propellant	112	6.48	3.24	1.62
Base Case + Run Tank Mods and 2 MT Additional Propellant	103	5.94	2.97	1.48

A modified run tank was also considered. Run tank geometry is constrained by, at the minimum, a combination of envelope size and required propellant loading. The run tank capacity was reduced from ~3.9 MT to ~1.2 MT and provided about a 35% dose reduction. Incorporating both run tank modifications and a 2 MT propellant reserve reduces the integral dose by ~46%.

Dose rates following engine shutdown were estimated at selected times during the lunar NTR mission. The engine operating history and the variation in dose rate experienced by a crew member located 100 feet away from the unshielded reactor core centerline (a rather pessimistic assumption) are shown in Table 4. Dose rates adjacent to the engine were calculated using the QAD point kernel

Table 4. Dose Rate Next to Engine at Selected Times During Lunar NTR Mission.

Maneuver	1575 MW _{th} Engine Operating (minutes)	Mission Elapsed Time (days)
Trans-Lunar Injection	28.4	11.0
Lunar Orbital Capture	7.2	14.5
Trans-Earth Injection	4.3	46.5
Earth Orbital Capture	9.2	50.0

Event	Dose Rate* (Rem/hr)
Full Power Operation	7.2×10^5
Trans-Lunar Injection Plus One Day	27.0
Just Prior to Lunar Orbital Capture Maneuver	5.4
Lunar Orbital Capture Plus One Day	11.0
Just Prior to Trans Earth Injection Maneuver	0.82
Just Prior to Earth Orbital Capture Maneuver	1.5
Earth Orbital Capture Plus One Day	10.0
Earth Orbital Capture Plus One Month	0.63
Earth Orbital Capture Plus One Year	0.011

*Dose point on axial midplane 100 feet from core centerline

code.¹³ Geometry and composition data used in the QAD model were taken from a NERVA flight engine common radiation analysis model.¹⁴ Fission product photon source strengths were calculated using the ORIGEN2¹⁵ isotopic generation and depletion code. It is quite evident that during full power operation lethal exposures would be accumulated in only two to three seconds. One day after TLI, however, the dose rate has dropped by a factor of more than 25,000 and after the coast period to the Moon it is down to ~5 Rem/hour. Following the LOC maneuver, the crew could depart the spacecraft staying within the protected cone area along the forward axis of the vehicle. After a 32-day lunar surface stay, the returning lunar excursion vehicle could fly past the unshielded NTR and receive less than 1 Rem/hour at the 100-foot separation distance. The normal crew location remains shielded in the protective cone along the forward axis of the vehicle. Shielding provided by the internal and external shields, propellant tank, and vehicle is even more effective following engine shutdown due to a softer photon source spectrum.

The all-propulsive Mars mission scenario illustrated in Figure 3 involves four NTR propulsion system maneuvers. Engine operating times and propellant loadings are listed in Table 5. The propellant cooldown and reserve allowances are 3% and 2%, respectively, of the impulse propellant required for the maneuver. Boiloff allowances are based on a liquid hydrogen loss rate of ~0.65 kg/m²-mth for the MOC and TEI/EOC tanks. The Mars vehicle con-

figuration shown in Figure 4 is 131.2 m in length. The crew location dose point was assumed to be 17 m from the forward end of the configuration. The dose point is located 107.4 m from the center of the reactor core. Estimated crew location integral doses are summarized in Table 6. Mars mission maneuver doses are lower than the doses for corresponding maneuvers in the lunar mission. The primary reason is the greater separation between engine and crew locations for the Mars vehicle.

Conclusions

Although an operating nuclear thermal propulsion engine is an intense radiation source, operating times are brief and large quantities of propellant are available for shielding during most of the time the engine is operating. Attention to vehicle design can make crew doses from NTR engine operations a small fraction of the dose received from natural radiation sources during a typical piloted Mars mission. Engine generated biological doses are reduced for the Mars mission due to the inherently longer vehicle lengths and the requirement for shielding against natural radiation. External shield mass can be reduced substantially for vehicles employing a radiation shelter. Elimination of the external shield may be practical from a crew dose standpoint. Biological dose rates from a shutdown engine will not unduly restrict operations in the vicinity of NTR vehicles.

Table 5. Maneuver Propellant Inventories for Mars Mission Scenario.

	Trans- Mars Injection	Mars Orbital Capture	Trans- Earth Injection	Earth Orbital Capture
Maneuver Duration (min)	103.6	36.9	28.0	6.9
Pre-Maneuver Propellant Loading (MT)	415.610	170.514	84.648	16.016
Nominal Propellant for Maneuver (MT)	228.656	81.333	61.851	15.253
Post-Maneuver Propellant Loading (MT)	186.954	89.181	22.797	0.763

Table 6. Crew Location Integral Doses for Reference Mars Mission Scenario.

	Crew Location Integral Dose (Rem)			
	No External Shield	4.5 MT External Disk Shield	Factor of 2 Habitat Shielding	Equivalent 25 g/cm ² Storm Shelter
Trans-Mars Injection	1.74	0.100	0.050	0.025
Mars Orbital Capture	0.619	0.036	0.018	0.009
Trans-Earth Injection	6.14	0.354	0.177	0.089
Earth Orbital Capture	28.9	1.67	0.833	0.417
Total For All Maneuvers	37.4	2.16	1.08	0.540

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Figure 1. Lunar Mission Scenario.

Figure 2. Lunar Transportation Vehicle Size Comparison.

Figure 3. Mars Mission Scenario.

Figure 4. Mars Transportation Vehicle.

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