Fiscal Year:	FY 2013	**Task Last Updated:**	FY 07/10/2013
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		
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City:	Hampton	**State:**	VA
Zip Code:	23681-2199	**Congressional District:**	1
Comments:			
Project Type:	Ground	**Solicitation / Funding Source:**	Directed Research
Start Date:	10/01/2007	**End Date:**	09/30/2015
No. of Post Docs:	4	**No. of PhD Degrees:**	0
No. of PhD Candidates:	0	**No. of Master' Degrees:**	0
No. of Master's Candidates:	0	**No. of Bachelor's Degrees:**	0
No. of Bachelor's Candidates:	0	**Monitoring Center:**	NASA LaRC
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Flight Program:			
Flight Assignment:			
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)		
Grant/Contract No.:	Directed Research		
Performance Goal No.:			
Performance Goal Text:			

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.
	Exposure estimates have been made for repair satellites at geosynchronous orbit. Communications and weather satellites in geosynchronous (GEO) and geostationary orbits (GSO) are revolutionizing our ability to almost instantly communicate with each other, capture high resolution global imagery for weather forecasting and obtain a multitude of other geophysical data for environmental protection purposes. The rapid increase in the number of satellites at GEO is partly due to the exponential expansion of the internet, its commercial potential, and the need to deliver a large amount of digital information in near real time. With the large number of satellites operating at GEO and particularly at GSO, there is a need to think of viable approaches to retrieve, rejuvenate, and perhaps repair these satellites. The first step in this process is a detailed understanding of the ionizing radiation environment at GEO. Currently, the most widely used trapped particle radiation environment definition near Earth is based on NASA’s static AP8/AE8 models which define the trapped proton and electron intensities. These models are based on a large number of satellite measurements carried out in the 1960s and 1970s. The AP8/AE8 models as well as a heavy ion galactic cosmic ray (GCR) model were used to define the radiation environments for protons, electrons and heavy ions at low Earth orbit (LEO), medium Earth orbit (MEO), and GEO. LEO and MEO dosimetric calculations are included in the analysis since any launch platform capable of delivering a payload to GEO will accumulate exposure during its transit through LEO and MEO. The computational approach (particle transport) taken was to use the static LEO, MEO, GEO, and geomagnetically attenuated GCR environments as input to the two deterministic particle transport codes called HZETRN and CEPTRN. This was done through exposure prediction within a spherical shell, a legacy Apollo era command service module configuration, and a large modular structure represented by a specific configuration of the International Space Station. Conclusions were drawn on the exposure levels accumulated by these geometries throughout a mission to GEO. Light ion and multiple nucleon removal cross sections due to electromagnetic dissociation were calculated. Light ion (H and He isotopes) and neutron production in galactic cosmic ray interactions are important for space radiation analyses. They occur via strong or electromagnetic dissociation (EMD) interactions. A parameterization for single nucleon, multiple nucleon and light ion production in EMD was developed which supersedes previous work in the following ways. The calculations were compared to a more extensive set of experimental data. EMD calculations for alpha particle production were in better agreement with experiment. Finally, a parameterization of multiple nucleon removal was developed and compared to data. Overall, the new work includes more reactions and compares better to experimental data than previous calculations. An extension of the radiation transport code HZETRN, for cosmic ray initiated electromagnetic cascades, was developed. Safe and efficient mission operations in space require an accurate understanding of the physical interactions of space radiation. As the primary space radiation interacts with intervening materials, the composition and spectrum of the radiation environment changes. The production of secondary particles can make a significant contribution to radiation exposure. HZETRN was extended to include the transport of electrons, positrons, and photons. The production of these particles is coupled to the initial cosmic ray radiation environment through the decay of neutral pions, which produce high energy photons, and through the decay of muons, which produce electrons and positrons. The photons, electrons, and positrons interact with materials producing more photons, electrons and positrons generating an electromagnetic cascade. Electron and positron production in Earth’s atmosphere was investigated and compared to experimental balloon-flight measurements. Reasonable agreement was seen between HZETRN and data.

Task Progress:	Validation of nuclear models used in space radiation shielding applications was undertaken. Validation metrics applicable to testing both model accuracy and consistency with experimental data were developed. The developed metrics treat experimental measurement uncertainty as an interval and are therefore applicable to cases in which epistemic uncertainty dominates the experimental data. To demonstrate the applicability of the metrics, nuclear physics models used by NASA for space radiation shielding applications were compared to an experimental database consisting of over 3600 experimental cross sections. A cumulative uncertainty metric was applied to the question of overall model accuracy, while a metric based on the median uncertainty was used to analyze the models from the perspective of model development by examining subsets of the model parameter space. Pion and electromagnetic contribution to dose and comparisons of HZETRN to Monte Carlo results and ISS data was studied. Recent work has indicated that pion production and the associated electromagnetic (EM) cascade may be an important contribution to the total astronaut exposure in space. Recent extensions to HZETRN allow the production and transport of pions, muons, electrons, positrons, and photons. The extended code was compared to the Monte Carlo codes, Geant4, PHITS, and FLUKA, in slab geometries exposed to galactic cosmic ray (GCR) boundary conditions. While improvements in the HZETRN transport formalism for the new particles are needed, it was shown that reasonable agreement on dose is found at larger shielding thicknesses commonly found on the International Space Station (ISS). The extended code was compared to ISS data on a minute-by-minute basis over a seven day period in 2001. The impact of pion/EM production on exposure estimates and validation results wa clearly shown. The Badhwar–O'Neill (BO) 2004 and 2010 models were used to generate the GCR boundary condition at each time-step allowing the impact of environmental model improvements on validation results to be quantified as well. It was found that the updated BO2010 model noticeably reduces overall exposure estimates from the BO2004 model, and the additional production mechanisms in HZETRN provide some compensation. It was shown that the overestimates provided by the BO2004 GCR model in previous validation studies led to deflated uncertainty estimates for environmental, physics, and transport models, and allowed an important physical interaction (pion/EM) to be overlooked in model development. Despite the additional pion/EM production mechanisms in HZETRN, a systematic under-prediction of total dose was observed in comparison to Monte Carlo results and measured data. Reduced discretization error was achieved with HZETRN. In a previous work, numerical methods in the code were reviewed, and new methods were developed that further improved efficiency and reduced overall discretization error. It was also shown that the remaining discretization error could be attributed to low energy light ions ($A < 4$) with residual ranges smaller than the physical step-size taken by the code. Accurately resolving the spectrum of low energy light particles is important in assessing risk associated with astronaut radiation exposure. Modifications to the light particle transport formalism were presented that accurately resolve the spectrum of low energy light ion target fragments. The modified formalism was shown to significantly reduce overall discretization error and allowed a physical approximation to be removed. For typical step-sizes and energy grids used in HZETRN, discretization errors for the revised light particle transport algorithms are shown to be less than 4% for aluminum and water shielding thicknesses as large as 100 g/cm2 exposed to both solar particle event and galactic cosmic ray environments. Heavy ion contributions to organ dose equivalent for the 1977 galactic cosmic ray spectrum was investigated. Estimates of organ dose equivalents for the skin, eye lens, blood forming organs, central nervous system, and heart of female astronauts from exposures to the 1977 solar minimum galactic cosmic radiation spectrum for various shielding geometries involving simple spheres and locations within the Space Transportation System (space shuttle) and the International Space Station (ISS) were made using the HZETRN 2010 space radiation transport code. The dose equivalent contributions were broken down by charge groups in order to better understand the sources of the exposures to these organs. For thin shields, contributions from ions heavier than alpha particles comprise at least half of the organ dose equivalent. For thick shields, such as the ISS locations, heavy ions contribute less than 30% and in some cases less than 10% of the organ dose equivalent. Secondary neutron production contributions in thick shields also tend to be as large, or larger, than the heavy ion contributions to the organ dose equivalents. Pion cross section parameterizations were developed for use in space radiation codes. The space radiation environment consists of energetic particles that originate from the Sun and from sources outside the solar system. It is necessary to understand how these particles interact with materials to design effective radiation shielding. The transport of radiation through materials can be described by the Boltzmann equation. Efficient space radiation transport codes often require parameterized energy-dependent spectral distributions. A recent study showed that pions may contribute considerably to the total dose in galactic cosmic ray environments. Consequently, accurate parameterized pion spectral distributions are needed. In other studies, the Badhwar parameterization has been used for inclusive pion production in high energy nucleon-nucleon and nucleon-nucleus collisions, whereas a thermal model has been used to describe pion production in low energy nuclear collisions. The thermal model was parameterized in terms of projectile energy, projectile nucleon number, and target nucleon number. Thermal and Badhwar model predictions of pion spectra from nucleon-nucleus and nucleus-nucleus collisions were compared for projectile energies ranging from 0.3 to 158 A GeV. It is recommended that the thermal model be used for projectile energies between 0.4 and 5 A GeV and the Badhwar model be used for higher projectile energies. This report was compiled from abstracts of papers listed in the bibliography.
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