Fiscal Year:	FY 2011	**Task Last Updated:**	FY 07/15/2011
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:**	3
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, 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)? with improved models and transport to improve estimates/reduce uncertainty of light ion and neutron production and transport through spacecraft materials and secondary environments on the lunar and Mars surface.
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.
	One of the most important products that the NASA Langley Space Radiation Group delivers are space radiation transport codes capable of predicting the radiation environment in a spacecraft or habitat, given the external environment. The NASA Langley Space Radiation Group develops the transport code HZETRN, which is the NASA standard code for space radiation. The HZETRN acronym stands for High charge (Z) and Energy TRaNsport. The Physics and Transport activities have been divided up into Phase 1 and Phase 2, with the dividing point being the year 2007. The present report will mainly describe Phase 2 activities. The focus of Phase 1 activities was on further development of the 1-dimensional version of HZETRN together with emphasis on heavy ion transport. The focus of Phase 2 activities is concerned with 3-dimensional transport. This involves the development of 3-dimensional transport models and the associated 3-dimensional nuclear reaction cross sections required as input. It also shifts the focus concerning the particles being transported. Heavy nuclear fragments tend to travel with the same speed and direction as the initial high energy nuclear beam, and therefore are well described with 1-dimensional methods. However, neutrons, light ions and mesons suffer significant deflections from straight line motion and require 3-dimensional methods. Therefore, the 3-dimensional focus of Phase 2 Physics and Transport automatically includes special consideration of neutrons, light ions and mesons. The last major update of HZETRN was with the release of the 2005 version. A new version was released at the end of the year 2010. The 2010 version contains improved transport methods and a new nuclear model, both of which are described below. The NUClear FRaGmentation (NUCFRG) model used in HZETRN calculates total cross sections for the production of nuclear fragments in high energy nucleus - nucleus collisions. The current third version of the code (NUCFRG3) now includes the following a new coalescence model for the formation of light ions and a new Coulomb dissociation model for the formation of light ions. HZETRN2010 is the most recent update to a series of space radiation transport codes developed at NASA Langley Research Center (LaRC). Since the last official release in 2005 (HZETRN2005), several modifications, improvements, and corrections have been made to the numerical methods, transport methodologies, and nuclear physics models. A large portion of the source code has been updated from Fortran 77 to Fortran 90 to allow dynamic memory allocation and increased user flexibility, and code documentation has been greatly improved. The following sections summarize these efforts and summarize the capabilities of HZETRN2010. The deterministic codes developed at NASA LaRC, referred to generally as HZETRN, are all based on the straight-ahead approximation where all particles and reaction products are assumed to propagate along a common axis. Numerical marching algorithms are derived by inverting the one-dimensional Boltzmann transport equation, and employing perturbative methods to allow rapid evaluation of the resulting integrals. As with any differential equation solver, continuous variables must be discretized to allow numerical evaluation. Convergence tests are often used to quantify the error associated with this discretization. A comprehensive convergence test for HZETRN has been completed. In that work, the need for double precision calculations was clearly identified along with a new convergence criterion related to low energy charged target fragments that had never been addressed in the literature. New numerical methods were also developed and shown to be

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nearly 10 - 100 times faster than their predecessors. Detailed convergence tests were then used to show that the new methods are also more accurate, and total discretization errors were quantified for several scenarios in which HZETRN is commonly used. The new methods have been implemented in HZETRN2010. Along with improved numerical methods, a low energy transport model was also developed for neutrons and light ions ($Z < 3$). The low energy model is an improvement on the straight-ahead approximation and allows the separation of neutron flux into forward and backward components. The elastic interactions that dominate low energy neutron transport are fully accounted for through a Neumann series solution allowing the multiple reflections (from forward to backward, and vice versa) to be included. The neutron transport model is also fully coupled into the HZETRN solution through a source term representing the production of low energy light target fragments from the low energy neutrons. The low energy model has been compared to various Monte Carlo codes and it was shown that HZETRN agrees with the Monte Carlo codes to the extent that they agree with each other. The low energy transport model has been implemented in HZETRN2010. The heavy ion ($Z > 2$) nuclear fragmentation model used in HZETRN was recently updated. In particular, a coalescence model for light ion formation and light ion production via electromagnetic dissociation has been included. The updated fragmentation model, NUCFRG3, has been implemented in HZETRN2010. Along with the improvements in the numerical methods, transport models, and nuclear physics models, the overall code architecture of HZETRN2010 has also been improved. The new code has been updated from Fortran 77 to Fortran 90 as much as possible, allowing a more efficient use of CPU power and memory. Dynamically allocated arrays have also been introduced to allow more user flexibility. There is no limit on the atomic complexity of the target (previous limit was 10 atomic elements). In multi-layer mode, there is no limit on the number of spatial grid points or total transport depth (previous limit was 20 points in each layer with maximum thickness of 100 g/cm^2). The multi-layer transport mode can be used with user-defined materials (previous materials were fixed to aluminum, polyethylene, and water). Users can select from a database of pre-defined environments, including free space SPE, free-space GCR, trapped protons in Low Earth Orbit (LEO), and GCR in LEO (previous code could do free-space SPE and free space GCR). User-defined environments can also be added through a database file, as discussed in the HZETRN2010 User Guide. Users can also select from a variety of response functions, including dose, dose equivalent using ICRP 60 quality factors, differential and integral LET spectra, and differential and integral flux spectra. HZETRN2010 also contains a new slab-geometry mode where users can specify a slab with no limit on the number of layers, layer thickness, or material complexity. The low energy transport model discussed previously is utilized in this mode. In general, the HZETRN2010 architecture is very simple - three source codes and a database of static data files. The first source code generates the nuclear and atomic cross sections for a user-defined material. The second source code transports a space radiation environment through a multilayer configuration or a slab geometry. The third source code computes the various dosimetric quantities discussed above. The 2010 version of HZETRN will be upgraded again in 2015. The new nuclear physics models, transport methods and validation methods being developed for the 2015 version will now be described.

Work is also continuing on pion transport and the associated electromagnetic cascade. One of the most interesting developments in space radiation recently has been the discovery that pions can contribute a substantial fraction of the radiation dose. One therefore needs to also take account of the associated electromagnetic cascade and transport methods have been developed that are capable of dealing with this. Work is also continuing on developing a nuclear database. With the Phase 1 activity in Physics & Transport described previously, there was both a theoretical and experimental program, with both focusing on heavy ion production. As previously mentioned, the focus of Phase 2 is on neutrons and light ions. An extensive survey of all nuclear physics experiments that are relevant to space radiation has recently been completed. This shows the gaps in measurements and this will be used to recommend future experiments.

The web site at http://spaceradiation.larc.nasa.gov/ has a list of all publications contained in this task throughout its history.

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