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International Space Station Radiation Shielding Model Development

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ABSTRACT

The projected radiation levels within the International Space Station (ISS) have been criticized by the Aerospace Safety Advisory Panel in their report to the NASA Administrator. Methods for optimal reconfiguration and augmentation of the ISS shielding are now being developed. The initial steps are to develop reconfigurable and realistic radiation shield models of the ISS modules, develop computational procedures for the highly anisotropic radiation environment, and implement parametric and organizational optimization procedures. The targets of the redesign process are the crew quarters where the astronauts sleep and determining the effects of ISS shadow shielding of an astronaut in a spacesuit. The ISS model as developed will be reconfigurable to follow the ISS. Swapping internal equipment rack assemblies via location mapping tables will be one option for shield optimization. Lightweight shield augmentation materials will be optimally fit to crew quarter areas using parametric optimization procedures to minimize the augmentation shield mass. The optimization process is being integrated into the Intelligence Synthesis Environment's (ISE's) immersive simulation facility at the Langley Research Center and will rely on High Performance Computing and Communication (HPCC) for rapid evaluation of shield parameter gradients.

INTRODUCTION

The Space Station Freedom was originally designed for a 28.5^{o} inclination low Earth orbit (LEO) for which the ionizing radiation environment is composed primarily of protons trapped in the geomagnetic field and the recommended exposure limits are based on older cancer risk data [1]. In the early 1990's, the Space Station concept became an international venture and moved to a highly inclined 51.6^{o} orbit where half the exposure is from the highly penetrating galactic cosmic rays. This orbit is more susceptible to exposure from a large solar particle event (SPE). During the large number of planned EVA's, the astronauts will be subjected to large-scale fluctuations of the outer zone electron environment during geomagnetic storm activity as recently emphasized [2]. Meanwhile, cancer risk associated with radiation exposures are found to be higher than previously expected [3, 4], resulting in lower allowable exposure limits in future space activity [5]. Even before the lower exposure limits were recommended, the Aerospace Safety Advisory Panel (ASAP) had criticized ISS exposures as being too high [6]. Aside from concerns over crew rotation and decommissioning, the federal regulatory requirement of keeping radiation exposures as low as reasonably achievable (ALARA) was not implemented in the ISS design [7]. In addition, the prior estimates of ISS exposures used an early version of the Langley Research Center HZETRN code which had over simplified neutron transport procedures and neglected target fragmentation contributions to the exposure [7]. Furthermore, prior calculations used a simplified astro-naut geometry as a uniform tissue sphere [7] in which the relation to more realistic geometries [10-12] were left unspecified. A second criticism of the ASAP [6] concerns the shielding provided by the Shuttle spacesuit used in ISS construction. A second effort to evaluate and improve the Shuttle spacesuit is underway [8,9] and the effects of the ISS shadow on spacesuit exposures will be addressed herein.

In the present paper we describe the analysis software, models and methods being used to meet the evolving requirements for optimizing astronaut exposures aboard ISS and evaluating the protection factors for astronauts working in spacesuits during ISS construction and maintenance. To accomplish this, the software and models must meet a number of requirements.

First, the models must accommodate the steady and long-lasting construction and reconfiguration of the structure and modules of the ISS. Processes are in place and being refined to track these changes accurately and easily using current Computer Aided Design (CAD) techniques. Additionally, the internal population and arrangement of equipment racks and crew quarters in the ISS modules and nodes will be varying almost continuously during its operation. To capture this, custom software has been developed to read mapping tables that denote the locations and types of racks in each module or node and insert them into the radiation shielding models. This process is separate from the interactive CAD process used for the modules themselves so that it may be automated to enable optimization of rack placement based upon calculated radiation levels within specific ISS areas (e.g., the crew quarters). Parametric geometry methods will be introduced into the ISS shielding geometry model that will allow the use of gradient-based optimization techniques to optimize the shield augmentation. Parametric augmentation shielding methods will be used to optimize the crew quarter exposures which can serve not only as a shelter from SPE but implementation of ALARA requirements.

TRANSPORT COMPUTATIONAL METHODS

The computational procedures for charged ions and neutrons are carried out by the HZETRN code, which includes improved neutron transport characteristics [13]. The code divides the interactions into a forward component and a diffuse component. The forward component is solved using the straightahead approximation that represents this component very accurately for high-energy ions and neutrons [14] and treats the isotropic angular dependence of the lower energy neutrons in a multigroup approximation [13]. The transmitted fluence is approximated accurately as long as the beam divergence is small compared to the radius of curvature of the shielding object [13]. The low energy neutron fluence depends strongly on the location of the distal boundary and the intervening material properties and must be adequately approximated in the transport procedures. The electron and bremsstrahlung transport is treated by a new code based on phenomenological models combined with basic physical databases and compares well with Monte Carlo code [9].

In order to optimize an augmenting shield composed of high-efficiency materials, high-speed computational procedures for the evaluation of the gradient of geometry parameters of the shield augmentation are needed. To accomplish this, a transport code for a massively parallel machine allowing multiparameter gradient methods to optimize the shield configuration is being developed. Since the augmentation is to be a retrofit, requiring post launch operations to augment existing ISS modules, the control of augmentation cost is an essential factor to lower the impact on ISS development and operations.

ISS SHIELDING GEOMETRY MODELS

The final ISS 16A configuration is a geometrically complex structure as can be seen in figure 1. It will be several more years before ISS could reach this configuration and it will require many additional launches and thousands of hours of on-orbit construction activity.

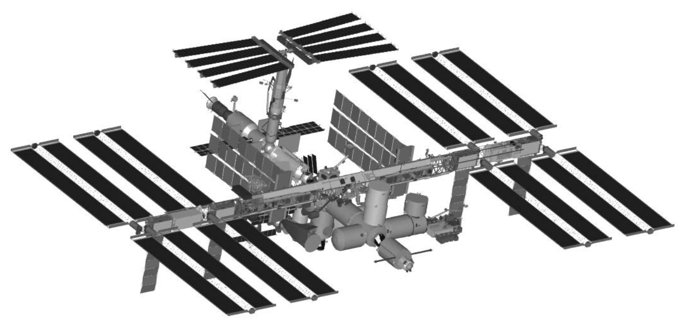

Fig. 1. ISS 16A configuration.

Fig. 2. Current ISS 5A configuration (NASA Photo).

The current orbiting ISS 5A configuration is shown in figure 2. As the ISS grows in size and complexity, one needs a reconfigurable ISS model built up from models of the basic modules and structure.

The interior equipment and storage racks have been standardized to reduce costs and the different rack types are characteristic of the rack contents. A typical equipment rack shielding model is shown in figure 3. For the ISS shielding model, the racks are placed into the ISS modules according to a rack location map specifying rack type and location. Rearrangement of the module interior can be accomplished by the re-specification of the location map. The shield model of the HAB module which contains the crew quarters in the 16A configuration is relatively complete and shown in figure 4. Not shown are interior fixtures and the "bump outs" giving added private living space extended into the hallway. Also shown in the figure is an unfinished crew quarter with a 3D directional dependent dose sphere (color-coded by dose per unit solid angle) and a generic astronaut model for use in crew shielding shadow effects.

Fig. 3. ISS equipment rack shield model.

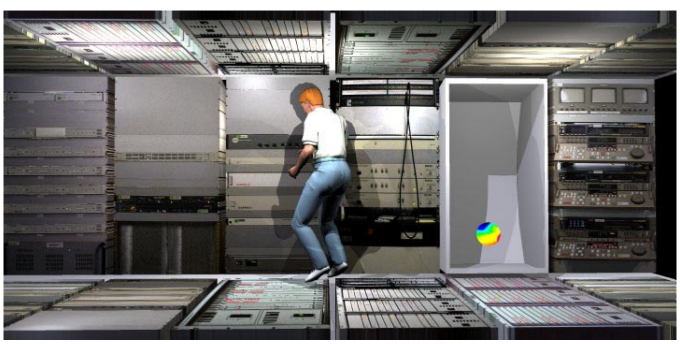

Fig. 4. Interior of the HAB module shield model with racks inserted.

The materials within the models (modules and racks) are identified by material type index and identified in a mapping table in relation to material type and shielding properties for use in the shielding analysis. The astronaut geometry for dose assessment is represented by the Computerized Anatomical Male (CAM) and Female (CAF) and currently represented by a uniform soft tissue composition [10-12] except for adjacent members shadow effects which use the generic astronaut model shown in figure 4.

SHUTTLE SPACESUIT SHIELDING MODEL

The Shuttle spacesuit model is undergoing develop-ment and the current status is described in detail elsewhere [8,9]. A "glass" visual presentation showing internal parts as now represented is given in figure 5. The suit materials are identified by a material index and mapping table to material type. The material list is given in reference [9] by Anderson et al.

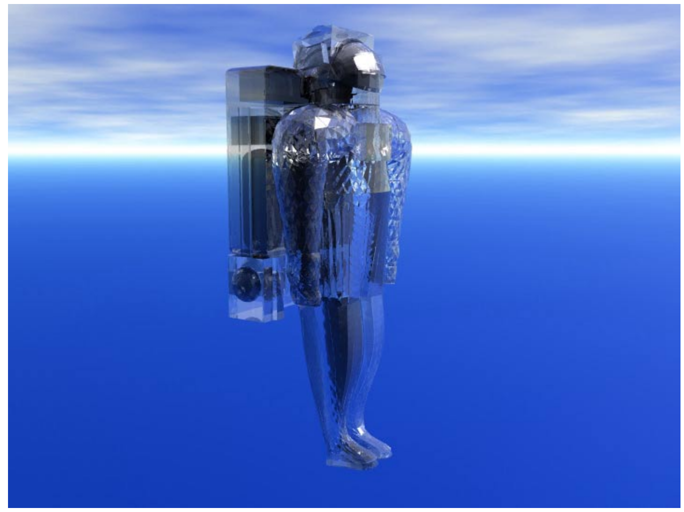

Fig. 5. Shuttle spacesuit model in "glass" presentation showing internal parts.

SHIELD ANALYSIS PROCEDURES

The development of shield analysis procedures has been a Langley Research Center (LaRC) activity for many years. Current methods allow for the calculation of shielding provided by objects created within a CAD system. Results of these analyses are visualized by plotting the shielding distribution as data values mapped to colors on the surface of a sphere (figure 6) and by overlaying the calculated material thicknesses on top of the 3-dimensional CAD model used for the shielding calculation (figure 8).

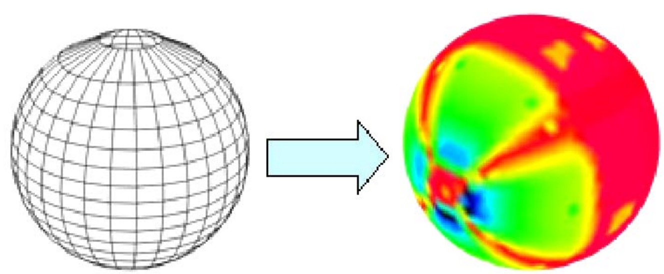

Fig. 6. The directional distribution of the exposure field in all directions, plotted on a sphere.

In this section we will describe some of the different methods currently in use or in development and describe how they will be applied to produce an optimum strategy for enhancing ISS shielding. Later, we will describe how these and other techniques [15, 16] are being integrated within a CAVE virtual reality system to facilitate more rapid and innovative solutions in an immersive and collaborative environment.

RAY TRACING SOFTWARE – The ray tracing software used at LaRC takes a user-specified target point and a user-specified distribution of rays emanating from that target point and calculates the locations of any intersections of the rays and the shield geometry. Ray-geometry intersection points are characterized by their location, whether the ray was going into or out of the object at the point of intersection, and the material type associated with that object. The intersections calculated along each ray are sorted so that material thicknesses may be calculated for objects in the order in which they are encountered by incoming radiation and associated with the appropriate materials.

The software used is called RadICal, and is described elsewhere [15]. It operates on a geometry model in the Alias/WaveFront "obj" file format. This file format was chosen because it is a relatively simple process to translate models to this format from virtually any 3-D CAD package. The output file for RadICal contains the sequence and thickness of the materials that are encountered by radiation as it approaches the target point. This file is used in conjunction with radiation transport calculations through various thicknesses of ordered materials.

RACK SWAPPING PROCEDURES – The first level of optimization in the ISS model will be to allow the interchange of racks and evaluation of effects on the radiation field at specific sites (for example, within the crew quarter). As described previously, the rack types and locations within each module and node will be specified by location mapping files. This approach has been developed to allow automatic reconfiguration and reevaluation of the ISS interior without the use of interactive CAD software. One of the primary advantages of this is that the mapping file may be created directly by a gradient-based optimization process. This will allow the internal rack arrangement to be optimized to reduce the amount of radiation in the crew cabins while meeting other constraints on power, rack-to-rack proximity, and crew cabin noise.

SHIELD AUGMENTATION OPTIMIZATION – A second level of optimization will involve the addition of a light weight shield material to the first level optimized design using the optimum rack location table found as a result of the rack swapping process. An augmentation insert will be added to the design surrounding locations that require additional shielding. Gradients of geometric factors will be evaluated to determine the best geometry modifications that will improve the design. Visualization methods will be most important in identifying design weakness for the application of this procedure.

IMMERSIVE SIMULATION & DESIGN – Currently, the ISS shielding model, Shuttle space suit shielding model, ray tracing software, rack swapping procedures, and shield augmentation optimization are being merged into a single immersive and collaborative virtual reality application at LaRC. This simulation will allow a design engineer to enter a simulation of the ISS and interactively place target points and evaluate the directional shielding distribution and directional doses for a particular ISS configuration and external radiation environment (see figure 7). In addition to calculating radiation doses in real-time, the user will be able to change the type and location of racks within the modules and immediately evaluate the impact of the changes. Parameterized augmentation shields will also be represented in this virtual environment and will allow modification by the designer. Other data such as acoustic simulation data may also be represented within this environment and may be used by the designer to trade advantages of various rack arrangements from the perspectives of both crew safety and crew comfort.

Fig. 7. Dose sphere in immersive environment indicating dose intensity in each direction.

ISS SHADOW AND EVA EXPOSURES

Further value will be gained from the combination of these separate elements in that they will enable detailed characterization of the radiation environment immediately surrounding the ISS. Due to the large amount of EVA activity required for ISS development and maintenance, the characterization of this shadow will be critical for the management of crewmember exposure. The LEO environment is highly directional and the exposure of the astronaut will depend heavily on location relative to the direction of the radiation field. Even at the present stage of construction, the ISS itself is expected to play and important role in EVA exposures as can be judged by figure 8.

Fig. 8. Astronaut on EVA at ISS 5A. (NASA Photo)

The shielding about an astronaut near the ISS 16A configuration is shown in figure 9. Shown in the figure is the wire frame display of the shielding models (in green) and the ray-object intersections (in red). This distribution was calculated for the ISS16 A configuration combined with a suited astronaut near the airlock. The importance of the ISS shield distribution on spacesuit exposure is clearly demonstrated.

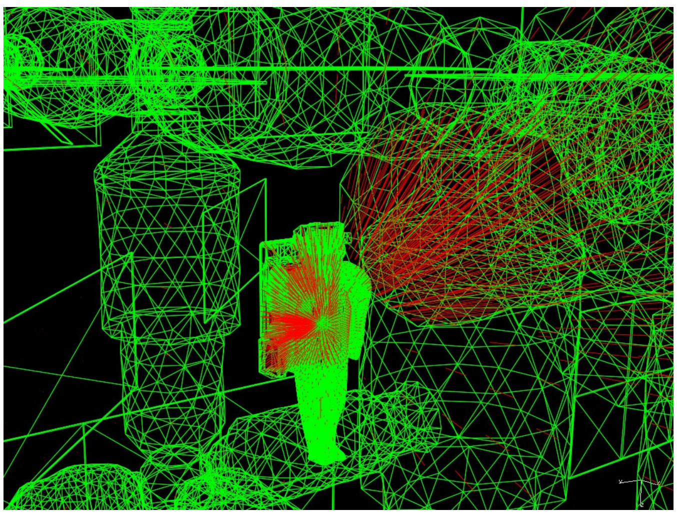

Fig. 9. Shielding distribution about a suited astronaut near the ISS 16A.

In addition to the shielding from the local space environmental components, the ISS will be an added source of neutrons produced by the impact of the local charged particle environment with the ISS structure. The present computational procedures are perfectly capable to evaluate this added particle component. It is anticipated that the shadow effect will not be overcompensated by the added neutron component.

CONCLUSION

The state of the art in radiation evaluation is being revolutionized by high-speed computational procedures and advanced visualization methods. Evaluation of shadow effects and the optimization of shield configurations will have an important impact on ISS construction and operations. Perhaps more importantly, shield design is becoming a more intuitive engineering task since powerful methods of radiation field evaluation are available to the nonspecialist who will more and more be given point-and-click tools for radiation effects evaluation and shielding design and optimization. This will allow a systems approach to design in which radiation effects and shielding is only one issue among many to be solved in parallel allowing optimization at the system level. This is a radical departure from prior design experience.

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