Space Radiation Analysis for the Mark III Spacesuit

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The NASA has continued the development of space systems by applying and integrating improved technologies that include safety issues, lightweight materials, and electronics. One such area is extravehicular (EVA) spacesuit development with the most recent Mark III spacesuit. In this paper the Mark III spacesuit is discussed in detail that includes the various components that comprise the spacesuit, materials and their chemical composition that make up the spacesuit, and a discussion of the 3-D CAD model of the Mark III spacesuit. In addition, the male (CAM) and female (CAF) computerized anatomical models are also discussed in detail. We "combined" the spacesuit and the human models, that is, we developed a method of incorporating the human models in the Mark III spacesuit and performed a ray-tracing technique to determine the space radiation shielding distributions for all of the critical body organs. These body organ shielding distributions include the BFO (Blood-Forming Organs), skin, eye, lungs, stomach, and colon, to name a few, for both the male and female. Using models of the trapped (Van Allen) proton and electron environments, radiation exposures were computed for a typical low earth orbit (LEO) EVA mission scenario including the geostationary (GEO) high electron environment. A radiation exposure assessment of these mission scenarios is made to determine whether or not the crew radiation exposure limits are satisfied, and if not, the additional shielding material that would be required to satisfy the crew limits.

Nomenclature

BFO	=	Blood-Forming Organ
CAD	=	Computer-Aided Design
CAF	=	Computerized Anatomical Female model
CAM	=	Computerized Anatomical Male model
mSv	=	milliSievert = 1/1000 Sievert = measure of biological response to absorbed dose
EVA	=	ExtraVehicular Activity
GEO	=	Geostationary Earth Orbit
GCR	=	Galactic Cosmic Radiation
GLE	=	Ground Level Event (Enhancement); an extremely large solar proton event (SPE)
HDPE	=	high density polyethylene (ρ = 0.95 g/cm^2)
ISS	=	International Space Station
LEO	=	Low Earth Orbit
MeV	=	million electron volts; a unit of particle energy
PLSS	=	Portable Life Support System; "backpack"
SPE	=	Solar Proton (Particle) Event

I. Introduction

THE amount of space radiation exposure to crewmembers is of utmost important when planning a mission. The crews are fairly well protected in most spacecraft due to its inherent bulk mass shielding. The primary concern of space radiation exposure is from high energy trapped (Van Allen) protons, solar proton events (SPEs), and extremely high energy galactic cosmic radiation (GCR) that can penetrate the spacecraft. Secondary neutrons are

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produced during nuclear reactions as the primary penetrating particles pass through the spacecraft. In addition, high energy electrons, namely those trapped (Van Allen) in the earth's magnetic field, are easily stopped with ~1.5-2.0 g/cm^2 aluminum. Typical ExtraVehicular Activity (EVA) spacesuits are very thinly shielded and do not provide adequate radiation protection to the EVA crewmembers during enhanced radiation conditions. EVAs are limited to approximately 8 hrs or less due to the spacesuit consumable constraints.

In this paper we discuss the Mark III spacesuit and its components, the 3-D CAD spacesuit model, the male and female anatomical models, the LEO and GEO space radiation environments, and radiation exposures associated with specific mission scenarios. We conclude with recommendations for Mark-III spacesuit EVA operations.

II. The Mark III Spacesuit

The Mark III rear entry hatch space suit is a technology demonstrator. It was originally designed as a zero-pre-breath suit, but over time, the suit evolved to include several different configurations. The suit weighs approximately 120 lbs and has an operating pressure range up to 8.3 psid. The hard upper torso (HUT) may be constructed of cast aluminum, heavy composite material, or lightweight composite[1].

Figure 1 shows a CAD rendering of the Mark III space suit along with a representative cross-section showing a typical material layup for a space suit like the Mark III[2].

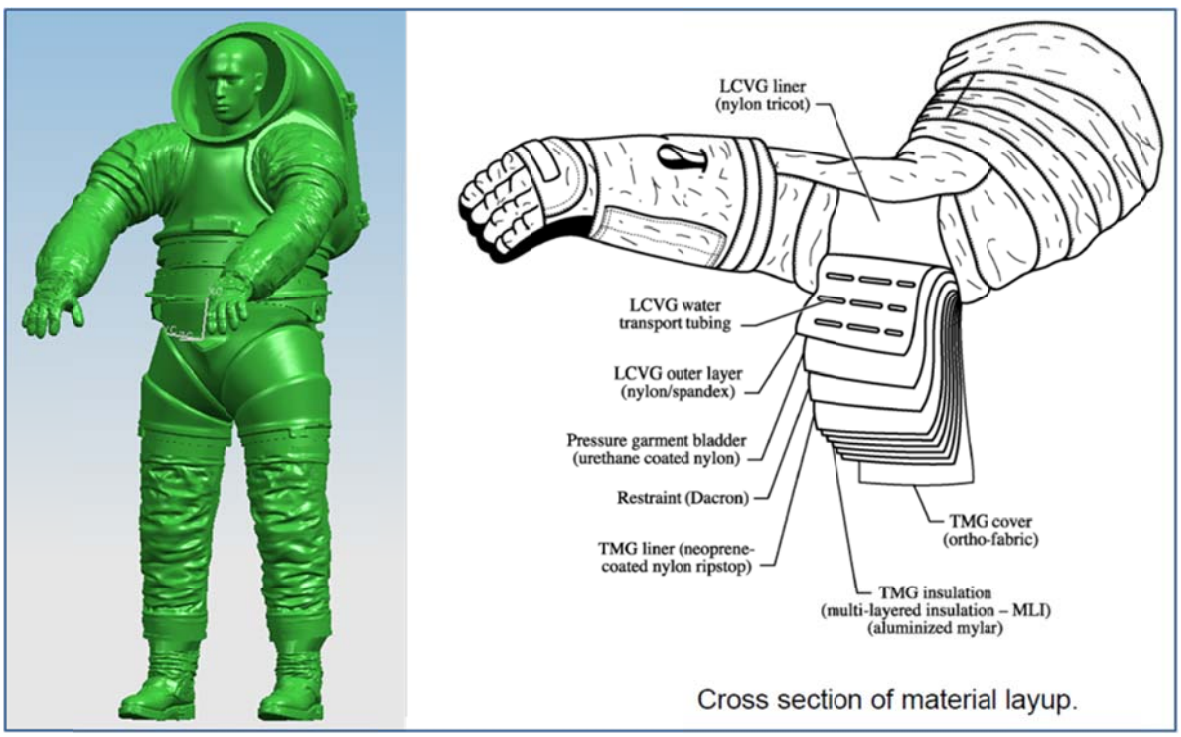

Figure 1. Mark III spacesuit CAD rendering and typical spacesuit material layup cross section.

III. 3-D CAD Model Discussion

The Mark III space suit CAD model was developed by laser scanning the outside surfaces of the pressurized suit to determine the outer envelope. The inside of the suit was modeled by scanning the outside of the internal pressure restraint layer only while it was at very low pressure. The two envelopes were combined analytically to produce the Mark III space suit CAD model. Figure 2 shows the assembled CAD model used for the raytracing shielding analysis, along with the individual components and materials that were assigned to each component.

The suit arms and legs consist of several layers of fabric material, including Nylon, Dacron, and MLI (Multi-Layer Insulation) with a total fabric thickness of ~0.244 cm (~0.096") [see Figure 1 for details][2]. As a result of the way the suit CAD model was constructed, the arm and leg components are represented by a single fabric layer, which is roughly 0.508 cm (0.2') thick or twice as thick as the actual fabric layer. To counter this material thickness

error in the model, the arms and legs were modeled as a single layer of Nylon with a reduced density of 0.57 g/cm^3 (Nylon ρ = 1.14 g/cm^3).

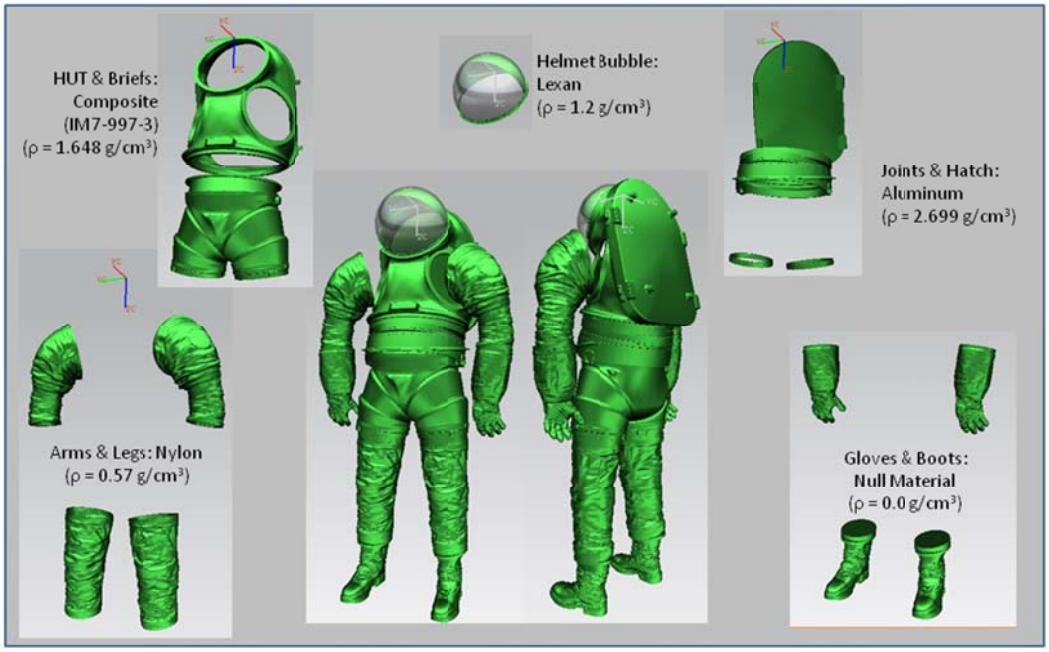

Figure 2. Mark III spacesuit CAD model components and assigned material types and properties.

A carbon composite material (IM7-977-3) was chosen for the Hard Upper Torso (HUT) and briefs because no information was available concerning whether the original suit modeled had been composite or aluminum. The composite material, IM7-977-3, was selected as the least conservative (lowest) for shielding mass. The original CAD model as shown in Figure 1 has the arms held out in front of the torso. In order to ensure that the suit arms line up with the arms for the astronaut anatomical models, they were moved so that they hung by the torso similar to the anatomical model arms. This resulted in some gaps in the suit model at the shoulders (refer to Figure 2), which were handled during post processing of the radiation shielding model ray tracing results by simulating the gaps as Nylon fabric material with a thickness of 0.244 cm (0.096”). After the ray tracing model had been constructed, it was discovered that the glove and boot components were completely solid, so they were removed from the raytracing analysis by modeling them as a null material with zero density. No suitable CAD model was available for the primary life support subsystem (PLSS) “backpack” for this study, so a simple aluminum backpack model of uniform density (ρ = 0.989 g/cm^3) was added to the space suit model to represent the PLSS mass. Figure 3 shows the final assembled Mark III radiation shielding model used for this analysis.

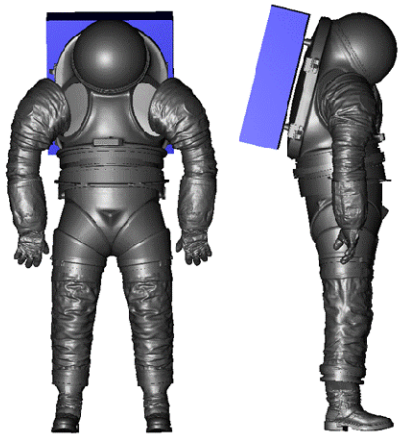

Figure 3. Mark III spacesuit radiation shielding ray tracing model.

IV. The CAM & CAF Anatomical Models

The Computerized Anatomical Male (CAM)[3] and Computerized Anatomical Female (CAF)[4] models are human models that we have been using for a number of years to determine the shielding distribution at a specific point in the human or within the critical body organs. Using a ray-tracing technique, the shielding distribution is generated over 4π steradian solid angle. We have found that approximately 1000 rays (or thicknesses) are quite adequate to quantify the amount of shielding distributed about the dose point of interest. Each ray is an equal solid angle, and the CAMERA[3] driver program keeps track of the materials (skin, bone, tissue, and organ) each ray intercepts. The shielding distribution is then an output data set (list of material thicknesses converted to aluminum equivalent) that is ordered from the thinnest to the thickest values.

A. The CAM Model

Based on the initial work of Kase[5] (1970) and corrected work of Billings & Yucker[3] (1973), they produced a computerized anatomical model of a standard 50th percentile USAF male that stands 69.1”(175.5 cm) and weighs 153.2 lbs. (69.45 kg). The CAM model is a high-fidelity human male model containing all of the critical body organs including the testes.

The model uses QUAD[6] geometry to produce a mathematical model having 2450 regions and 1095 surfaces and uses a right hand coordinate system with the origin located at the top of the head with the

- z-axis pointing toward the feet
- x-axis pointing out the chest
- y-axis out the right side

There are nine (9) primary human body materials and corresponding material densities:

- lung
- organ
- intestine
- muscle
- bone
- marrow
- skeleton
- tissue
- water

The computer program, CAMERA[3], was developed to provide shielding distributions for any (x, y, z) coordinate point in or on the CAM model using a ray-tracing technique, 500 to 1000 rays are used to generate a shielding distribution (in g/cm^2 aluminum equivalent thicknesses). CAMERA can also be utilized to produce cross-sectional computer plots as shown in Figure 4 below. Figure 5 shows three views of the anatomical male human and the internal organs.

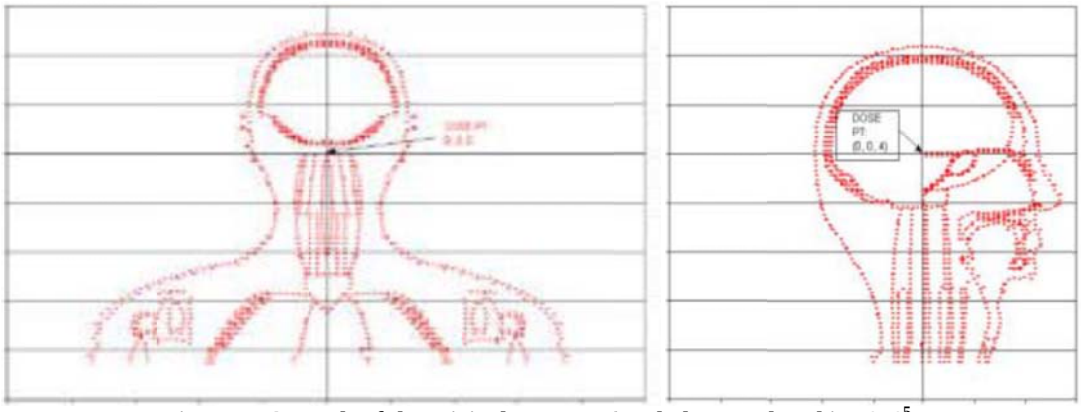

Figure 4. A couple of the original cross-sectional plots produced in 1976[5].

Figure 5. The CAM 3-D anatomical model.

A. The CAF Model

The CAF[4] model represents a 50th-percentile US Air Force female. When the CAF model was developed the CAM model was used as a basis and the male model was scaled by 92%; the testes were replaced with the breasts, uterus, and ovaries. Both the CAM and CAF models can be further scaled, since the models were constructed into four major sections.

B. Critical Body Organ Shielding Distributions

Atwell[7,8] have utilized the CAM and CAF models in various spacecraft and spacesuits by generating shielding distributions for a number of body organs. As stated above, a shielding distribution is generated for a given (x,y,z)-point by a ray-tracing method having equal solid angles over 4π solid angle. Usually, approximately 1000 solid angles adequately describe the shielding distribution where each solid angle represents a thickness of the various body materials intercepted by each ray. Our methodology uses 968 rays or thicknesses to represent an (x,y,z) shielding distribution. Figure 6 shows several CAM body organ shielding distributions.

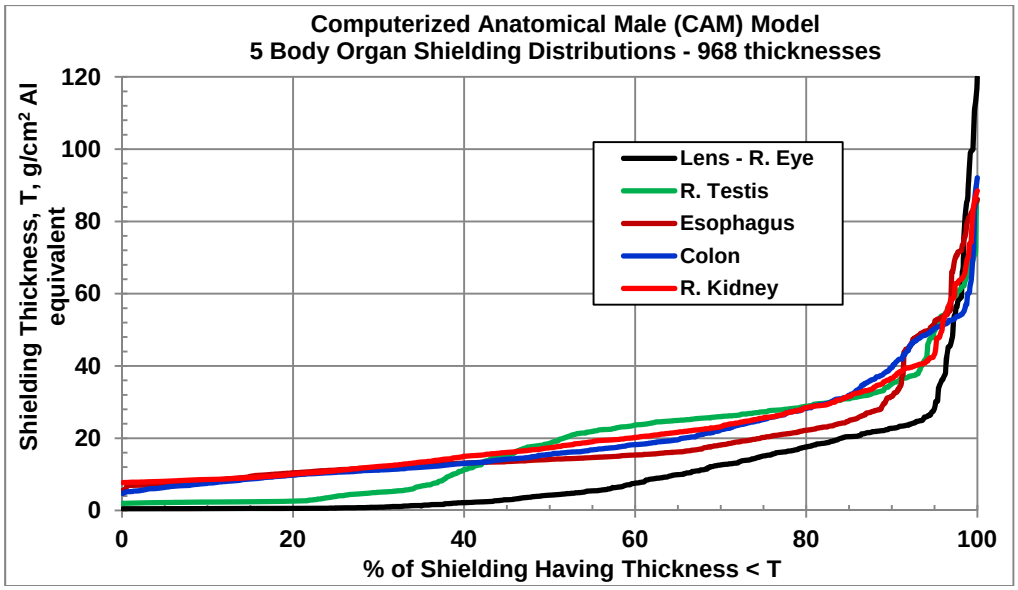

Figure 6. CAM body organ shielding distributions (968 thicknesses) for 5 specific male organs.

C. Combined Mark III Spacesuit and Organ Shielding Distributions

We "mathematically" placed the CAM and CAF models inside the Mark III 3-D CAD spacesuit model and generated shielding distributions for several locations in (BFO – Blood-Forming Organ) and on (skin) the male and female. Figures 7 and 8 are CAM shielding distributions for several skin and BFO locations, respectively.

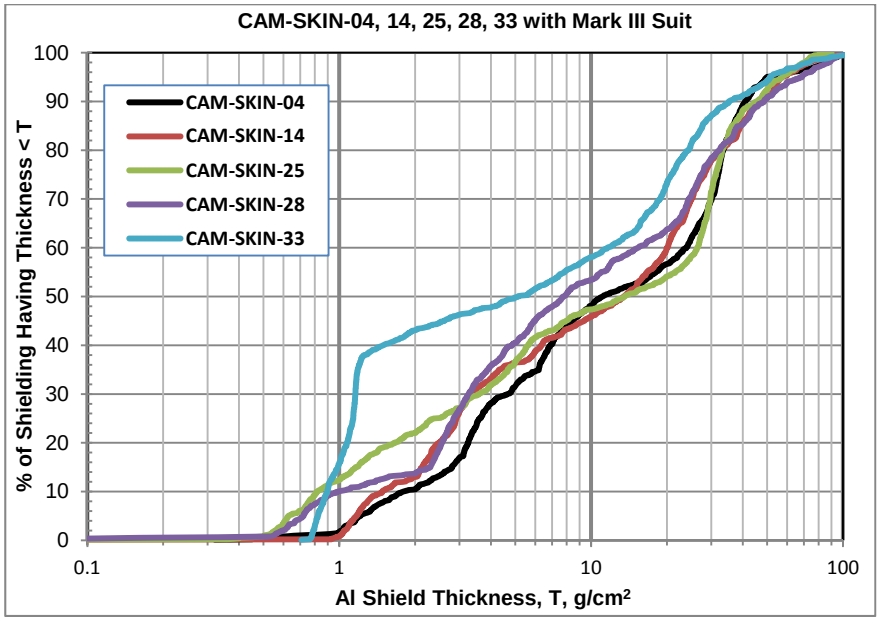

Figure 7. CAM shielding distributions for several skin points.

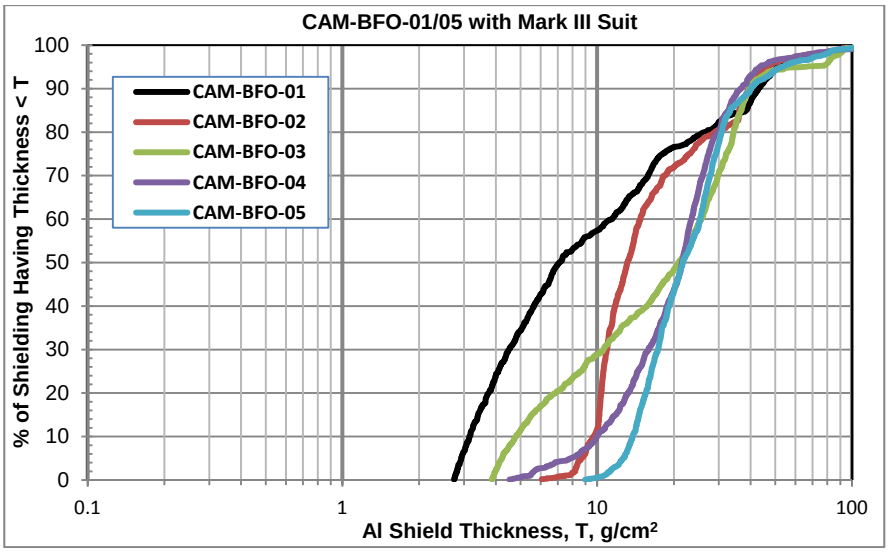

Figure 8. CAM shielding distributions for several BFO points.

Figures 9 and 10 show the CAF shielding distributions for several skin and BFO locations, respectively.

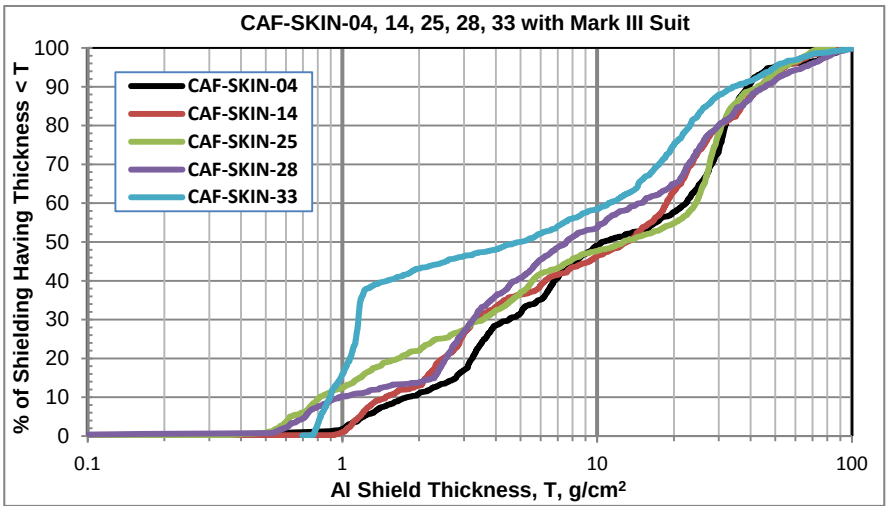

Figure 9. CAF shielding distributions for several skin points.

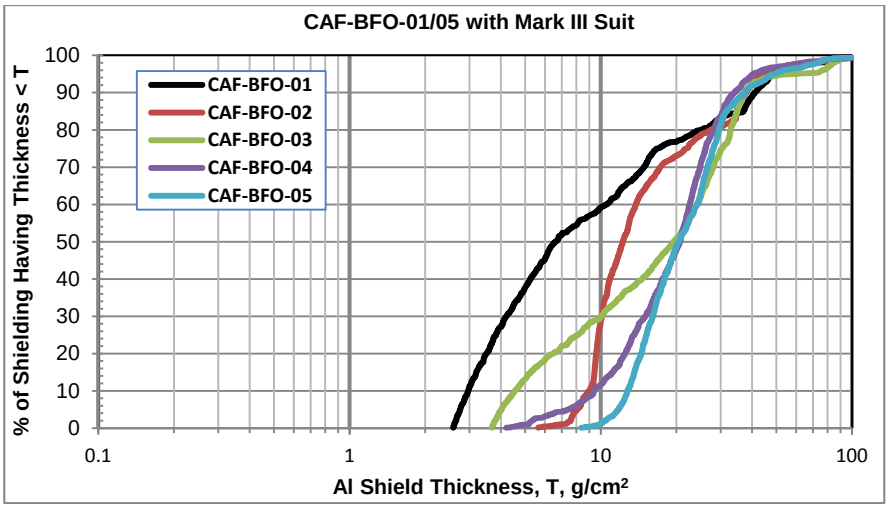

Figure 10. CAF shielding distributions for several BFO points.

These CAM and CAF shielding distributions are used in section VII to compute the respective skin and BFO space radiation exposures.

V. LEO Radiation Environment

We used a typical ISS orbit (400 km x 51.6° inclination) and the SPENVIS[9] on-line tool to compute the trapped proton[10] and electron[11] differential and integral spectra as shown in Figs. 11 and 12 for solar minimum for an 8 hr EVA.

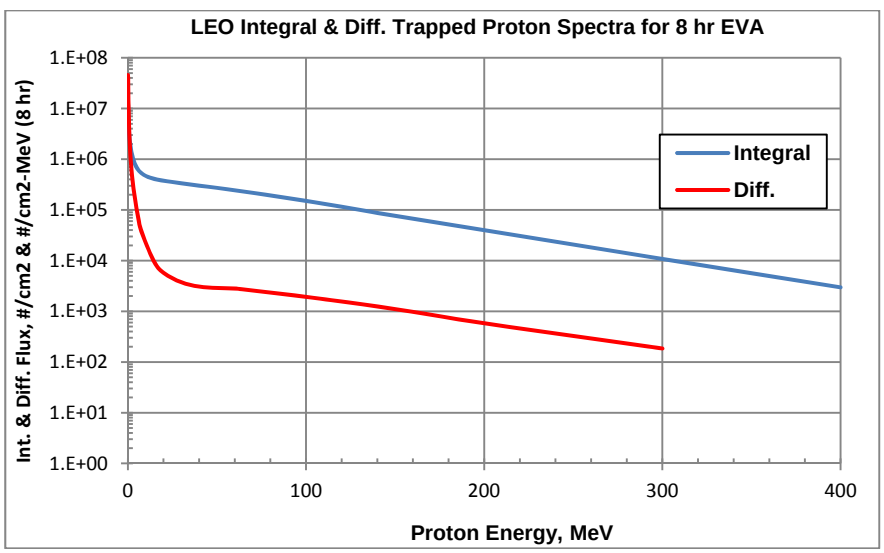

Figure 11. LEO integral and differential trapped proton spectra (solar MIN) for an 8 hr EVA.

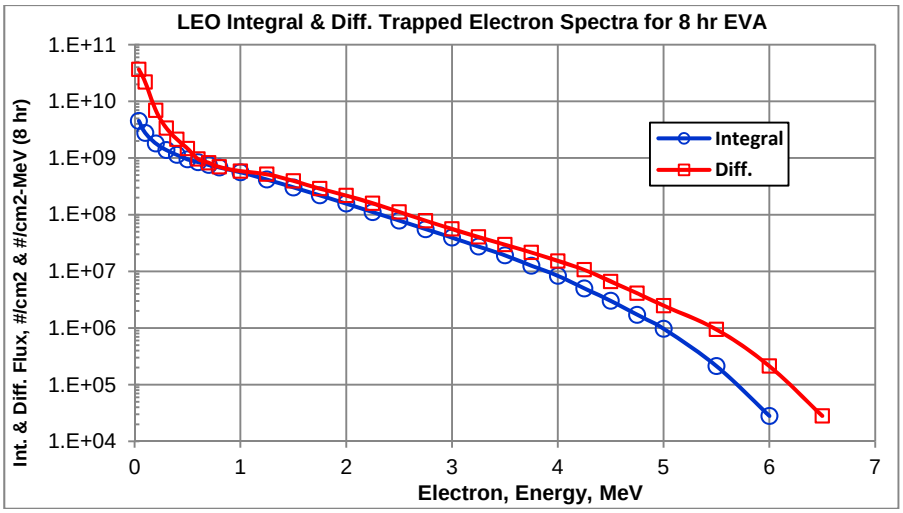

Figure 12. LEO integral and differential trapped electron spectra (solar MIN) for an 8 hr EVA.

VI. GEO Radiation Environment

GEO (35,786 km x 0° inclination) electron[11] spectrum is shown in Figure 13 for solar minimum (epoch 2012). The proton environment is negligible at GEO; the maximum proton energy is ~4 MeV. Thus, at GEO we are only concerned with radiation exposures due to the trapped electrons (and, of course, GCR and SPEs).

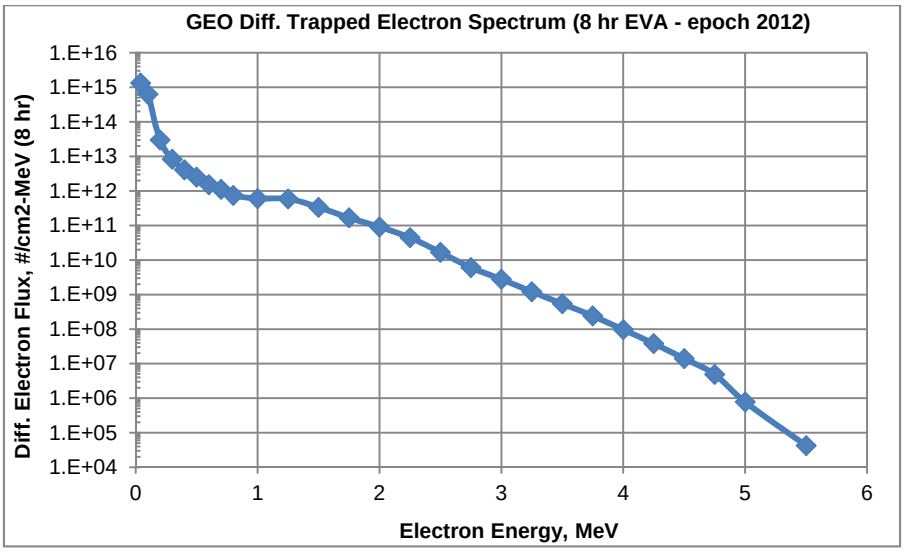

Figure 13. GEO differential trapped electron spectrum (solar MIN) for an 8 hr EVA.

At the GEO radiation environment the earth's magnetic field is very weak and the high energy particles from GCR and SPE's that have nearly free access. The solar proton environment is will not be considered in this paper, since any EVA activity would not take place in an enhanced radiation environment and the crew would seek maximum shielding shelter inside the spacecraft.

The GCR environment at GEO is a constant background source of radiation exposure and varies with the 11-year solar cycle. Figure 14 shows the free space GEO GCR environment for solar minimum and solar maximum for four ion species: proton (hydrogen), helium (He - alpha particle), oxygen (O), and iron (Fe).

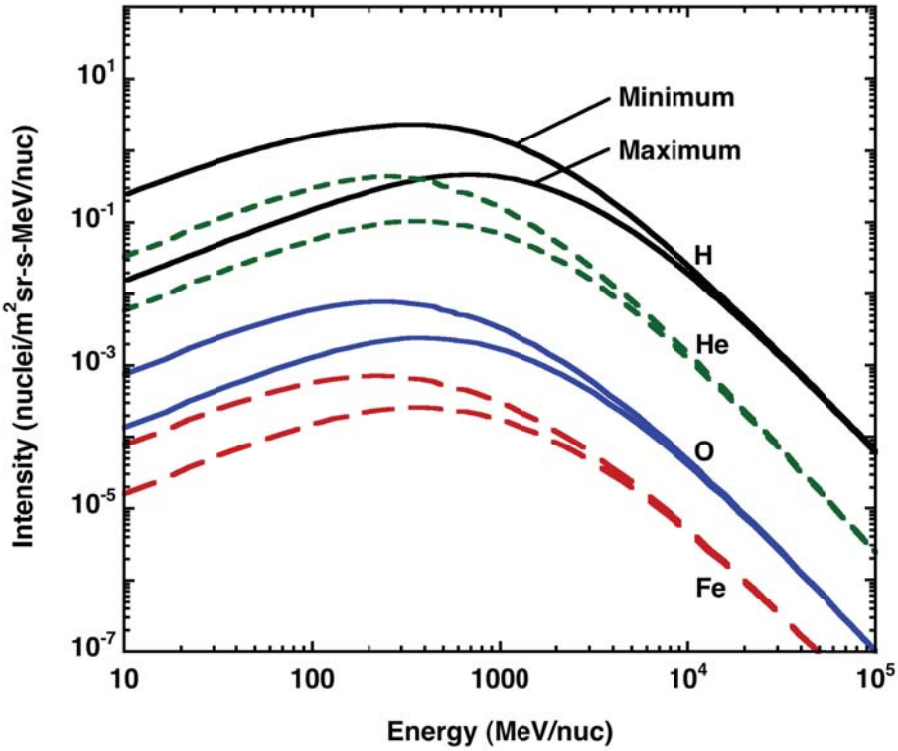

Figure 14. GCR differential spectrum (solar MIN) at GEO.

VII. Radiation Exposures

Using the NASA LaRC codes, the trapped proton and GCR (HZETRN code[14]) doses and the trapped electron (CEPTRN code[15]) doses for several skin and BFO were calculated for the LEO and GEO environments as shown in Figures 15 and 16 for the CAM. Similarly, Figures 17 and 18 show several CAF skin and BFO exposures. It is noted that the 30-day skin limit (1500 mSv) was exceeded for two of the CAM skin locations (#25 & #28). Whereas, the 30-day BFO limit (250 mSv) was not exceeded for any of the BFO locations. The LEO exposures include the trapped protons, trapped electrons, and the geomagnetically-attenuated GCR particles. The GEO exposures include the outer belt trapped electrons and the unattenuated GCR particles. Radiation exposures at other body locations are discussed in the last section of the paper (Table 1).

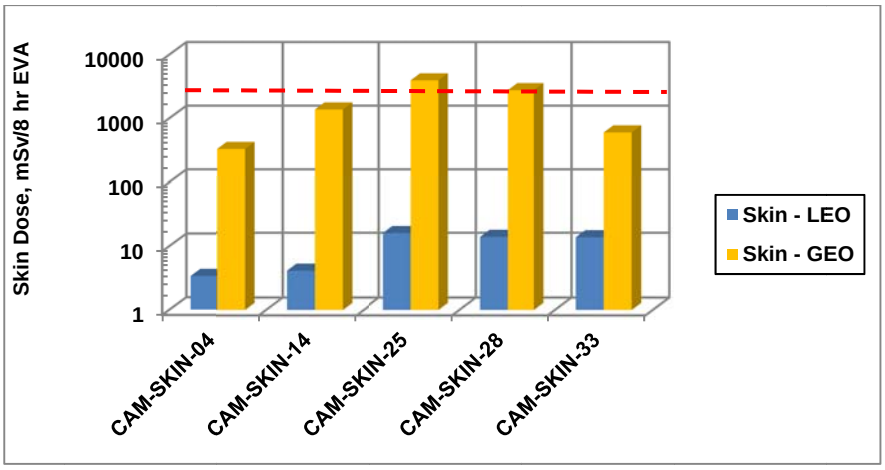

Figure 15. 8-hr EVA skin doses for several CAM skin points for LEO and GEO. The red dash line shows the 30-day astronaut skin limit.

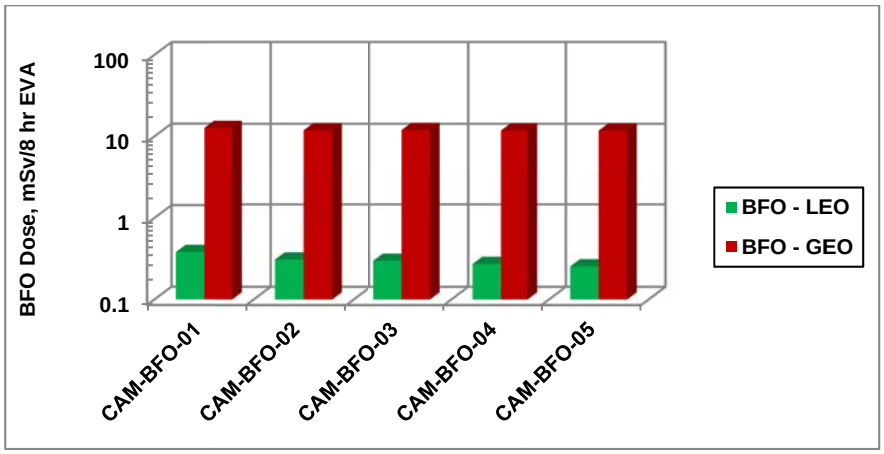

Figure 16. 8-hr EVA BFO doses for several CAM BFO points for LEO and GEO.

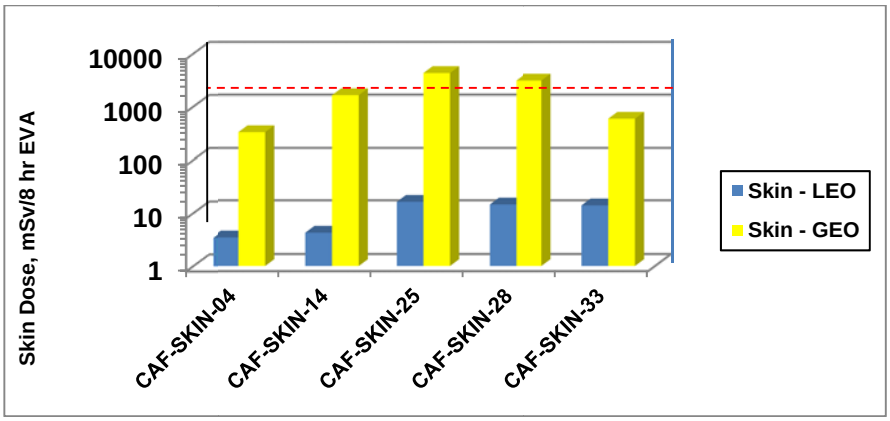

Figure 17. 8-hr EVA skin doses for several CAF skin points for LEO and GEO. The red dash line shows the 30-day astronaut skin limit.

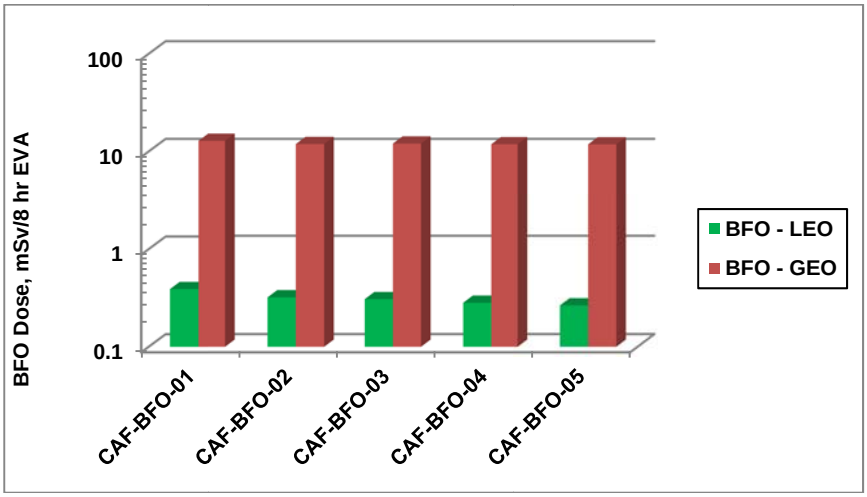

Figure 18. 8-hr EVA BFO doses for several CAF BFO points for LEO and GEO.

VIII. Conclusions

In this paper we discussed the development of the Mark III spacesuit and the 3-D CAD model. We combined mathematically the spacesuit model with the CAM and CAF models to compute shielding distributions for a number of body organ and skin locations. These shielding distributions were used with high energy particle transport codes to calculate radiation exposures for the LEO and GEO radiation environments. For LEO EVA operations no crew exposure limits are exceeded for any CAM and CAF body locations.

Table 1 is a summary of all of the CAM and CAF radiation exposures for both LEO and GEO. The yellow highlighted values exceed the current crew limits.

Table 1. Organ Exposures for an 8-hr EVA

Organ	Male		Female	
	LEO	GEO	LEO	GEO
	mSv	mSv	mSv	mSv
Skin	8.83	10484.0	10.53	13764.0
Eye	3.36	6560.6	3.89	8700.3
Avg. BFO	0.03	11.84	0.03	11.93
Bladder	0.02	11.86	0.02	11.88
Colon	0.02	11.87	0.02	11.89
Esophagus	0.02	11.85	0.02	11.86
Kidney	0.02	11.85	0.02	11.86
Liver	0.02	11.81	0.02	11.83
Lung	0.02	11.85	0.02	11.87
Pancreas	0.02	11.83	0.02	11.85
Stomach	0.02	11.83	0.02	11.84
Thyroid	0.11	13.69	0.43	14.26

It is noted that for the computed radiation exposures none of the BFO locations and specific body organs exceeded the 30-day crew limit of 1500 mSv. However, a number of the skin locations and the lens of the eye (30-day crew limit = 1000 mSv) were exceeded. We have determined that with the addition of 3.4 g/cm^2 (~1 1/3") HDPE the crew limits for all locations can be satisfied at GEO.

Adding additional protective high density polyethylene (HDPE) spacesuit shielding needs to be investigated; there may be mobility and dexterity issues that need to be considered. And finally, it may be that for GEO operations, such as satellite servicing, may require remote operations. This will be investigated in future work.

Acknowledgments

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