Fiscal Year:	FY 2014	**Task Last Updated:**	FY 07/14/2014
PI Name:	Norbury, John Ph.D.		
Project Title:	Measurements and Transport Phase 2 Physics Project		
Division Name:	Human Research		
Program/Discipline:	HUMAN RESEARCH		
Program/Discipline--Element/Subdiscipline:	HUMAN RESEARCH--Radiation health		
Joint Agency Name:		**TechPort:**	No
Human Research Program Elements:	(1) **SR**:Space Radiation		
Human Research Program Risks:	(1) **ARS**:Risk of Acute Radiation Syndromes Due to Solar Particle Events (SPEs) (2) **Cancer**:Risk of Radiation Carcinogenesis (3) **CNS**:Risk of Acute (In-flight) and Late Central Nervous System Effects from Radiation Exposure (4) **Degen**:Risk of Cardiovascular Disease and Other Degenerative Tissue Effects From Radiation Exposure and Secondary Spaceflight Stressors		
Space Biology Element:	None		
Space Biology Cross-Element Discipline:	None		
Space Biology Special Category:	None		
PI Email:	John.w.norbury@nasa.gov	**Fax:**	FY
PI Organization Type:	NASA CENTER	**Phone:**	757-864-1480
Organization Name:	NASA Langley Research Center		
PI Address 1:	Mail Stop 188E		
PI Address 2:	LaRC-D309		
PI Web Page:			
City:	Hampton	**State:**	VA
Zip Code:	23681-2199	**Congressional District:**	1
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Project Type:	GROUND	**Solicitation / Funding Source:**	Directed Research
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Contact Monitor:	Simonsen, Lisa	**Contact Phone:**	
Contact Email:	lisa.c.simonsen@nasa.gov		
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Key Personnel Changes/Previous PI:			
COI Name (Institution):	Blattnig, Steve (NASA Langley Research Center) Clowdsley, Martha (NASA Langley Research Center) Slaba, Tony (NASA Langley Research Center) Simonsen, Lisa (NASA Langley Research Center) Werneth, Charles (NASA Langley Research Center) Norman, Ryan (NASA Langley Research Center)		
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Task Description:

Currently, the deterministic space radiation transport code HZETRN (High charge (Z) and Energy TRaNsport), is the major tool used by NASA to evaluate radiation environments inside spacecraft. Deterministic codes have been shown to be superior to Monte Carlo transport for engineering studies. However HZETRN is a one dimensional transport code. The transport of heavy ions ($Z > 2$) has been shown to be valid in the one dimensional approximation because the relativistic heavy ions found in the space radiation spectrum pass through materials relatively un-deflected from their initial trajectories. The cross sections required for one dimensional transport are total absorption and spectral distributions. Meson production and the associated electromagnetic cascade have not yet been incorporated into HZETRN. Phase 1 studies have shown the importance of these processes, which must be included in Phase 2. This project implements the recommendations of several workshops by emphasizing the development of a more accurate description of neutron and light ion transport. Neutrons and light ions scatter at large angles and the one dimensional approximation is no longer valid. Therefore, the one dimensional code HZETRN must begin to include the three dimensional transport of light ions and neutrons to more accurately quantify secondary radiation environments in tissue while maintaining computational speed and efficiency. Such a three dimensional transport code in turn requires fully double differential cross sections as input.
Phase II Measurements and Physics Project focuses on light ion production and transport to develop space radiation transport codes capable of predicting primary and secondary spectra of space radiation environment interaction behind typical spacecraft shielding, planetary surfaces, and atmospheres with increased accuracy. Configuration managed V&V'ed source codes are released to the radiation user community including Exploration, RHO, and Operations as well as industry partners or commercial entities. Current exploration vehicle requirements specify that HZETRN shall be utilized by the government for radiation requirement verification. Transport codes directly support verification of NASA STD 3001 Vol. 2 requirements.

Phase 2 focus:

• Current focus is on light ion and neutron transport and production including 3-D effects of neutron backscattered and inclusion of dose received from pion production

• Future nuclear physic improvements will focus on improved models needed for definition of Mars Surface Environment

Implementation of Phase 2 Physics supports closing the following gaps,

• Cancer - 11: What are the most effective shielding approaches to mitigate cancer risks?

• Cancer - 12: What level of accuracy do NASA's space environment, transport code and cross sections describe radiation environments in space (ISS, Lunar, or Mars)? Pion production models are also being worked on.

Rationale for HRP Directed Research:

Research Impact/Earth Benefits:

The radiation transport codes developed at NASA Langley Research Center can potentially be used in other applications such as proton and heavy ion therapy treatments for cancer.

Improvements to photonuclear cross sections were made. The Weisskopf-Ewing (WE) and Hauser-Feshbach (HF) theory are statistical methods, which are often used to calculate photonuclear cross sections for compound nucleus reactions. In our past work, WE methodology was presented and photonuclear reaction cross sections for nucleon emission were calculated using WE theory. Now, the previous results, which neglect pre-equilibrium emissions and do not include multiple particle emission, were compared to those calculated with HF theory and experimental data. For the reactions we considered, it was found that the WE theory and HF method are in reasonable agreement below the two neutron separation energy assuming an energy dependent branching ratio for intermediate and heavy nuclei.
The Nowcast of Atmospheric Ionizing Radiation for Aviation Safety (NAIRAS) has been developed. It makes integral use of the HZETRN code, which has been developed under the Human Research Program. NAIRAS is a real-time, global, physics-based model used to assess radiation exposure to commercial aircrews and passengers. The model is a free-running physics-based model in the sense that there are no adjustment factors applied to nudge the model into agreement with measurements. The model predicts dosimetric quantities in the atmosphere from both galactic cosmic rays (GCR) and solar energetic particles, including the response of the geomagnetic field to interplanetary dynamical processes and its subsequent influence on atmospheric dose. The focus of the work is on atmospheric GCR exposure during geomagnetically quiet conditions, with three main objectives. First, provide detailed descriptions of the NAIRAS GCR transport and dosimetry methodologies. Second, present a climatology of effective dose and ambient dose equivalent rates at typical commercial airline altitudes representative of solar cycle maximum and solar cycle minimum conditions and spanning the full range of geomagnetic cutoff rigidities. Third, conduct an initial validation of the NAIRAS model by comparing predictions of ambient dose equivalent rates with tabulated reference measurement data and recent aircraft radiation measurements taken in 2008 during the minimum between solar cycle 23 and solar cycle 24. By applying the criterion of the International Commission on Radiation Units and Measurements (ICRU) on acceptable levels of aircraft radiation dose uncertainty for ambient dose equivalent greater than or equal to an annual dose of 1 mSv, the NAIRAS model is within 25% of the measured data, which fall within the ICRU acceptable uncertainty limit of 30%. The NAIRAS model predictions of ambient dose equivalent rate are generally within 50% of the measured data for any single-point comparison. The largest differences occur at low latitudes and high cutoffs, where the radiation dose level is low. Nevertheless, analysis suggests that these single-point differences will be within 30% when a new deterministic pion-initiated electromagnetic cascade code is integrated into NAIRAS, an effort which is currently underway.

Estimates of Carrington class solar particle even radiation exposures were made as a function of altitude in the atmosphere of Mars. Radiation exposure estimates for crew members on the surface of Mars may vary widely because of the large variations in terrain altitude. The maximum altitude difference between the highest (top of Olympus Mons) and the lowest (bottom of the Hellas impact basin) points on Mars is about 32 km. In this work estimates of radiation exposures as a function of altitude, from the Hellas impact basin to Olympus Mons, are made for a solar particle event proton radiation environment comparable to the Carrington event of 1859. We assume that the proton energy distribution for this Carrington-type event is similar to that of the Band Function fit of the February 1956 event. In this work we use the HZETRN 2010 radiation transport code, originally developed at NASA Langley Research Center, and the Computerized Anatomical Male and Female human geometry models to estimate exposures for aluminum shield areal densities similar to those provided by a spacesuit, surface lander, and permanent habitat as a function of altitude in the Mars atmosphere. Comparisons of the predicted organ exposures with current NASA Permissible Exposure Limits (PELs) are made.

A comparative study of space radiation organ doses and associated cancer risks using Particle and Heavy Ion Transport Code System (PHITS) and HZETRN was performed. NASA currently uses one dimensional deterministic transport to generate values of the organ dose equivalent needed to calculate stochastic radiation risk following crew space exposures. In this study, organ absorbed doses and dose equivalents were calculated for 50th percentile male and female astronaut phantoms using both the NASA High Charge and Energy Transport Code to perform one-dimensional deterministic transport and the Particle and Heavy Ion Transport Code System to perform three-dimensional Monte Carlo transport. Two measures of radiation risk, effective dose and risk of exposure-induced death (REID) are calculated using the organ dose equivalents resulting from the two methods of radiation transport. For the space radiation environments and simplified shielding configurations considered, small differences (<8%) in the effective dose and REID are found. However, for the galactic cosmic ray (GCR) boundary condition, compensating errors are observed, indicating that comparisons between the integral measurements of complex radiation environments and code calculations can be misleading. Code-to-code benchmarks allow for the comparison of differential quantities, such as secondary particle differential fluence, to provide insight into differences observed in integral quantities for particular components of the GCR spectrum.

Task Progress:

The new radiation belt AE9/AP9/SPM model for a cislunar mission was evaluated. Space mission planners continue to experience challenges associated with human space flight. Concerned with the omnipresence of harmful ionizing radiation in space, at the mission design stage, mission planners must evaluate the amount of exposure the crew of a spacecraft is subjected to during the transit trajectory from low Earth orbit (LEO) to geosynchronous orbit (GEO) and beyond (free space). The Earth's geomagnetic field is located within the domain of LEO-GEO and, depending on latitude, extends out some 40,000 - 60,000 km. This field contains the Van Allen trapped electrons, protons, and low-energy plasmas, such as the nuclei of hydrogen, helium, oxygen, and to a lesser degree other atoms. In addition, there exist the geomagnetically attenuated energetic galactic cosmic rays (GCR). These particles are potentially harmful to improperly shielded crew members and onboard subsystems. Mitigation strategies to limit the exposure due to free space GCR and sporadic solar energetic particles (SEP) such as flare and coronal mass ejection (CME) must also be exercised beyond the trapped field. Presented in this work is the exposure analysis for a multi-vehicle mission planned for the epoch of February 2020 from LEO to the Earth-moon Lagrange-point two (L2), located approximately 63,000 km beyond the orbit of the Earth-moon binary system. Space operation at L2 provides a gravitationally stable orbit for a vehicle and partially eliminates the need for periodic thrust-vectoring to maintain orbital stability. In the cislunar (Earth-moon) space of L2, the mission trajectory and timeline in this work call for a cargo vehicle to rendezvous with a crew vehicle. This is followed by 15 days of space activities at L2 while the cargo and crew vehicles are docked after which the crew returns to Earth. The mission epoch of 2020 is specifically chosen as it is anticipated that the next solar minimum (i.e. end of cycle 24) in the Sun's approximate 11 years cycle will take place around this time. From a mission planning point of view, this date is ideal as the predictable GCR exposure will be at a maximum, while the sporadic SEP will be at a minimum. In addition, it is anticipated that by 2020 a vehicle capable of launching a crew of four will be operationally ready. During the LEO–GEO transit, the crew and cargo vehicles will encounter exposure from trapped particles and attenuated GCR, followed by free space exposure due to GCR and SEP during solar active times. Within the trapped field, a challenge arises from properly calculating the amount of exposure acquired. Within this field, in the absence of SEP (i.e. solar quiet times), the vehicles will have to transit through an inner proton belt, an inner and outer electron belts, and an attenuated GCR field. There exist a number of models to define the intensities of the trapped particles during the quiet and active SEP. Among the more established trapped models are the historic and popular electron/proton AE8/AP8 model dating back to the 1980s, the historic and less popular electron/proton Combined Release and Radiation Effects Satellite (CRRES) model dating back to 1990s, and the recently released electron/proton/space plasma AE9/AP9/SPM model.

Radiation shielding effectiveness with correlated uncertainties was evaluated. The space radiation environment is composed of energetic particles which can deliver harmful doses of radiation that may lead to acute radiation sickness, cancer, and even death for insufficiently shielded crew members. Spacecraft shielding must provide structural integrity and minimize the risk associated with radiation exposure. The risk of radiation exposure induced death (REID) is a measure of the risk of dying from cancer induced by radiation exposure. Uncertainties in the risk projection model, quality factor, and spectral fluence are folded into the calculation of the REID by sampling from probability distribution functions. Consequently, determining optimal shielding materials that reduce the REID in a statistically significant manner has been found to be difficult. In this work, the difference of the REID distributions for different materials is used to study the effect of composition on shielding effectiveness. It is shown that the use of correlated uncertainties allows for the determination of statistically significant differences between materials despite the large uncertainties in the quality factor. This is in contrast to previous methods where uncertainties have been generally treated as uncorrelated. It is concluded that the use of correlated quality factor uncertainties greatly reduces the uncertainty in the assessment of shielding effectiveness for the mitigation of radiation exposure.

Nucleus-nucleus relativistic multiple scattering theory with delta degrees of freedom was studied. It is well known that multiple scattering theories are very useful in the study of nucleon-nucleus and nucleus-nucleus scattering processes. The derivation of a nonrelativistic multiple scattering theory (NRMST) is well established and clear. A key component to the formulation of an NRMST is the ability to separate the unperturbed Hamiltonian from the residual interaction. For the relativistic problem, it is not clear how to perform this separation starting from a field theoretical Lagrangian. Instead, one starts from an infinite set of Feynman diagrams, which play the role of the kernel in the Bethe-Salpeter equation for nucleus-nucleus scattering. Once the kernel is defined, it is straightforward to develop a relativistic multiple scattering theory (RMST). To be more complete than previous studies, delta degrees of freedom are included, which is a minimum requirement to explain pion production. It is demonstrated that an RMST can be formulated by expressing the kernel in a form that is similar to the residual interaction in the NRMST.

Finite sum expressions for elastic and reaction cross section were derived. Nuclear cross section calculations are often performed by using the partial wave method or the Eikonal method through Glauber theory. The expressions for the total cross section, total elastic cross section, and total reaction cross section in the partial wave method involve infinite sums and do not utilize simplifying approximations. Conversely, the Eikonal method gives these expressions in terms of integrals but utilizes the high energy and small angle approximations. In this paper, by using the fact that the lth partial wave component of the T-matrix can be very accurately approximated by its Born term, the infinite sums in each of the expressions for the differential cross section, total elastic cross section, total cross section, and total reaction cross section are re-written in terms of finite sums plus closed form expressions. The differential cross sections are compared to the Eikonal results for elastic scattering. Total cross sections, total reaction cross sections, and total elastic cross sections are compared to the Eikonal results.

Influence of dust loading on atmospheric ionizing radiation on Mars was studied. Measuring the radiation environment at the surface of Mars is the primary goal of the Radiation Assessment Detector on the NASA Mars Science Laboratory's Curiosity rover. One of the conditions that Curiosity will likely encounter is a dust storm. The objective of this paper is to compute the cosmic ray ionization in different conditions, including dust storms, as these various conditions are likely to be encountered by Curiosity at some point. In the present work, the Nowcast of Atmospheric Ionizing Radiation for Aviation Safety model, recently modified for Mars, was used along with the Badhwar & O'Neill 2010 galactic cosmic ray model. In addition to galactic cosmic rays, five different solar energetic particle event spectra were considered. For all input radiation environments, radiation dose throughout the atmosphere and at the surface was investigated as a function of atmospheric dust loading. It is demonstrated that for galactic cosmic rays, the ionization depends strongly on the atmosphere profile. Moreover, it is shown that solar energetic particle events strongly increase the ionization throughout the atmosphere, including ground level, and can account for the radio blackout conditions observed by the Mars Advanced Radar for Subsurface and Ionospheric Sounding instrument on the Mars Express spacecraft. These results demonstrate that the cosmic rays' influence on the Martian surface chemistry is strongly dependent on solar and atmospheric conditions that should be taken into account for future studies.

An analytical-HZETRN model for rapid assessment of active magnetic radiation shielding was developed. The use of active radiation shielding designs has the potential to reduce the radiation exposure received by astronauts on deep space missions at a significantly lower mass penalty than designs utilizing only passive shielding. Unfortunately, the determination of the radiation exposure inside these shielded environments often involves lengthy and computationally intensive Monte Carlo analysis. In order to evaluate the large trade space of design parameters associated with a magnetic radiation shield design, an analytical model was developed for the determination of flux inside a solenoid magnetic field due to the Galactic Cosmic Radiation (GCR) radiation environment. This analytical model was then coupled with NASA's radiation transport code, HZETRN, to account for the effects of passive/structural shielding mass. The resulting model can rapidly obtain results for a given configuration and can therefore be used to analyze an entire trade space of potential variables in less time than is required for even a single Monte Carlo run. Analyzing this trade space for a solenoid magnetic shield design indicates that active shield bending powers greater than about 15 Tm and passive/structural shielding thicknesses greater than 40 g/cm2 have a limited impact on reducing dose equivalent values. Also, it is shown that higher magnetic field strengths are more effective than thicker magnetic fields at reducing dose equivalent.

A sensitivity analysis for galactic cosmic ray environments was performed. Accurate galactic cosmic ray (GCR) models are required to assess crew exposure during long-duration missions to the Moon or Mars. Many of these models have been developed and compared to available measurements, with uncertainty estimates usually stated to be less than 15%. However, when the models are evaluated over a common epoch and propagated through to effective dose, relative differences exceeding 50% are observed. This indicates that the metrics used to communicate GCR model uncertainty can be better tied to exposure quantities of interest for shielding applications. This is the first of three papers focused on addressing this need. In this work, the focus is on quantifying the extent to which each GCR ion and energy group, prior to entering any shielding material or body tissue, contributes to effective dose behind shielding. Results can be used to more accurately calibrate model-free parameters and provide a mechanism for refocusing validation efforts on measurements taken over important energy regions. Results can also be used as references to guide future nuclear cross-section measurements and radiobiology experiments. It is found that GCR with $Z > 2$ and boundary energies below 500 MeV/n induce less than 5% of the total effective dose behind shielding. This finding is important given that most of the GCR models are developed and validated against Advanced Composition Explorer/Cosmic Ray Isotope Spectrometer (ACE/CRIS) measurements taken below 500 MeV/n. It is therefore possible for two models to very accurately reproduce the ACE/CRIS data while inducing very different effective dose values behind shielding.

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