A General-Purpose Simulator for Evaluating Astronaut Radiation Exposure

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ABSTRACT

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Abstract

Purpose: Current Monte Carlo simulations modeling space radiation exposure typically use simplistic human phantoms with low anatomical detail and minimal variability in physical characteristics. This thesis describes the development of a GEANT4-based simulation framework (EVEREST – Evaluation of Variable-Environment Radiation Exposure during Space Travel) that incorporates highly realistic and diverse 4D extended cardiac-torso (XCAT) digital phantoms, combined with advanced NASA models of planetary atmospheres, spaceflight trajectories, and space radiation spectra, to evaluate radiation exposure in interplanetary missions and on planetary habitats.

Methods: Galactic cosmic radiation spectra as a function of time and radial distance from the Sun were modeled using the Badhwar-O’Neill 2020 model, while the Van Allen belt spectra were modeled using the AE-8/AP-8 models, and solar particle event spectra could be selected from historical data. The magnetic field input to the AE-8/AP-8 model was generated using the 13th generation International Geomagnetic Reference Field. Planetary atmospheres were modeled using NASA Global Reference Atmospheric Models, which provide mean atmospheric data for any altitude, latitude, longitude, and time, and the effect of Earth’s magnetic field was accounted for using a geomagnetic cutoff rigidity algorithm. Planetary orbits, trajectories, and relative positions of objects in the Solar System were determined using the NAIF SPICE observation geometry information.
system. Finally, highly detailed extended cardiac-torso (XCAT) digital phantoms were integrated into EVEREST in order to accurately model radiation exposure to individual organs. XCAT phantoms model over 100 segmented structures, range in age from neonate to 78 years, and cover various combinations of height, weight, and BMI. The EVEREST framework itself was designed using a novel lookup table method, in which different stages of particle propagation were divided into separate simulations, which are then convolved in post-processing.

Results: EVEREST was validated against personal radiation dosimeter data collected by the lunar module pilot on the Apollo 15 mission and also flux data from the Mars Science Laboratory Radiation Assessment Detector (RAD). Simulation results were found to agree very well with dosimeter readings by the Apollo 15 command module pilot. Comparison of Martian surface particle fluxes simulated by EVEREST to RAD data demonstrated an agreement to within an order of magnitude, with the best agreement seen for protons, $^4$He, $Z = 6-8$, $Z = 14-24$, and $Z > 24$. Finally, as a proof of concept, EVEREST was used to evaluate radiation exposure to a population of eight XCAT phantoms (3 adult and 1 pediatric, male and female) under three different nominal shielding configurations on the surface of Mars (unshielded, 50 cm thick ice, and 50 cm thick Martian regolith) at four different timepoints during the day (12 am, 6 am, 12 pm, and 6 pm). Using the federal yearly occupational dose limit of 50 mSv (effective dose) as a metric, it was found that the phantoms evaluated would reach this limit within 70.9 – 83.8 days unshielded, 139.2 –
161.2 days with 50 cm ice shielding, and 188.1 – 235.7 days with 50 cm Martian regolith shielding, if terrestrial radiation protection standards were to be applied. The results revealed that the brain receives one of the highest organ doses in the body and that unshielded radiation exposure is lowest at midnight when analyzed across all phantoms. Based on these findings, it is recommended that extra care be taken to provide additional radiation shielding in astronauts’ helmets and that extended forays outside of the habitat be planned for late evening to reduce the biological impact of radiation exposure.

Conclusion: EVEREST is a tested and validated framework for accurate estimation of total body and organ dose in space. EVEREST’s geometric versatility makes it ideal for evaluating doses to diverse populations of XCAT phantoms within different types of planetary habitats and spacecraft, enabling optimization of mission planning with respect to radiation exposure in the near future. The model has currently been validated for Lunar and Martian missions, and the framework can be applied to any space travel mission or planetary mission where the atmospheric models for that planet are available.
Dedication

To my father, who has provided me with inspiration, and my mother, who has provided me with motivation.
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1. Introduction

While interplanetary exploration has so far been left to more resilient robotic probes, these metal counterparts will soon be joined by human companions. In 2017, NASA’s *Artemis* program was authorized by Space Policy Directive 1 with the goal of landing the next humans on the Moon by 2024 and laying the foundation for the first crewed mission to Mars [1]. In addition to other common technical challenges of spaceflight, these future missions will need to contend with the harmful effects of radiation in space – both during interplanetary missions and eventually on planetary habitats. As a result, understanding the space radiation environment and its risk to astronauts is a critical factor in enabling long-term missions beyond low-Earth-orbit.

The radiation environment in interplanetary space and on the surfaces of other worlds is very complex and is influenced by factors including radial distance from the Sun, solar activity, and planetary atmospheres and magnetic fields. Uncertainties in radiation dose estimates can significantly restrict the lengths of space missions, as NASA sets astronaut exposures to a 3% maximum risk of exposure-induced death (REID), a metric determined based on the upper 95% confidence level of estimated dose [2], [3]. These recommendations are based on NCRP reports, which also recommend tracking exposure on an age- and gender-specific basis. Age of first exposure directly affects lifetime cancer risk (younger people are more susceptible to radiation-induced carcinogenesis during their lifetime).
Exposures and doses are typically evaluated using mathematical simulation models that account for cosmic and solar radiation, mission-specific parameters, and models of the human body. While cosmic and solar radiation and mission parameters are well understood, the human body models used in most simulations lack the detail and sophistication needed for predicting astronaut dose in an individualized manner. For example, simplistic human models used in many current simulations cannot model individual-specific anatomical attributes such as height, weight, age, and BMI [4], [5]. These factors are known to play important roles in radiation-induced carcinogenesis. Simple human body models often are unable to accurately model the dose to deep organs due to the modulation of fluence by the density of the tissue mass that lie between the skin surface and those organs. Furthermore, the complex and variable shielding configurations utilized for each astronaut within a spacecraft necessitates more advanced and individualized human body models that permit evaluation of organ-specific radiation exposure levels over the course of a mission [6]. As we explore long-term habitats on Mars, it is also important to evaluate radiation effects to a diverse population of humans, including adults, children, and neonates, living in a Martian habitat.

This thesis describes the development and validation of a general-purpose GEANT4-based Monte Carlo toolkit, named EVEREST — Evaluation of Variable-Environment Radiation Exposure during Space Travel, which incorporates highly detailed, anatomically realistic digital human phantoms with the sophistication to model
individual humans, combined with advanced NASA models of planetary atmospheres, spaceflight trajectories, and space radiation spectra, to evaluate radiation exposure in interplanetary missions and on planetary habitats.
2. **Background**

2.1 **GEANT4 Monte-Carlo Framework**

*EVEREST* is fundamentally a GEANT4-based model. GEANT4 is an open-source object-oriented radiation transport simulation toolkit based on the C++ programming language developed by a worldwide collaboration led by CERN [7]–[9]. It accounts for a diverse range of interactions of a variety of particles in matter across a wide energy range (meV – GeV) and provides all the tools required for detector simulation including geometry, tracking, and detector response management. Any object or material can be created in GEANT4, including user-defined compounds and mixtures, planetary surfaces, and human tissue, making it an ideal option for dose analysis experiments. Each simulated interaction in GEANT4 carries information about the position and time of the step, the momentum and energy of the track, the energy deposition of the step, and geometrical information. GEANT4 is capable of simulating magnetic and electric fields at planetary scales and generating radiation with user-defined spatial, angular, and energy distributions. This functionality is well-suited for the modeling of complex space radiation spectra. Finally, GEANT4 is capable of importing voxelized volumes, including highly detailed extended cardiac-torso (XCAT) digital phantoms.

2.2 **XCAT Phantoms**

XCAT digital phantoms are highly detailed, anatomically realistic, state-of-the-art computerized human body models developed by the Carl E. Ravin Advanced Imaging
Laboratories (RAI Labs) at Duke University for multimodality imaging research [10]. The XCAT library is a series of anatomically variable XCAT phantoms [11]. Each anatomy is defined using non-uniform rational b-splines (NURBS) and includes 128 defined structures based on actual human data. The XCAT library models range in age from neonatal (8 – 40 weeks in-utero fetus) to elderly adult (78 years) and cover various height and weight percentiles corresponding to a human population [12]. In addition, XCAT phantoms can be customized to match a specific real human (through medical CT data). XCAT models can be voxelized and exported at any user-defined resolution and have been readily integrated into GEANT4 in the past [13]. These qualities make XCAT phantoms ideal for use in simulating any kind of space mission, including extensive colonies on other worlds comprised of large and diverse human populations.

Figure 1: A set of eight XCAT phantoms utilized in this project. These phantoms represent a sample of a human population in age, gender, and BMI.
2.3 The Radiation Environment in Space

The space weather environment is typically categorized into three sources of ionizing radiation: galactic cosmic radiation (GCR), solar particle events (SPEs), and the solar wind.

The GCR spectrum is a slowly varying and approximately isotropic background source of energetic, fully ionized particles spanning the periodic table that originate from outside of the Solar System [14], [15]. It consists primarily of protons and alpha particles, with a small fraction of heavier ions ranging through atomic number Z=8 (nickel). Despite the infrequency of heavy ions, they contribute significantly to radiation dose due to their greater energies. The solar wind consists mainly of low energy protons, electrons, and alpha particles of kinetic energy between 0.5 and 10 keV emanating from the Sun. Because of their low energies, solar wind particles are unlikely to penetrate even modest shielding, and are generally ignored in simulations as the computational burden would far exceed any improvement in dose estimates. SPEs, on the other hand, consist of solar wind particles accelerated to near the speed of light by magnetic disturbances on the surface of the Sun, such as solar flares or coronal mass ejections. SPEs are sporadic and have unpredictable particle energy spectra [16]. Both the intensity of the solar wind and the frequency of SPEs are modulated by the 11-year solar activity cycle [17], [18]. Conversely, the intensity of galactic cosmic radiation varies inversely with solar activity [19].
addition, the intensity of interplanetary cosmic radiation exhibits a noticeable radial gradient relative to the Sun [20], [21].

Near the Earth, solar radiation and GCR can become trapped within the geomagnetic field in a set of zones known as the Van Allen belts. An inner belt is comprised mainly of medium energy (hundreds of keV) electrons and high energy (>100 MeV) protons between 1000 and 12000 km above the surface of the Earth, while an outer belt is dominated by high energy (0.04 – 7 MeV) electrons and extends to 60000 km above the surface. The fluences of particles in these regions are much greater than in typical interplanetary space [22].

In and below low-Earth orbit, however, both the Earth’s magnetic field and its atmosphere provide significant shielding from space radiation [23], [24]. Both the Moon and Mars possess comparatively negligible magnetic fields [25], [26]. Although planetary atmospheres generally provide shielding from radiation, when a primary cosmic ray strikes an atmosphere, it interacts with the medium to produce a cascade of secondary particles that may reach the planetary surface and contribute to radiation exposure [27].

2.4 Badhwar-O’Neill Model

The Badhwar-O’Neill (BON) model, first developed in the 1990s and most recently updated in 2020, has been used widely within NASA to describe the GCR environment encountered in deep space [28], [29]. The BON model relies on the steady-state, spherically symmetric Fokker-Planck equation, which has been shown to accurately account for the
propagation of the local interstellar spectrum (LIS) of GCRs through the heliosphere.

Under these assumptions, the Fokker-Planck equation is

\[
\frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 V_{sw} U \right) - \frac{1}{3r^2} \frac{\partial}{\partial r} \left[ \frac{\partial}{\partial T} \left( \alpha T U \right) \right] = \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \kappa \frac{\partial U}{\partial r} \right),
\]

where \( r \) is the radial distance from the Sun (cm), \( T \) is the ion kinetic energy (MeV/n), \( V_{sw} = 4 \times 10^7 \) cm/s is the solar wind speed (specified as a constant), \( \alpha = (T + 2m)/(T + m) \), \( \kappa(r, T) \) is the particle diffusion coefficient tensor, and \( U(r, T, Z) \) is the omnidirectional GCR particle flux (particles / cm\(^2\) · MeV/n · day) for each ion, specified by atomic number \( Z \). At the boundary \( r = R_B \) of the heliosphere, assumed to be at a radius of 100 AU, \( U(R_B, T, Z) = f_{LIS}(T, Z) \) is the LIS.

The LIS is described within the BON model by the parametrization,

\[
f_{LIS}(T, Z) = j_0 \beta^\delta (T + m)^{-\gamma},
\]

where \( m \) is the proton rest mass (MeV), \( \beta = v/c \) is the ion velocity relative to the speed of light, and \( j_0, \gamma, \) and \( \delta \) are free parameters for each ion, tabulated in Appendix B in [29]. The \( \delta \) parameter controls the lower energy behavior in conjunction with the solar modulation potential.

The diffusion coefficient, \( \kappa \), describes the effect of the Sun’s magnetic field at any radial position, \( r \), and time, \( t \), and is given by

\[
\kappa(r, t) = \frac{\beta R k_0 \left[ 1 + \left( \frac{r}{R_0} \right)^2 \right]}{\phi(t)},
\]
where $R$ is the ion rigidity (MV), $r_0 = 4.0$ AU, $k_0 = 8.8 \times 10^{20}$ cm$^2$/s, and $\phi(t)$ is the solar modulation potential which can be determined from the smoothed international sunspot number (SSN), with an empirical delay function [30], as detailed in [29]. SSN data is available from January 1749 (Solar Cycle 1) through December 2019 (Solar Cycle 24). Additionally, predicted SSN data for Solar Cycle 25 (through December 2034) has been made available in 2019 by an international panel co-chaired by NOAA and NASA.

As detailed in [29], Equation (1) can be reduced to the form of a parabolic partial differential equation, whereupon the Crank-Nicolson method can be applied to produce a finite difference equation that can then be written in the form of a tridiagonal matrix, which can ultimately be solved analytically via the Thomas algorithm to obtain the omnidirectional GCR flux spectrum $U(r, T, Z)$ at radius $r$ for each ion.

![Figure 2: Left: BON model differential flux spectra for galactic carbon (Z=6) at 1 AU (Earth’s semimajor axis) and 1.524 AU (Mars’ semimajor axis) on Jan 1, 2021. Right: BON model differential flux spectra for galactic carbon (Z=6) and iron (Z=26) at 1 AU on Jan 1, 2021.](image-url)
Figure 3: Variation in BON model proton integral flux versus radial distance from the Sun over 100 astronomical units (left) and 2.0 astronomical units (right) on Jan 1, 2021. The plot on the right shows the sizes of the orbits of Venus, Earth, and Mars for reference.

### 2.5 Solar Energetic Particles

Solar particle events are unpredictable in both frequency and energy spectra. As such, there exist no computational models that can be used to reliably determine the radiation dose from this source during a space mission. Instead, simulations involving solar energetic particles are typically run either by using historical spectra that have been tabulated over the last century [31] or by using user-defined spectra.

SPEs are directional (following the spiral heliospheric magnetic field lines) at very large scales, but become nearly isotropic at smaller scales after about 1 astronomical unit from the Sun due to scattering off of magnetic inhomogeneities [32]. This indicates that even behind a planet that is in the path of a solar magnetic field line, it would be impossible to completely shield a spacecraft from solar energetic particles.
2.6 AE-8/AP-8 RADBELT Van Allen Belt Models

The outer and inner Van Allen belts are accurately described by the AE-8 and AP-8 computational models, respectively [33]–[35]. These models output the omnidirectional flux for trapped protons and electrons as a function of magnetic field strength, magnetic latitude, and altitude, where the magnetic field strength can be determined using the International Geomagnetic Reference Field [23]. Electron flux can be calculated within the range of 0.4 – 7.0 MeV and proton flux can be calculated within the range of 1.0 to 1000 MeV.

![Cross sectional views of integral electron (left) and proton (right) fluxes predicted by the AE-8 and AP-8 Van Allen belt models, respectively, for Jan 1, 2021. The Earth is shown as a black circle.](image)

2.7 Geomagnetic Cutoff Rigidity

The Earth has one of the strongest planetary magnetic fields in the Solar System, and this field significantly reduces the number of charged particles that are capable of reaching low-Earth orbit or the surface. Despite the capability within GEANT4 for
simulating the motion of charged particles in magnetic fields, this task is extremely computationally intensive. Instead, this project makes use of an approximation known as the cutoff rigidity [36].

A particle’s rigidity is defined as its momentum divided by its charge. This property has been shown to correlate with whether a particle will penetrate Earth’s magnetic field or be deflected. Thus, the concept of the cutoff rigidity is that particles with rigidities below a cutoff threshold are discarded from consideration. For particles traveling normal to the surface of the Earth, the vertical cutoff rigidity at the surface $R_v$, in units of GV, can be defined as

$$R_v = 14.9 \cdot \cos^4(\lambda),$$  \hspace{1cm} (4)

where $\lambda$ is the geomagnetic latitude.

Adjusting for altitude $H$,

$$R_{v,adj} = R_v \cdot \left(\frac{r_{Earth}}{r_{Earth} + H}\right)^{2.0533},$$  \hspace{1cm} (5)

where $r_{Earth}$ is the radius of the Earth.

Finally, the apparent cutoff for the entire sky, regardless of a particle’s direction of momentum, is

$$R = \begin{cases} 
R_{v,adj} \cdot \left(1.00005566 \times 10^{-5} + 2.912 \times 10^{-4} \cdot R_{v,adj}\right) & \text{ if } R_{v,adj} < 8.66 \text{ GV} \\
R_{v,adj} \cdot \left(1.03438 \times 10^{-2} + 1.362 \times 10^{-3} \cdot R_{v,adj}\right) & \text{ if } R_{v,adj} > 10.4 \text{ GV} \\
R_{v,adj} \cdot \left(0.7747 + 2.642 \times 10^{-2} \cdot R_{v,adj}\right) & \text{ otherwise}
\end{cases}$$  \hspace{1cm} (6)

This cutoff condition applies to all charged GCR and SPE particles.
2.8 **Global Reference Atmospheric Models**

For modeling atmospheric shielding of radiation *EVEREST* utilizes NASA’s planetary global reference atmospheric models (GRAMs), which provide engineering-oriented empirical models of planetary atmospheres based on spacecraft data, including mean atmospheric density, temperature, pressure, and chemical composition for any location (height, latitude, longitude) and time (seasonal or diurnal). GRAMS are currently available for Earth, Mars, Venus, and Saturn’s moon Titan [37], [38]. Mars-GRAM additionally includes dust storm effects [39].

![Figure 5: Left: Earth-GRAM density (blue) and temperature (orange) versus altitude above Durham, NC on January 1, 2020 at 12 am and 12 pm EST. Right: Mars-GRAM density (blue) and temperature (orange) versus altitude in the presence and absence of an atmospheric dust storm.](image)

2.9 **NAIF SPICE API**

NASA’s Navigation and Ancillary Information Facility (NAIF) offers an open-source space observation geometry information system known as "SPICE". The SPICE system includes a suite of software known as the SPICE Toolkit consisting of application
program interfaces (APIs) that users incorporate in their own application programs to read SPICE ancillary data files and, using those data, compute derived observation geometry. The SPICE toolkit’s standard kernels can be used to compute the positions and attributes of the Sun and every planet and moon in various coordinate systems and reference frames at any user-specified time [40], [41]. Such information is important for determining the distance to the Sun for BON spectra calculation and occlusion of radiation by nearby planetary objects.

2.10 Planetary Shielding

Generally, a good assumption in determining the total radiation flux at a position in space is that nearby planetary objects will shield the observer by the proportion of the sky that they subtend. Specifically, it has been shown experimentally that GCR proton fluxes for kinetic energies > 15 MeV are reduced in proportion to the fraction of the sky subtended by the Moon [42]. For a single nearby object, its solid angle is given by

\[
\Omega_{\text{shielded}} = 2\pi \cdot \left(1 - \frac{\sqrt{d^2 - R^2}}{d}\right),
\]  

(7)

where \(d\) is the distance to the object’s center and \(R\) is its radius. Thus, the percent shielding is given by

\[
\% \text{ shielding} = \frac{\Omega_{\text{shielded}}}{4\pi} = \frac{1}{2} \cdot \left(1 - \frac{\sqrt{d^2 - R^2}}{d}\right).
\]  

(8)

This means that on the surface of a large object, the shielding is 50%.
In order to account for objects with overlapping solid angles, a Monte Carlo method is used in which a grid is defined as the equirectangular projection of the field of view, and any pixels that overlap with an object’s solid angle are marked as obstructed. Pixels are weighted by the one over the cosine of the azimuth, and the fraction of weighted obstructed pixels to weighted total pixels gives the overall planetary shielding.

![Figure 6: An example “shielding grid” with two nearby objects which are overlapping in the field of view, using $10^5$ pixels. White pixels indicate an occluded view angle.](image)

**2.11 Dosimetry for Space Radiation**

Once the spectra of space radiation (and all the factors that modulate it) are known, it is necessary to determine how the constituent particles interact with the body to result in a biological effect.

When particles interact with the body (or the voxels of an XCAT phantom), they deposit energy. In EVEREST, the physics of this process is handled in GEANT4. The concentration of deposited energy per unit mass is the absorbed radiation dose, $D_{T,R}$, and is given units of Gray (1 Gy = 1 J/kg).
While absorbed dose is an effective physical quantity, different types of radiation depositing the same energy can result in a different biological effect. Radiation with high linear energy transfer (LET) interacts with the medium far more frequently along its path than low-LET radiation. Because the mean free path of high LET-radiation is much smaller, it has a greater probability of producing double-strand breaks in DNA, which are much more difficult for the cellular machinery to repair than single-strand breaks, and thus are more biologically damaging [43]. As a result, the ICRP has developed the concept of equivalent dose, $H_T$, which is calculated for individual tissues or organs and accounts for the different radiobiological effect of different types of radiation.

$$H_T = \sum_R w_R \cdot D_{T,R},$$  

where the radiation weighting factor $w_R$ is given by the values in Table 1 for each type of radiation. Because equivalent dose is a biological, rather than physical quantity, it is measured in units of Sieverts.

**Table 1: Radiation weighting factors $w_R$ according to ICRP Report 103 [44].**

<table>
<thead>
<tr>
<th>Radiation</th>
<th>Energy</th>
<th>Radiation weighting factor $w_R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photons, electrons, muons</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Neutrons</td>
<td>$&lt;1$ MeV</td>
<td>$2.5 + 18.2 \cdot e^{-[\ln(E)]^2/6}$</td>
</tr>
<tr>
<td></td>
<td>$1-50$ MeV</td>
<td>$5.0 + 17.0 \cdot e^{-[\ln(2\cdot E)]^2/6}$</td>
</tr>
<tr>
<td></td>
<td>$&gt;50$ MeV</td>
<td>$2.5 + 3.25 \cdot e^{-[\ln(0.04\cdot E)]^2/6}$</td>
</tr>
<tr>
<td>Protons, charged pions</td>
<td>2</td>
<td>20</td>
</tr>
<tr>
<td>Nuclei with $Z&gt;1$</td>
<td></td>
<td>20</td>
</tr>
</tbody>
</table>
In addition to the variable biological effects of different types of radiation, different tissues and organs within the body have different probabilities of developing complications following exposure to radiation. As a result, the ICRP has developed the concept of effective dose, \( E \), which represents the risk that cancer will develop somewhere in the body after radiation exposure and is also measured in units of Sv. In the context of ICRP effective dose, 1 Sv represents a 5.5% probability of developing cancer [44]. This is a population-based measure and should be taken to mean that for a group of people all exposed to 1 Sv effective dose, it should be expected that 5.5% of the group would eventually develop cancer.

\[
E = \sum_{T} w_T \cdot H_T, \tag{10}
\]

where the tissue weighting factor \( w_T \) is given by the values in Table 2 for each organ.

**Table 2: Tissue weighting factors \( w_T \) according to ICRP Report 103 [44].**

<table>
<thead>
<tr>
<th>Tissue</th>
<th>Tissue Weighting Factor ( w_T )</th>
<th>( \sum w_T )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bone-marrow (red), colon, lung, stomach, breast, remaining tissues</td>
<td>0.12</td>
<td>0.72</td>
</tr>
<tr>
<td>Gonads</td>
<td>0.08</td>
<td>0.08</td>
</tr>
<tr>
<td>Bladder, esophagus, liver, thyroid</td>
<td>0.04</td>
<td>0.16</td>
</tr>
<tr>
<td>Bone surface, brain, salivary glands, skin</td>
<td>0.01</td>
<td>0.04</td>
</tr>
<tr>
<td>Total:</td>
<td></td>
<td>1.00</td>
</tr>
</tbody>
</table>
In the ICRP system of dosimetry, while equivalent dose has proven useful in medical analyses, the tissue weighting factors for calculating effective dose have been derived based on studies of atomic bomb survivors, who were exposed to high dose rates. This may not be suitable for space applications, where the dose rate is generally lower, than that of terrestrial occupational or medical exposures, with the exception of the Van Allen belts or solar particle events. Additionally, the ICRP tissue weighting factors are gender- and age-averaged, which can lead to further inaccuracies in a space radiation environment [45]. As a result, NASA has developed a cancer risk projection model for Radiation Exposure Induced Death from cancer (REID) in which the equivalent dose is calculated using a quality factor, $QF_{\text{NASA}}$, for which the formulation and numerical values are substantially different from those of the ICRP radiation weighting factor $w_R$ [45]. NASA’s equivalent dose is calculated in a similar manner to the ICRP, 

$$H_T = \sum_R D_{T,R} \cdot \frac{QF_{\text{NASA}}}{DDREF},$$  \hfill (11)

where $DDREF$ is the Dose and Dose-Rate Effectiveness Factor, which accounts for the usually lower biological effectiveness (per unit dose) of radiation exposures at low doses and dose rates as compared with exposures at high doses and dose rates. A value of 2 is generally used for $DDREF$ [46].

The NASA quality factor is calculated using 

$$QF_{\text{NASA}} = [1 - P(Z,E)] + \frac{6.24 \cdot \sum \alpha_{\gamma}}{\text{LET}} \cdot P(Z,E),$$  \hfill (12)

with
\[ P(Z, E) = \left(1 - e^{-Z^{*2}/\kappa \beta^2}\right)^m \cdot \left(1 - e^{-E/0.2}\right), \tag{13} \]

where

\[ Z^{*} = Z \cdot \left(1 - e^{-125\beta/Z^{2/3}}\right) \tag{14} \]

accounts for the pickup of electrons from the medium by the ion as it slows down. Thus, the NASA quality factor is fundamentally a function of \( Z^{*2}/\beta^2 \). The values for the parameters \( m, \kappa, \) and \( \Sigma_0/\alpha_r \) have been derived using cell cultures and mouse models for both the probability of solid-cancer-induced death and leukemia-induced death and are listed in Table 3.

**Table 3: NASA radiation quality factor parameters for use in Equations (12) & (13).**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Solid Cancer</th>
<th>Leukemia</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m )</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>( \kappa )</td>
<td>550 (1000)</td>
<td>550 (1000)</td>
</tr>
<tr>
<td>( \Sigma_0/\alpha_r ) (( \mu )m^2Gy)</td>
<td>7000/6.24</td>
<td>1750/6.24</td>
</tr>
</tbody>
</table>

Cancer mortality for a given equivalent dose \( H_T \), age \( a \), and age at exposure \( a_E \) is given by

\[ \lambda_M(H_T, a, a_E) = \lambda_\gamma(a, a_E) \cdot H_T, \tag{15} \]

where \( \lambda_\gamma \) is the rate coefficient (\( y^{-1} \) Gy\(^{-1} \)) for a linear fit to the acute gamma-ray exposure data from epidemiological studies.

Finally, the \( \text{REID} \) can be calculated using

\[ \text{REID}(a, a_E) = \sum_{j=1}^{N_m} \int_{a_{E_j}}^{a_E} \lambda_M(j, t, a_{E_j}) \cdot S_0(t) \cdot e^{-\Sigma_{k=1}^{N_m} t_{a_E} \lambda_M(a_{E_j}, \lambda_{k}(H_{T_{max}} z a_{E_k})) dz dt, \tag{16} \]
where \( S_0(t) \) is the survival function for a background population and \( N_m \) is the number of space missions [45].

NASA’s radiation dosimetry system, while very effective as a formulation, has been facing some criticism in recent years as a result of the parameters listed in Table 3 having been derived from cell culture studies and mouse models, rather than human data. As a result, the NASA calculations of equivalent dose and \( REID \) may not be applicable to human subjects. On the other hand, as mentioned earlier, the ICRP formulation of effective dose may not be applicable either. Therefore, \( EVEREST \) has been designed to report absorbed dose and ICRP equivalent dose, and these are the metrics that will be used to discuss dose throughout the remainder of this thesis.

2.12 Biological Consequences of Space Radiation

Radiation effects on humans can be either acute or chronic. Acute effects are felt almost immediately and occur after a large dose is accumulated in a short amount of time. Symptoms of acute radiation exposure include nausea, vomiting, fatigue, and central nervous system diseases, which may impact motor function and behavior [48]. Acute effects of very high doses include radiation sickness, significant skin injury, and even death [49]. On the other hand, chronic exposure can eventually lead to long-term degenerative tissue effects, such as cataracts, circulatory diseases, digestive diseases, immunological changes, and premature aging [50]. In the context of space radiation, acute
exposures of high doses may occur during passage through the Van Allen belts or during a solar particle event, while chronic exposure of a low dose occurs as a result of GCR.

When high-energy radiation interacts with human tissue, it tears through DNA molecules, damaging the genetic instructions encoded for cell reproduction and function. Incomplete or incorrect repair of DNA can result in unnatural cell mutation, loss of function, and, as these defective cells replicate, eventually cancer [51].

Compounding these effects, various recent studies have discussed the possibility that DNA damage repair is compromised under reduced gravity, increasing biological sensitivity to the same radiation in space versus on Earth [52], [53]. Of note, this reduced gravity effect lends further credence to the concept that the biological effect of radiation in space may not scale well to terrestrial paradigms, specifically the current formulations of equivalent and effective dose.
3. **EVEREST Simulation Design**

For the purposes of simulating radiation exposure in space, missions can be classified as either spaceflight or planetary exploration. In each of these scenarios, radiation is modulated by several boundaries before reaching the astronaut. For planetary simulations, these boundaries might include the planet’s atmosphere and the habitat walls, while for spaceflight simulations the boundary would be the spacecraft hull. When designing *EVEREST*, a simulation framework was sought that (a) does not discriminate between different scenarios (e.g., simulating modulation of radiation by an atmospheric boundary uses identical code as simulating modulation of radiation by a spacecraft hull boundary) and (b) could easily interchange simulation parameters (e.g., the design of the habitat for a planetary surface simulation) without being required to run an entire simulation with every interaction a second time. One solution is to create a database for the results of the interactions of each particle of each energy with a given boundary. Once these “lookup tables” are generated, it is possible to build a tree with each level corresponding to each boundary, and then propagate the dose back to the highest level before performing a weighted sum by the known free-space spectrum. This process is what has been termed as the lookup table method for *EVEREST*.

Integrating the radiation transport modeling capabilities of GEANT4 with XCAT phantoms and versatile physics models including the BON and AE-8/AP-8 spectrum
models, NASA global reference atmospheric models, the SPICE API, and the lookup table method, EVEREST becomes an all-in-one, mostly open-source framework for simulating any space mission in any environment.

3.1 Lookup Table Method Description

In the lookup table method, a single scenario is essentially divided into multiple simulations corresponding to each boundary type, and results are propagated through each simulation. As an example, to determine the radiation dose to an XCAT phantom within a spacecraft traveling in free space, the XCAT phantom and the spacecraft would be placed into two separate simulations: one in which a set number of primary particles of each species and energy is propagated through the hull of the spacecraft to a detector that records the secondary particle spectra, and a second in which the XCAT phantom is irradiated by a set number of its own primary particles of each species and energy. Planetary surface simulations would be similar to the spacecraft simulation, with the source surrounding the atmosphere and the detector covering the surface of the planet. Following these simulations’ completion, for each primary particle from the spacecraft (or planet) simulation, the dose values from the phantom simulation corresponding to the secondary particles from the spacecraft (or planet) simulation are summed, and then weighted by the expected real-world (e.g., BON model) spectrum of the primary particles. If there is more than one nested boundary simulation before the phantom simulation, as would be the case if the phantom was inside a habitat on the surface of a planet with an
atmosphere, the secondary particles from the habitat simulation would first be mapped to the primary particles for the atmosphere simulation. Thus, simulations in EVEREST consist of an arbitrarily long sequence of primary-to-secondary boundary simulations, followed by a single phantom dose simulation. For each boundary simulation, results are stored in non-binary trees, where the top level consists of the primary particles’ names and energies, and each leaf consists of the daughter particles’ names and energies. Similarly, for the phantom simulation, the top level consists of its primary particles’ names and energies, while each leaf contains a vector of organ doses and equivalent doses.

![Diagram](image)

Figure 7: An illustration of one possible scenario (with two boundary simulations and one phantom dose simulation) for convolution of two organ dose values \(D_1^i\) and \(D_2^i\) back to two types of primary particles \(P_1\) and \(P_2\) in the highest-level simulation. The primary particle nodes would be weighted by the expected real-world spectra and the doses would be summed again to determine final organ doses.
As mentioned, one advantage of this methodology lies in the fact that components of a simulation can be easily interchanged in order to slightly vary the scenario. In the first example, this could mean substituting one XCAT phantom for another in order to determine how a different body type would be affected in the same environment, without having to run the spacecraft simulation a second time. A second advantage is the exponential increase in the effective number of simulated particle histories with each added simulation stage. For each primary particle producing a set of daughter particles, when propagated to the next simulation, every daughter particle is duplicated by the number of matching primary particles in the second simulation.

### 3.2 Real-World Simulation Time

The geometry factor $G$ is used to correlate simulated dose to a real-world dose rate. For a spherical isotropic source or detector, it is given by

$$G = \int_\omega \int_S (\hat{r} \cdot d\vec{S}) d\Omega = 4\pi r^2 \cdot \int_0^{2\pi} \int_0^\pi \cos(\theta) \sin(\theta) \, d\theta \, d\phi = 4\pi^2 r^2, \quad (17)$$

where $r$ is the radius of the source or detector [54]. The flux through a spherical surface is

$$f = \frac{N}{G \cdot T}, \quad (18)$$

where $N$ particles are passing through the surface in time $T$. Thus, the dose rate is

$$\dot{D} = \frac{D}{T} = \frac{D \cdot f \cdot G}{N}. \quad (19)$$

Extending this to the lookup table formalism, the expected dose rate given a free-space flux of $f_{\text{free}}^{T,R}$ for a particle of energy $T$ and species $R$ should be
\[ \dot{N} = \left( \sum_{T,R} f_{\text{free}}^{T,R} \cdot D_{T,R} \right) \cdot \frac{G_{\text{phantom}}}{N_{\text{phantom}}} \cdot \left( \prod_{i} \frac{G_{\text{source},i}}{N_{i} \cdot G_{\text{det},i}} \right), \] (20)

where \( G_{\text{phantom}} \) is the source geometry factor for the phantom simulation, \( N_{\text{phantom}} \) is the number of primary particles generated in the phantom simulation for each particle and energy, \( N_{i} \) is the number of primary particles generated in boundary simulation \( i \) for each particle and energy, and \( G_{\text{source},i} \) and \( G_{\text{det},i} \) are the geometry factors of the source and secondary flux detector, respectively.

### 3.3 Component GEANT4 Model Attributes

Both the boundary and phantom simulations in EVEREST use the QBBC physics list, which is recommended for medical and space physics simulations [55].

For all boundary simulations, the flux detector is modeled in a parallel geometry with a null material pointer, allowing it to overlap with volumes in the physical geometry [56]. For the spacecraft and habitat simulations, “.obj” format CAD models are loaded into the simulation using the third-party “CADMesh” header file [57].

For the phantom simulation, voxelized XCAT models are imported into GEANT4 using the specialized parameterization class \( G4\text{PhantomParameterisation} \), which enables an optimized navigation process in which knowledge of a voxel’s position is used to predict the next voxel to be hit [58]. Elemental compositions and densities of XCAT tissues and organs were obtained from Table A1 in ICRU Report 46 [59].

Results from each simulation are serialized using the open-source “cereal” C++ serialization library before being written to binary data files [60].
3.4 **Efficiency Optimization**

3.4.1 Primary Energy Cutoff

GEANT4 computation time generally scales with increasing particle energy, meaning that for iterations involving very high energies, the simulations may become stuck on a single event for hours or even days. Because the maximum energies for the AE-8 and AP-8 radiation belt models are 7 MeV and 400 MeV, respectively, this issue is only a concern for the BON model spectra. From Figure 8, the BON model proton spectra become negligible at $\sim 10^4$ MeV, where ‘negligible’ is defined by the flux at the low-energy end of the spectrum. While it is not possible to define a single cutoff value for absolute kinetic energy across all particles, the value of $10^4$ MeV holds when considering kinetic energy per nucleon, instead. Thus, the maximum kinetic energy per nucleon for each charged particle is set at this value of $10^4$ MeV.

![Figure 8: Differential BON model spectra for proton, carbon-12, and iron-56, plotted against total kinetic energy (solid lines) and kinetic energy per nucleon (dashed lines).](image)

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3.4.2 Phantom Primary Particle Species Restriction

Due to the extremely high number of possible secondary particles produced by radiation interactions, it would be highly impractical to run phantom dose simulations for each potential type and energy of secondary particle produced by the boundary simulations. In order to limit the number of secondary particles that need to be considered, first, two boundary simulations were run. One simulation was to determine the secondary spectra on the surface of Mars. The second simulation was to determine the secondary spectra within a generic spacecraft (aluminum spherical shell of hull thickness 1”). Both simulations used the BON model as the free space radiation field. The secondary spectra from these simulations were then used to irradiate the ICRU Sphere phantom (30 cm diameter; composed of 76.2% oxygen, 11.1% carbon, 10.1% hydrogen, and 2.6% nitrogen; density = 1 g/cm³), which is often used to represent generic human body dose response [61]. Based on the results shown in Figures 9 and 10, simulated primary particles were limited to protons, neutrons, gammas, electrons, positrons, positive and negative pions, positive and negative muons, alphas, deuterons, H4, and He3, which together can be expected to contribute to around 99.9% of equivalent dose in space environments, in addition to the most common isotope of each heavy ion. If a secondary particle was a heavy ion of a rarer isotope, it was treated as the most common isotope of equivalent atomic number when generating the lookup table. This is a valid approximation as heavy ion interactions scale much more strongly with atomic number than atomic mass [62].
Figure 9: Contribution to equivalent dose to the ICRU sphere by each secondary particle from the Mars atmosphere simulation. Particles before Li4 contribute 99.9% to dose.

Figure 10: Contribution to equivalent dose to the ICRU sphere by each secondary particle from the spacecraft simulation. Particles before Li8 contribute 99.9% to dose.
4. Model Validation

*EVEREST* has been validated against two sources of real-world data, the Apollo 15 lunar mission (for evaluation of overall trajectory simulation performance) and the Mars Science Laboratory (MSL) radiation assessment detector (RAD) instrument on Mars (for evaluation of atmospheric physics accuracy). The Apollo missions were chosen as they were the only missions which sent humans into deep space, while the MSL RAD data was chosen as it is the only empirical radiation data from the surface of Mars.

4.1 The Apollo 15 Mission

During the second half of the 20th century, nine Apollo crews flew to the Moon, beginning with Apollo 8 in 1968. Fortunately for the Apollo astronauts, no solar particle events occurred during any of these missions, as NCRP Report 98 estimates that a crew on the lunar surface at the time of the SPE that occurred on August 4, 1972 would have received a skin dose of 6000 mSv and dose to blood-forming organs of 1300 mSv [2]. Instead, the vast majority of the dose received by the astronauts came from passage through the Van Allen belts and galactic cosmic radiation.

For all of the crewed Apollo missions, the each of the astronauts wore a personal radiation dosimeter (PRD) inside their suits, which continually updated dose readings and were visually read out to mission control at various points during the missions. Additionally, each astronaut carried three passive emulsion/thermoluminescent dosimeters, which were interpreted once the crew returned to Earth [63].
While there is a wealth of radiation data for each Apollo mission, none of the default SPICE kernels included any significant trajectory data for the Apollo missions. The European Space Agency (ESA) SPICE service provides a kernel for Apollo 15 that is valid for lunar orbit (the most complex part of the trajectory), but not for launch, translunar coast, and transearth coast. Additionally, large portions of this Apollo 15 SPICE kernel were reconstructed by ESA scientists in order to account for missing data.

The Apollo 15 PRD readouts are given below in Table 4, as transcribed from the raw Technical Air-to-Ground Voice Transcription [64].

<table>
<thead>
<tr>
<th>Mission Time (hh:mm:ss)</th>
<th>Position</th>
<th>Mission commander (mGy) (malfunction)</th>
<th>Command module pilot (mGy)</th>
<th>Lunar module pilot (mGy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>39:17:37</td>
<td>Translunar coast (TLC)</td>
<td>2.0</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>49:27:21</td>
<td>TLC</td>
<td>2.3</td>
<td>0.9</td>
<td>1.0</td>
</tr>
<tr>
<td>70:26:29</td>
<td>TLC</td>
<td>4.6</td>
<td>1.2</td>
<td>1.3</td>
</tr>
<tr>
<td>86:01:11</td>
<td>Lunar orbit</td>
<td>7.2</td>
<td>1.4</td>
<td>1.6</td>
</tr>
<tr>
<td>109:30:30</td>
<td>Lunar surface (commander and lunar module pilot); Lunar orbit (command module pilot)</td>
<td>-</td>
<td>1.7</td>
<td>2.0</td>
</tr>
<tr>
<td>182:56:20</td>
<td>Lunar orbit</td>
<td>7.4</td>
<td>2.3</td>
<td>2.9</td>
</tr>
<tr>
<td>193:25:58</td>
<td>Lunar orbit</td>
<td>17.5</td>
<td>2.4</td>
<td>3.1</td>
</tr>
<tr>
<td>212:29:55</td>
<td>Lunar orbit</td>
<td>18.2</td>
<td>2.6</td>
<td>3.3</td>
</tr>
<tr>
<td>236:58:14</td>
<td>Transearth coast (TEC)</td>
<td>19.3</td>
<td>2.8</td>
<td>3.7</td>
</tr>
<tr>
<td>237:59:03</td>
<td>TEC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>263:08:27</td>
<td>TEC</td>
<td>3.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>287:56:03</td>
<td>TEC</td>
<td>3.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>295:11:54</td>
<td>Splashdown</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The passive dosimeters worn by all three astronauts averaged 3.00 mGy at skin depth for the mission [63].

### 4.1.1 Apollo Astronaut XCAT Phantom

A single XCAT phantom was chosen to represent the Apollo 15 astronauts. This phantom was modeled as an adult 36-year-old male of weight 166 pounds and height 5‘10”, and was voxelized at 2 mm isotropic resolution.

![Figure 11: Anterior-posterior, lateral, and posterior-anterior views of the XCAT phantom used in the Apollo 15 simulation.](image)

### 4.1.2 Apollo CAD Models

Because NASA does not publicly offer any detailed CAD models of the Apollo spacecraft, a third-party 3D model was purchased from the CAD marketplace TurboSquid.
Before using the model, it was inspected for accuracy compared to 2-dimensional NASA schematics. The Apollo model included all components made of metal in the spacecraft. Spacecraft tanks were correlated to their respective contents using NASA schematics, and were manually filled in GEANT4 [66]–[68].

Figure 12: GEANT4 visualizations of the Apollo 15 spacecraft configurations post-launch (top), during translunar coast (middle), and during transearth coast (bottom). Aluminum is shown in light gray, titanium alloy (6Al-4V) in bronze, stainless steel in dark gray, liquid hydrogen in blue, liquid oxygen in red, water in purple, liquid helium in pink, nitrogen tetroxide (oxidizer) in green, monomethylhydrazine (service module fuel) in light yellow, and Aerozine 50 (lunar module fuel) in dark yellow. In each case, the secondary particle flux detector is placed at the center of the command module (black wireframe sphere).
4.1.3 Flight Trajectory

As mentioned, Apollo 15 was the only crewed moon mission with a large portion of the trajectory available in a SPICE kernel, offered by the European Space Agency on GitHub. Regardless, this kernel is only valid for the lunar orbit portion of the trajectory, and as a result, the remainder of the trajectory needed to be reconstructed using Table 3-III in the Apollo 15 Mission Report, which reports trajectory parameters (interchangeably relative to the Earth or Moon) at 38 time points [69]. All trajectory points were then transformed into the J2000 Earth-centered inertial reference frame relative to the Sun, and resampled to a uniform timestep of 6 minutes using a modified Akima piecewise cubic Hermite interpolation [70], [71].

In brief, the spacecraft launched on July 26, 1971 at 13:34:06 UTC from the Kennedy Space Center in Florida. It completed nearly two orbits of the Earth at an altitude of 93 miles, before translunar injection at around 2 hours and 50 minutes into the mission. At around 3 and a half hours into the mission, the command and service module (CSM) docked to the lunar module for its translunar flight configuration. At 100 hours and 39 minutes into the mission, the lunar module detached from the CSM. Apart from a brief re-docking of the lunar module after lunar ascent and jettison of the service module half an hour before landing, the remaining portion of the spacecraft consisted of the CSM until the end of the mission on August 7, 1971 at 20:45:53 UTC [69].
Figure 13: Apollo 15 flight path in the lunar inertial reference frame, relative to Earth. Red indicates spacecraft launch configuration, green indicates spacecraft translunar configuration, and blue indicates spacecraft transearth configuration.

Figure 14: Percent planetary shielding of GCR radiation over the Apollo 15 mission span. The high initial and final shielding was due to proximity to Earth, while the shielding between approximately 75 and 225 hours was due to lunar orbit.

4.1.4 Results and Comparison to Empirical Data

All simulations were run using the Duke Compute Cluster. The phantom simulation was run with a total of $1.44 \times 10^8$ histories distributed across 8,000 primary
events per combination of particle type and energy, with 36 particle types (Z=1-28 heavy ions, neutrons, gammas, electrons, positrons, positive and negative pions, positive and negative muons) and 500 energy bins. One boundary simulation was run for each of the three Apollo spacecraft configurations. Each boundary simulation was run with a total of $4.71 \times 10^7$ histories distributed across 3,250 primary events per combination of particle type and energy, with 29 particle types (Z=1-28 heavy ions and electrons) and 500 energy bins. The simulation criteria resulted in average percent standard deviations below 0.1%.

Figure 15: EVEREST-predicted cumulative absorbed dose versus mission time for the Apollo 15 astronaut XCAT phantom, compared to the PRD recorded dose for the command module pilot, who was the only astronaut to remain in lunar orbit. The average percent standard deviation in absorbed dose rate over the course of the mission was 0.043%, too small to be seen in the figure.
Figure 15 demonstrates excellent agreement between the absorbed dose simulated using \textit{EVEREST} and the Apollo 15 command module pilot’s PRD readings, particularly during the course of the latter half of the mission, following separation of the lunar module. The reason for comparing the simulated doses to the PRD readings for the command module pilot only was that the lunar module pilot and commander descended to the lunar surface.

The radiation exposure during the return passage through the Van Allen region appears considerably lower than that during the outbound passage, emphasizing the significant impact of near-Earth trajectory on exposure to radiation belt particles. Because these portions of the overall trajectory were manually extrapolated, the simulated doses at the start and end of the mission have the largest potential for error.

Though this effect is not seen in the empirical PRD readings, the dose rate during transearth coast was greater than that during translunar coast. This is expected, as the lunar module, which provided additional shielding to the command module, was not present during the return trajectory (Figures 12 and 13).

\textbf{4.1.5 Additional Results and Analysis}

In addition to enabling direct comparison to Apollo 15 empirical PRD data, this simulation study allows for further analysis that would not have been possible otherwise, as the PRDs only report estimates of full body absorbed dose, rather than organ absorbed doses and equivalent doses.
Figure 16: *EVEREST*-predicted cumulative absorbed dose and equivalent dose versus mission time for the Apollo 15 astronaut XCAT phantom. The average percent standard deviations in absorbed and equivalent dose rate over the course of the mission were 0.043\% and 0.024\%, respectively, too small to be seen in the figure.

Figure 16 shows both the simulated absorbed dose, as in Figure 15, but also the simulated equivalent dose for the Apollo 15 mission. This figure indicates, by inspecting the ratio of simulated equivalent dose to absorbed dose, that the average radiation weighting factor was lowest (~2) during passage through the Van Allen belts, regardless of the steep increase in dose, while the average radiation weighting factor in deep space was between 5 and 6. This result agrees with the expectations that most of the dose received during passage through the Van Allen belts was inflicted by electrons ($w_R = 1$).
and protons ($w_R = 2$), while in deep space a significant contributor to dose were heavy ions ($w_R = 20$). This result implies that while the Van Allen belts contributed significantly to the overall absorbed dose for the mission, they contributed much less to the overall equivalent dose.

In comparison to typical medical exposures, the dose received by the astronauts on Apollo 15 was rather minimal. As an example, the AAPM-ACR diagnostic reference level for an adult chest CT scan is 21 mGy [72], or approximately 6 times the absorbed dose received by the Apollo 15 command module pilot. Also note that the dose received by the Apollo crews occurred over the course of several days, while a typical CT scan lasts several minutes. In terms of equivalent dose, the reference chest photon CT scan would still have a dose of 21 mSv, which is similar to the simulated overall equivalent dose received by the Apollo 15 command module pilot of 17.45 mSv. However, again, it is important to keep in mind that the dose rate on Apollo 15 was significantly lower than a medical exposure in any case.

Table 5: Simulated overall organ absorbed dose values for the Apollo 15 mission. In addition, dose is reported for Van Allen radiation only, GCR only, and combined. All values are in mGy ($\pm$ uncertainty).
Table 6: Simulated overall organ equivalent dose values for the Apollo 15 mission. In addition, dose is reported for Van Allen radiation only, GCR only, and combined. All values are in mSv (± uncertainty).

<table>
<thead>
<tr>
<th></th>
<th>Gonads</th>
<th>Bone Marrow</th>
<th>Colon</th>
<th>Lung</th>
<th>Stomach</th>
<th>Bladder</th>
<th>Liver</th>
<th>Esophagus</th>
<th>Thyroid</th>
<th>Skin</th>
<th>Bone</th>
<th>Salivary Glands</th>
<th>Brain</th>
<th>Remainder</th>
<th>Total</th>
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<td>1.449</td>
<td>1.145</td>
<td>1.251</td>
<td>0.964</td>
<td>0.728</td>
<td>0.990</td>
<td>0.817</td>
<td>1.347</td>
<td>2.349</td>
<td>1.443</td>
<td>1.593</td>
<td>1.818</td>
<td>1.516</td>
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</tr>
<tr>
<td></td>
<td>(1.8%)</td>
<td>(0.4%)</td>
<td>(1.0%)</td>
<td>(0.9%)</td>
<td>(1.6%)</td>
<td>(1.4%)</td>
<td>(0.5%)</td>
<td>(1.5%)</td>
<td>(2.1%)</td>
<td>(0.2%)</td>
<td>(0.4%)</td>
<td>(1.0%)</td>
<td>(0.7%)</td>
<td>(0.1%)</td>
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<tr>
<td></td>
<td>(~0%)</td>
<td>(~0%)</td>
<td>(~0%)</td>
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<td>(0.2%)</td>
<td>(~0%)</td>
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<td>(~0%)</td>
<td>(~0%)</td>
<td>(~0%)</td>
<td>(~0%)</td>
</tr>
</tbody>
</table>

Tables 5 and 6 record the final organ absorbed and equivalent doses for the Apollo 15 mission, for both the Van Allen and GCR components, and also in total. The largest doses were seen in the skin and brain, both relatively less radiosensitive organs. However, the salivary glands, gonads, and bone marrow, all radiosensitive organs and tissues, also received relatively high doses as well. In addition, while the brain is less radiosensitive, it is a critical organ for normal human function.

Figure 17 shows a graphical representation of the total absorbed dose deposited in different organs following the Apollo 15 mission, while Figure 18 shows the dose split into the Van Allen radiation and GCR components. The colorbars in Figures 17 and 18 have been scaled such that skin dose is always the same color, allowing for examination of how dose scales with depth.
Figure 17: Medial frontal (left) and sagittal (right) views of the mission-total organ absorbed graphical dose map for the Apollo 15 astronaut XCAT phantom.
As can be seen in Figure 18, the overall dose received from GCR during the Apollo 15 mission was relatively uniformly distributed throughout the body, while the overall dose received from passage through the Van Allen belts fell off rapidly with depth. Figure 17 demonstrates that the overall dose deposited by both GCR and Van Allen belt radiation varied moderately throughout the body, with deeper organs receiving less dose.

While the Van Allen belts contributed less to overall radiation exposure during the course of the mission than GCR, this exposure occurred over the course of minutes, and
thus the dose rate during passage through the Van Allen belts was over three orders of magnitude greater than the average GCR dose rate.

4.2 Mars Science Laboratory Radiation Assessment Detector

The Mars Science Laboratory (MSL) Curiosity rover landed in Gale Crater on Mars on August 6, 2012. Since then, the onboard Radiation Assessment Detector (RAD) instrument has provided the only direct measurements of the radiation environment on the surface of Mars. The RAD is capable of measuring the differential energy spectra of particles which stop in plastic and CsI scintillators, following passage through two silicon detectors which define an acceptance angle of approximately 30 degrees [73]. The RAD can differentiate particles into groups of ion species using measurements of their stopping power [74]. Reference [73] reports averaged particle spectra over sols 13-173 for protons, deuterons, tritons, $^3$He, and $^4$He and for groups of ions with atomic number $Z = 3 - 5$, $Z = 6 - 8$, $Z = 9 - 13$, $Z = 14 - 24$, and $Z > 24$.

The flux of particles on the Martian surface at the Curiosity rover landing site was simulated using a modified version of an EVEREST boundary simulation in which the BON model GCR input spectra was directly simulated using the source, rather than the results being weighted afterwards. The planetary atmosphere was simulated using the Mars-GRAM atmospheric profile above Gale Crater at local noon on sol 93 with 300 atmospheric layers, each 1 km thick. The source was an isotropic sphere encompassing the top layer of the atmosphere with a geometry factor as defined in Equation (17), while
the detector was a sphere surrounding the planet 1 m above the surface. The detector only registered events within an acceptance angle of 30 degrees, or a maximum deviation from the surface normal of $\pi /6$. Thus, the geometry factor of the detector was determined by

$$G_{det} = \int_{\Omega} \int_{S} (\hat{r} \cdot dS) d\Omega = 4\pi r_{det}^2 \cdot \int_{0}^{\frac{\pi}{2}} \int_{\frac{\pi}{6}}^{\frac{\pi}{2}} \cos(\theta) \sin(\theta) d\theta d\phi = \pi^2 r_{det}^2. \quad (21)$$

A schematic of the simulation geometry is shown in Figure 19.

![Figure 19: Schematic of the geometry for the MSL RAD validation simulation. The outer dashed line represents the isotropic spherical source, and the inner dashed line represents the secondary particle detector with an acceptance angle of 30 degrees from the surface normal. The atmosphere is composed of 300 concentric spherical shells, each 1 km thick.](image)
4.2.1 Results and Comparison to Empirical Data

Simulations were performed using the Duke Compute Cluster. 390 compute nodes were used, with 150,000 primary events per simulation, for a total of $5.85 \times 10^7$ histories.

Figure 20: Particle fluxes measured by the MSL RAD (solid lines) in Gale Crater on Mars from sol 13 to 173, compared to simulated fluxes using EVEREST (dashed lines) on sol 93 for ions and isotopes with charges $Z = 1$ and 2.
Figure 21: Particle fluxes measured by the MSL RAD (solid lines) in Gale Crater on Mars from sol 13 to 173, compared to simulated fluxes using *EVEREST* (dashed lines) on sol 93 for ions with charge $Z > 2$.

Figures 20 and 21 demonstrate that *EVEREST* generally agrees with MSL RAD measurements to within an order of magnitude. The best agreement is seen for protons, $^4$He, $Z = 6 - 8$, $Z = 14 - 24$, and $Z > 24$. The greatest disagreement is seen for non-primary particles, i.e., deuterons, tritons, and $^3$He, for which *EVEREST* underestimates the flux by up to an order of magnitude.
5. Predictions of Astronaut Radiation Exposure in Martian Habitats

As a proof of concept, EVEREST was used to evaluate radiation exposure to a population of eight XCAT phantoms under three different shielding configurations on the surface of Mars at Gale Crater, and at four different timepoints during the day on March 31, 2021.

5.1 Simulation Design

Eight XCAT phantoms, identical to those shown in Figure 1, and reproduced in Figure 2, were each evaluated using an EVEREST phantom simulation. These phantoms included 25th, 50th, and 75th percentile BMI adult males and females, and a pediatric 10-year-old male and pediatric 10-year-old female, representative of a population living in a permanent Martian settlement.

The eight phantom simulations were each run with a total of $1.44 \times 10^8$ histories distributed across 8,000 primary events per combination of particle type and kinetic energy, 36 particle types ($Z=1$-28 heavy ions, neutrons, gammas, electrons, positrons, positive and negative pions, positive and negative muons), and 500 energy bins.
Four atmospheric boundary simulations were run using the Mars-GRAM atmospheric profile above Gale Crater, for each of four timepoints on March 31, 2021: 12 am, 6 am, 12 pm, and 6 pm local time. The atmosphere was modeled as 300 concentric spherical shells, each 1 km thick. Each atmospheric simulation was run with a total of 350,000 histories distributed across 25 primary events per combination of particle type and kinetic energy, 28 particle types (Z=1-28 heavy ions), and 500 energy bins. A schematic of the atmospheric simulation geometry is shown in Figure 23. The number of primary
events was limited by the amount of storage space required for the large number of secondary particles produced.

Figure 23: Schematic of the simulation geometry for the EVEREST atmospheric boundary simulations used in the Mars habitat study. The outer dashed line represents the isotropic spherical source, and the inner dashed line represents the secondary particle detector. The atmosphere is composed of 300 concentric spherical shells, each 1 km thick.

Finally, two Mars habitat boundary simulations were run, where the two habitats were either composed of ice (solid H₂O, ρ = 0.92 g/cm³) or concrete composed of Martian regolith. Both the ice and concrete habitat were 50 cm thick dome structures of radius 10 meters. Each habitat was situated atop a 100-meter cubed block of Martian surface regolith, in order to account for albedo radiation. The surface regolith was given a density of 1.52 g/cm³ [75], while the concrete was given a density of 2.4 g/cm³ [76]. The surface
regolith and concrete were given identical chemical compositions, as listed in Table 7. Radiation emanated from a hemispherical isotropic source surrounding the habitat. Each habitat simulation was run with a total of $8.46 \times 10^7$ histories distributed across 4,700 primary events per combination of particle type and kinetic energy, 36 particle types ($Z=1$-28 heavy ions, neutrons, gammas, electrons, positrons, positive and negative pions, positive and negative muons), and 500 energy bins. GEANT4 visualizations of the habitat simulation geometries are shown in Figure 24.

**Table 7: Material composition of Martian regolith [77].**

<table>
<thead>
<tr>
<th>Compound</th>
<th>Mass Fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO$_2$</td>
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</tr>
<tr>
<td>TiO$_2$</td>
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</tr>
<tr>
<td>Al$_2$O</td>
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</tr>
<tr>
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<td>MnO</td>
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</tr>
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<td>MgO</td>
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<td>CaO</td>
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<td>P$_2$O$_5$</td>
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</tr>
</tbody>
</table>

Figure 24: GEANT4 visualizations of the Martian regolith (left) and ice (right) habitats used in the Mars habitat study. The secondary particle flux detector is shown as a black wireframe sphere in each case.
5.2 Results and Discussion

Table 8 records organ absorbed dose rate values for each phantom under each shielding configuration (unshielded, 50 cm ice, and 50 cm Mars regolith concrete) at high noon (12 pm) local time. Table 9 records the same results but for equivalent dose rate.

Table 8: Organ absorbed dose values for each phantom under each shielding configuration at local noon. All values are in mGy/day (± uncertainty).

<table>
<thead>
<tr>
<th>Male, 10-Year-Old</th>
<th>Gonads</th>
<th>Bone Marrow</th>
<th>Colon</th>
<th>Lung</th>
<th>Stomach</th>
<th>Breast</th>
<th>Bladder</th>
<th>Liver</th>
<th>Esophagus</th>
<th>Thyroid</th>
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<th>Salivary Glands</th>
<th>Brain</th>
<th>Remainder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unshielded</td>
<td>0.1226</td>
<td>0.1369</td>
<td>0.1258</td>
<td>0.1321</td>
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<td>0.1213</td>
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</tr>
<tr>
<td></td>
<td>(0.8%)</td>
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<td>(0.1%)</td>
<td>(0.1%)</td>
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<td></td>
<td>(0.2%)</td>
<td>(0.1%)</td>
<td>(0.3%)</td>
<td>(0.5%)</td>
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<td>(-0%)</td>
<td>(-0%)</td>
<td>(0.2%)</td>
<td>(0.1%)</td>
</tr>
<tr>
<td>Ice (50 cm)</td>
<td>0.1123</td>
<td>0.1111</td>
<td>0.1012</td>
<td>0.1025</td>
<td>0.0912</td>
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<td>0.104</td>
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<td>(0.1%)</td>
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<tr>
<td>Regolith Concrete (50 cm)</td>
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<td>0.0779</td>
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<td>0.0722</td>
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</tr>
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</table>

<table>
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<tr>
<th>Female, 10-Year-Old</th>
<th>Gonads</th>
<th>Bone Marrow</th>
<th>Colon</th>
<th>Lung</th>
<th>Stomach</th>
<th>Breast</th>
<th>Bladder</th>
<th>Liver</th>
<th>Esophagus</th>
<th>Thyroid</th>
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<th>Salivary Glands</th>
<th>Brain</th>
<th>Remainder</th>
</tr>
</thead>
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<td>(-0%)</td>
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</tr>
<tr>
<td>Ice (50 cm)</td>
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<td>(-0%)</td>
<td>(-0%)</td>
<td>(-0%)</td>
<td>(0.3%)</td>
<td>(0.1%)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Female, 25th %tile BMI</th>
<th>Gonads</th>
<th>Bone Marrow</th>
<th>Colon</th>
<th>Lung</th>
<th>Stomach</th>
<th>Breast</th>
<th>Bladder</th>
<th>Liver</th>
<th>Esophagus</th>
<th>Thyroid</th>
<th>Skin</th>
<th>Bone</th>
<th>Salivary Glands</th>
<th>Brain</th>
<th>Remainder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unshielded</td>
<td>0.0939</td>
<td>0.1381</td>
<td>0.1326</td>
<td>0.1343</td>
<td>0.1343</td>
<td>--</td>
<td>0.127</td>
<td>0.1042</td>
<td>0.1252</td>
<td>0.1474</td>
<td>0.1438</td>
<td>0.1294</td>
<td>0.1327</td>
<td>0.1422</td>
<td>0.1341</td>
</tr>
<tr>
<td></td>
<td>(-0%)</td>
<td>(0.1%)</td>
<td>(0.1%)</td>
<td>(0.1%)</td>
<td>(0.2%)</td>
<td></td>
<td>(0.2%)</td>
<td>(0.1%)</td>
<td>(0.3%)</td>
<td>(0.7%)</td>
<td>(-0%)</td>
<td>(-0%)</td>
<td>(-0%)</td>
<td>(0.3%)</td>
<td>(0.1%)</td>
</tr>
<tr>
<td>Ice (50 cm)</td>
<td>0.0793</td>
<td>0.112</td>
<td>0.1067</td>
<td>0.1101</td>
<td>0.1071</td>
<td>0.121</td>
<td>0.0857</td>
<td>0.1007</td>
<td>0.1204</td>
<td>0.1085</td>
<td>0.1148</td>
<td>0.1054</td>
<td>0.0988</td>
<td>0.1215</td>
<td>0.1089</td>
</tr>
<tr>
<td></td>
<td>(-0%)</td>
<td>(0.1%)</td>
<td>(0.1%)</td>
<td>(0.1%)</td>
<td>(0.2%)</td>
<td>(0.2%)</td>
<td>(0.2%)</td>
<td>(0.1%)</td>
<td>(0.3%)</td>
<td>(0.5%)</td>
<td>(-0%)</td>
<td>(-0%)</td>
<td>(-0%)</td>
<td>(0.2%)</td>
<td>(0.1%)</td>
</tr>
</tbody>
</table>

51
As shown in Table 8, the absorbed dose values were generally highest for the unshielded configuration and lowest for the 50 cm regolith concrete habitat. Of note, however, is that the absorbed dose values for the organs receiving the highest doses under the 50 cm ice habitat were greater than the absorbed dose values for the organs receiving...
the lowest doses in the unshielded configuration for all of the phantoms, and, similarly, the absorbed dose values for the organs receiving the highest doses under the 50 cm regolith concrete habitat were greater than the absorbed dose values for the organs receiving the lowest doses under the 50 cm ice habitat. The brain and salivary glands consistently received the highest absorbed doses in the unshielded configurations, while both the ice and regolith concrete habitats appear to distribute the dose more uniformly throughout the body.

Table 9: Organ equivalent dose values for each phantom under each shielding configuration at local noon. All values are in mSv/day (± uncertainty).
<table>
<thead>
<tr>
<th>Female, 25th %ile BMI</th>
<th>Gonads</th>
<th>Bone Marrow</th>
<th>Colon</th>
<th>Lung</th>
<th>Stomach</th>
<th>Breast</th>
<th>Bladder</th>
<th>Liver</th>
<th>Esophagus</th>
<th>Thyroid</th>
<th>Skin</th>
<th>Bone</th>
<th>Salivary Glands</th>
<th>Brain</th>
<th>Remainder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unshielded</td>
<td>0.5025</td>
<td>0.7302</td>
<td>0.655</td>
<td>0.6958</td>
<td>0.7128</td>
<td>0.7155</td>
<td>0.5588</td>
<td>0.6456</td>
<td>0.6972</td>
<td>0.6634</td>
<td>0.7422</td>
<td>0.6826</td>
<td>0.7363</td>
<td>0.8064</td>
<td>0.7126</td>
</tr>
<tr>
<td>Ice (50 cm)</td>
<td>0.2906</td>
<td>0.3771</td>
<td>0.3423</td>
<td>0.3647</td>
<td>0.3359</td>
<td>0.4169</td>
<td>0.2971</td>
<td>0.332</td>
<td>0.3905</td>
<td>0.3117</td>
<td>0.3863</td>
<td>0.3459</td>
<td>0.3393</td>
<td>0.4349</td>
<td>0.3671</td>
</tr>
<tr>
<td>Regolith Concrete (50 cm)</td>
<td>0.1927</td>
<td>0.283</td>
<td>0.2515</td>
<td>0.2619</td>
<td>0.2263</td>
<td>0.3351</td>
<td>0.2045</td>
<td>0.25</td>
<td>0.3066</td>
<td>0.2868</td>
<td>0.3336</td>
<td>0.2456</td>
<td>0.2854</td>
<td>0.2929</td>
<td>0.2833</td>
</tr>
<tr>
<td>Male, 50th %ile BMI</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unshielded</td>
<td>0.6275</td>
<td>0.7378</td>
<td>0.6661</td>
<td>0.6968</td>
<td>0.6656</td>
<td>--</td>
<td>0.6099</td>
<td>0.6795</td>
<td>0.7074</td>
<td>0.7458</td>
<td>0.7533</td>
<td>0.695</td>
<td>0.7522</td>
<td>0.8537</td>
<td>0.7159</td>
</tr>
<tr>
<td>Ice (50 cm)</td>
<td>0.3005</td>
<td>0.3843</td>
<td>0.3344</td>
<td>0.3552</td>
<td>0.3232</td>
<td>--</td>
<td>0.3476</td>
<td>0.3512</td>
<td>0.3727</td>
<td>0.3796</td>
<td>0.3974</td>
<td>0.3558</td>
<td>0.3878</td>
<td>0.4517</td>
<td>0.3732</td>
</tr>
<tr>
<td>Regolith Concrete (50 cm)</td>
<td>0.2414</td>
<td>0.2808</td>
<td>0.2356</td>
<td>0.2487</td>
<td>0.2329</td>
<td>--</td>
<td>0.2142</td>
<td>0.2385</td>
<td>0.2717</td>
<td>0.233</td>
<td>0.3271</td>
<td>0.2447</td>
<td>0.3297</td>
<td>0.3235</td>
<td>0.2814</td>
</tr>
<tr>
<td>Female, 75th %ile BMI</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unshielded</td>
<td>0.6689</td>
<td>0.7331</td>
<td>0.673</td>
<td>0.7114</td>
<td>0.6958</td>
<td>0.74</td>
<td>0.6845</td>
<td>0.673</td>
<td>0.6706</td>
<td>0.7085</td>
<td>0.7444</td>
<td>0.6878</td>
<td>0.7802</td>
<td>0.7674</td>
<td>0.7159</td>
</tr>
<tr>
<td>Ice (50 cm)</td>
<td>0.2915</td>
<td>0.3839</td>
<td>0.3381</td>
<td>0.3721</td>
<td>0.3768</td>
<td>0.3771</td>
<td>0.395</td>
<td>0.3465</td>
<td>0.322</td>
<td>0.2962</td>
<td>0.3878</td>
<td>0.3502</td>
<td>0.4073</td>
<td>0.4032</td>
<td>0.3688</td>
</tr>
<tr>
<td>Regolith Concrete (50 cm)</td>
<td>0.2368</td>
<td>0.276</td>
<td>0.253</td>
<td>0.2479</td>
<td>0.2373</td>
<td>0.3161</td>
<td>0.2369</td>
<td>0.2396</td>
<td>0.2375</td>
<td>0.2576</td>
<td>0.3259</td>
<td>0.2441</td>
<td>0.3337</td>
<td>0.2904</td>
<td>0.2742</td>
</tr>
<tr>
<td>Male, 75th %ile BMI</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unshielded</td>
<td>0.6197</td>
<td>0.7291</td>
<td>0.638</td>
<td>0.6784</td>
<td>0.6567</td>
<td>--</td>
<td>0.6082</td>
<td>0.6652</td>
<td>0.6331</td>
<td>0.7599</td>
<td>0.7539</td>
<td>0.6945</td>
<td>0.7834</td>
<td>0.8653</td>
<td>0.712</td>
</tr>
<tr>
<td>Ice (50 cm)</td>
<td>0.4463</td>
<td>0.3734</td>
<td>0.3182</td>
<td>0.3456</td>
<td>0.3382</td>
<td>--</td>
<td>0.3047</td>
<td>0.3429</td>
<td>0.3242</td>
<td>0.3116</td>
<td>0.3979</td>
<td>0.3516</td>
<td>0.3374</td>
<td>0.4609</td>
<td>0.3738</td>
</tr>
<tr>
<td>Regolith Concrete (50 cm)</td>
<td>0.2748</td>
<td>0.2712</td>
<td>0.213</td>
<td>0.2443</td>
<td>0.2038</td>
<td>--</td>
<td>0.2029</td>
<td>0.2335</td>
<td>0.2108</td>
<td>0.1977</td>
<td>0.3267</td>
<td>0.238</td>
<td>0.2883</td>
<td>0.3221</td>
<td>0.2724</td>
</tr>
<tr>
<td>Female, 75th %ile BMI</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unshielded</td>
<td>0.4629</td>
<td>0.7307</td>
<td>0.6538</td>
<td>0.7009</td>
<td>0.6503</td>
<td>0.7083</td>
<td>0.6603</td>
<td>0.6965</td>
<td>0.5482</td>
<td>0.7482</td>
<td>0.7438</td>
<td>0.6858</td>
<td>0.7806</td>
<td>0.7916</td>
<td>0.7047</td>
</tr>
<tr>
<td>Ice (50 cm)</td>
<td>0.1965</td>
<td>0.3826</td>
<td>0.3393</td>
<td>0.3373</td>
<td>0.3531</td>
<td>0.3676</td>
<td>0.3619</td>
<td>0.3439</td>
<td>0.3545</td>
<td>0.258</td>
<td>0.3855</td>
<td>0.3498</td>
<td>0.3738</td>
<td>0.4242</td>
<td>0.3645</td>
</tr>
<tr>
<td>Regolith Concrete (50 cm)</td>
<td>0.2111</td>
<td>0.2799</td>
<td>0.2412</td>
<td>0.2326</td>
<td>0.2387</td>
<td>0.3113</td>
<td>0.3088</td>
<td>0.2181</td>
<td>0.2653</td>
<td>0.2355</td>
<td>0.3261</td>
<td>0.2397</td>
<td>0.2856</td>
<td>0.3032</td>
<td>0.2695</td>
</tr>
</tbody>
</table>
Table 9 demonstrates that the equivalent dose is much greater relative to the absorbed dose for the unshielded configuration than under either the 50 cm ice habitat or the 50 cm regolith concrete habitat. This is most likely due to the contribution of primary high-Z GCR particles contributing to dose in the unshielded configuration, which are otherwise mostly stopped by the habitats. Again, the brain and salivary glands often received the highest doses in the unshielded configuration, though less so under the ice and regolith concrete habitats. Equivalent doses for specific organs are seen to often vary on the order of several percent from phantom to phantom.

Tables 10 and 11 record the total body absorbed and equivalent doses for each phantom under each shielding configuration (unshielded, 50 cm ice, and 50 cm Mars regolith concrete) at each timepoint during the day (12 am, 6 am, 12 pm, and 6 pm local time).

**Table 10: Total body absorbed dose for each phantom under each shielding configuration and at each timepoint during the day. All values are in mGy/day. Standard deviations were all < 0.1%.

<table>
<thead>
<tr>
<th></th>
<th>Unshielded</th>
<th>Ice (50 cm)</th>
<th>Regolith Concrete (50 cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>12 am</td>
<td>6 am</td>
<td>12 pm</td>
</tr>
<tr>
<td>Male, 10-Year-Old</td>
<td>0.1294</td>
<td>0.1356</td>
<td>0.1331</td>
</tr>
<tr>
<td>Female, 10-Year-Old</td>
<td>0.1308</td>
<td>0.1365</td>
<td>0.1334</td>
</tr>
<tr>
<td>Male, 25th %tile BMI</td>
<td>0.1309</td>
<td>0.1367</td>
<td>0.1338</td>
</tr>
<tr>
<td>Female, 25th %tile BMI</td>
<td>0.1314</td>
<td>0.1364</td>
<td>0.1337</td>
</tr>
<tr>
<td>Male, 50th %tile BMI</td>
<td>0.1334</td>
<td>0.1391</td>
<td>0.1364</td>
</tr>
<tr>
<td>Female, 50th %tile BMI</td>
<td>0.1309</td>
<td>0.1364</td>
<td>0.1335</td>
</tr>
<tr>
<td>Male, 75th %tile BMI</td>
<td>0.1337</td>
<td>0.1389</td>
<td>0.1363</td>
</tr>
<tr>
<td>Female, 75th %tile BMI</td>
<td>0.13</td>
<td>0.1354</td>
<td>0.1328</td>
</tr>
</tbody>
</table>
Table 11: Total body equivalent dose for each phantom under each shielding configuration and at each timepoint during the day. All values are in mSv/day. Standard deviations were all < 0.1%.

<table>
<thead>
<tr>
<th></th>
<th>Unshielded</th>
<th>Ice (50 cm)</th>
<th>Regolith Concrete (50 cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>12 am</td>
<td>6 am</td>
<td>12 pm</td>
</tr>
<tr>
<td>Male, 10-Year-Old</td>
<td>0.6944</td>
<td>0.7122</td>
<td>0.7188</td>
</tr>
<tr>
<td>Female, 10-Year-Old</td>
<td>0.6937</td>
<td>0.7091</td>
<td>0.7147</td>
</tr>
<tr>
<td>Male, 25th %tile BMI</td>
<td>0.6945</td>
<td>0.7133</td>
<td>0.7173</td>
</tr>
<tr>
<td>Female, 25th %tile BMI</td>
<td>0.6887</td>
<td>0.7053</td>
<td>0.7112</td>
</tr>
<tr>
<td>Male, 50th %tile BMI</td>
<td>0.6963</td>
<td>0.7133</td>
<td>0.7176</td>
</tr>
<tr>
<td>Female, 50th %tile BMI</td>
<td>0.6917</td>
<td>0.7107</td>
<td>0.715</td>
</tr>
<tr>
<td>Male, 75th %tile BMI</td>
<td>0.693</td>
<td>0.7085</td>
<td>0.7136</td>
</tr>
<tr>
<td>Female, 75th %tile BMI</td>
<td>0.6846</td>
<td>0.6992</td>
<td>0.7057</td>
</tr>
</tbody>
</table>

Both Table 10 and Table 11 demonstrate that the total body absorbed and equivalent doses varied minimally across time of day and phantom identity as compared to the variation across shielding configurations. As expected, the greatest amount of dose was deposited in the unshielded configuration, followed by the 50 cm ice habitat, and finally the 50 cm regolith concrete habitat. Though not immediately evident from the color scale, both absorbed dose and equivalent dose varied more across time of day than between different phantoms for a given shielding configuration. Under both the unshielded configuration and the ice habitat, the least amount of dose was generally deposited at midnight (12 am), though for the regolith concrete habitat, the least amount of dose was generally deposited at high noon (12 pm). These diurnal variations in dose are likely a complex function of particle type, atmospheric density, atmospheric chemical composition, and shielding. In addition, as already seen in Tables 8 and 9, the equivalent
dose is much greater relative to the absorbed dose for the unshielded configuration than under either the 50 cm ice habitat or the 50 cm regolith concrete habitat. Specifically, the average radiation weighting factor for the unshielded configuration ranged between 5.10 and 5.40, while for the 50 cm ice habitat this value ranged from 3.27 to 3.44 and for the 50 cm regolith concrete habitat it ranged from 3.16 to 3.37.

As mentioned in the previous section, the AAPM-ACR diagnostic reference level for an adult chest CT scan is 21 mGy [72]. Table 12 records the number of days spent on the surface of Mars for each shielding configuration before the radiation dose received is equal to that of an adult chest CT scan, in terms of both absorbed dose and equivalent dose, averaged across all eight phantoms.

| Table 12: Number of days spent on the surface of Mars for each shielding configuration before the radiation dose received is equal to that of an adult chest CT scan, in terms of absorbed and equivalent dose. |
|---|---|---|
| | Days on Mars per adult chest CT scan | |
| | Absorbed Dose | Equivalent Dose |
| Unshielded | 156.6 ± 1.7 | 29.7 ± 0.2 |
| Ice (50 cm) | 192.8 ± 1.9 | 57.6 ± 0.5 |
| Regolith Concrete (50 cm) | 241.4 ± 3.4 | 74.1 ± 1.5 |

In addition, although the concept of ICRP effective dose is generally not applicable to space applications, these values can be compared to the United States Code of Federal Regulations yearly occupational effective dose limit of 50 mSv [78]. The ICRP effective dose rate for the eight phantoms in each shielding configuration ranged from 0.597 to 0.705 mSv/day for the unshielded configuration, from 0.310 to 0.359 mSv/day under the
50 cm ice habitat, and from 0.212 to 0.266 mSv/day under the 50 cm regolith concrete habitat. Table 13 records the range of days spent on the surface of Mars for each shielding configuration before the yearly occupational dose limit is reached for the eight phantoms in this study, if terrestrial radiation protection standards were to be applied.

Table 13: Ranges of number of days spent on the surface of Mars for each shielding configuration before the yearly occupational dose limit is reached for the eight phantoms in this study.

<table>
<thead>
<tr>
<th>Shielding Configuration</th>
<th>Days to yearly occupational dose limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unshielded</td>
<td>70.9 – 83.8</td>
</tr>
<tr>
<td>Ice (50 cm)</td>
<td>139.2 – 161.2</td>
</tr>
<tr>
<td>Regolith Concrete (50 cm)</td>
<td>188.1 – 235.7</td>
</tr>
</tbody>
</table>

Note that these values do not account for possible solar particle events, which were not considered for this study.

Based on this study, several possible measures might be taken to further protect astronauts from harmful space radiation. First, although the brain is relatively less radiosensitive, it is a critical organ, and appears to receive one of the highest doses in the body on the surface of Mars. In order to mitigate this effect, extra shielding could be added to the helmets of Mars extravehicular activity (EVA) suits. Second, the unshielded dose rate on Mars appears to be marginally lower at midnight than at other points during the day, indicating that it might be beneficial to plan longer EVAs when astronauts are spending a significant amount of time outside of the habitat for late evening. Finally, a concrete habitat composed of Martian regolith was found to perform marginally better than a habitat composed of ice of the same thickness, in terms of radiation protection.
6. Summary, Conclusion, and Future Work

The purpose of this project was to develop and validate a general-purpose GEANT4-based Monte Carlo toolkit, named EVEREST, incorporating highly detailed, anatomically realistic digital human phantoms with the sophistication to model individual humans, combined with advanced NASA models of planetary atmospheres, spaceflight trajectories, and space radiation spectra, to evaluate radiation exposure in interplanetary missions and on planetary habitats. Galactic cosmic radiation spectra were modeled using the Badhwar-O’Neill 2020 model, the Van Allen belt spectra were modeled using the AE-8/AP-8 models, and solar particle event spectra could be selected from historical data. The magnetic field input to the AE-8/AP-8 model was generated using the 13th generation International Geomagnetic Reference Field. Planetary atmospheres were modeled using NASA Global Reference Atmospheric Models, and the effect of Earth’s magnetic field was accounted for using a geomagnetic cutoff rigidity algorithm. Planetary orbits, trajectories, and relative positions of objects in the Solar System were determined using the NAIF SPICE API. Finally, highly detailed extended cardiac-torso (XCAT) digital phantoms were integrated into EVEREST in order to accurately model radiation exposure to individual organs.

The EVEREST framework was designed using a novel lookup table method, in which different stages of particle propagation were divided into separate simulations, which are then convolved in post-processing. This increases model efficiency and allows
simulation attributes, such as spacecraft model, to be easily interchanged, without having to run all of the physics again.

**EVEREST** was validated against personal radiation dosimeter data collected by the lunar module pilot on the Apollo 15 mission and also flux data from the Mars Science Laboratory Radiation Assessment Detector. Apollo 15 was chosen because it is the only crewed spaceflight beyond low-Earth orbit with a significant part of its trajectory having been digitized. Simulation results were found to agree remarkably well with dosimeter readings by the command module pilot. Likewise, the MSL RAD instrument has provided the only direct measurements of the radiation environment on the surface of Mars. Comparison of Martian surface particle fluxes simulated by **EVEREST** to RAD data demonstrated an agreement to within an order of magnitude, with the best agreement seen for protons, \(^4\text{He}, Z = 6 - 8, Z = 14 - 24, \text{and } Z > 24\).

As a proof of concept, **EVEREST** was used to evaluate radiation exposure to a population of eight XCAT phantoms (25th, 50th, and 75th percentile BMI adult males and females, and a pediatric 10-year-old male and pediatric 10-year-old female) under three different shielding configurations (unshielded, a 50 cm thick dome habitat made of ice, and a 50 cm thick concrete dome habitat composed of Martian regolith) on the surface of Mars at Gale Crater, and at four different timepoints during the day (12 am, 6 am, 12 pm, and 6 pm local time) on March 31, 2021. Key findings of this study included the results that the brain receives one of the highest organ doses in the body, that unshielded
radiation exposure is lowest at midnight, and that concrete composed of Martian regolith provides better shielding than ice for the same thickness. It was found that federal yearly occupational dose limits would be reached in between 70.9 and 83.8 days unshielded, between 139.2 and 161.2 days under the 50 cm thick ice habitat, and between 188.1 and 235.7 days under the 50 cm thick concrete habitat composed of Martian regolith, if terrestrial radiation protection standards were to be applied. Finally, it is recommended that extra care be taken to provide radiation shielding in Mars astronauts’ helmets and that extended EVAs be planned for late evening.

6.1 Limitations and Future Work

Despite EVEREST’s success in terms of physics and total body absorbed dose validation, the detailed organ dosimetry estimations are limited, as a human body’s position and orientation within a spacecraft or habitat (which was not taken into account in the current model) likely has an effect on the radiation field to which specific organs are exposed [45]. Currently, EVEREST assumes that the radiation field within a spacecraft or habitat is uniform. Without compromising the benefits of the lookup table method, future improvements to EVEREST would include modifying the secondary particle flux detector in the boundary simulations to account for position and directionality of incoming particles.

Dose results throughout this thesis have been reported in both absorbed and ICRP equivalent dose. In addition, for comparison of the Mars habitat results to federal yearly
occupational dose limits, ICRP effective dose was calculated. However, as there is
mounting evidence that the body’s ability to repair DNA damage is compromised under
reduced gravity [52], [53], the standard biological effectiveness of different types of
radiation, i.e. their radiation weighting factors, may be less applicable. Thus, the only
results that can be taken entirely at face value in this thesis are the reported absorbed dose
values, which represent a physical quantity, while equivalent doses may still be relatively
accurate. On the other hand, ICRP effective dose is certainly not applicable for Mars
surface radiation, and its calculations served only in order to determine how quickly the
yearly occupational limits are reached if terrestrial radiation protection standards were to
be applied.

As a tested and validated general-purpose simulator, EVEREST offers a wealth of
potential future applications and research avenues. As NASA is currently planning
several crewed Artemis missions to the Moon with extended stays on the lunar surface in
the upcoming decade, EVEREST can be leveraged to optimize mission design with respect
to radiation protection. For such missions, this can be in the form of designing optimal
shielding for the spacecraft and lunar habitats, or the proportion of time spent in orbit
versus on the surface. Looking further into the future, EVEREST may be used to optimize
flight paths to Mars. As shown in Figure 3, the flux of galactic cosmic radiation increases
with radial distance from the Sun. Thus, a trajectory to Mars that spends more time closer
to the Sun may ultimately be better in terms of radiation protection. Such a trajectory
might first travel inwards towards the Sun, before performing a gravity assist using Venus, picking up speed for the portion of the trip between the orbits of Earth and Mars. Finally, this model is capable of being used to evaluate radiation exposure on even more exotic missions, such as expeditions to Saturn’s moon Titan or on floating habitats in the clouds of Venus.
References


Uncertainties.pdf.


