The Monte Carlo Method: Versatility Unbounded in a Dynamic Computing World
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RADIOPROTECTION FOR INTERPLANETARY MANNED MISSIONS

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ABSTRACT

The study of the dosimetric effects of space radiation on astronauts is an important concern of space missions for the exploration of the Solar System. To protect the crew, shielding must be designed, the environment must be anticipated and monitored and a warning system must be put in place. A Geant4 simulation has been developed for a first quantitative study of existing vehicle concepts and Moon/Mars surface habitat designs, and the radiation exposure of crews therein. We will show the results of the dosimetric analysis of proposed innovative shielding solutions in various geometrical set-ups, complemented with a critical analysis of Geant4 tools currently available for this type of studies. This work represents the first approach in the European AURORA programme to estimate quantitatively a crucial issue in the manned exploration of the Solar System.

Key Words: Astronaut,radioprotection, dose, Geant4

1 INTRODUCTION

The study of the effects of interplanetary space radiation on astronauts is an important concern of space missions for the human exploration of the Solar System, for the danger represented by the radiation hazard to crew. A strategy to protect the astronauts is to study possible shielding solutions to apply to vehicles and planet surface habitats.

A Geant4 simulation was developed to perform a first quantitative dosimetric study of existing vehicle concepts and surface habitat designs, and the radiation exposure of crews therein; a set of candidate shielding configurations was evaluated with respect to some radiation exposure hypothesis.

The project took place in the context of the European AURORA [1] programme for the robotic and human exploration of the Solar System.

2 THE SPACE RADIATION ENVIRONMENT

Among the space radiation environment components, it is widely recognized that the Galactic Cosmic Rays (GCR) and the Solar Particle Events (SPE) can produce harmful effects on the crew [2].

The spectra of GCR and SPE were modeled in the simulation; the dosimetric effect of a subset of GCR particles was considered: in particular the proton, α particle, carbon, oxygen, silicon and iron ion GCR components were selected.

Solar Particle Events (SPE) consist in proton, α particles and heavy ions emitted into space from solar flares. In this study the proton and α SPE components were studied.

A conservative approach was adopted in the study; GCR and SPE fluxes were given in the worst condition observed.

The GCR fluxes derived from CREME [3] as the envelope of the GCR fluxes observed in 1977 and 1975, at 1 AU, during solar minimum activity; this condition corresponds to the most conservative assumption from a radioprotection point of view).

The SPE fluxes followed the model of CREME [3]; they derived from the envelopes of the SPE fluxes of the events registered in October 1989 and August 1972 at 1 AU.

The GCR and SPE particle fluxes were modeled in the energy range between 1. MeV and 100. GeV.

3 CONCEPTUAL MODELS OF ASTRONAUTS' HABITATS

Various conceptual models of vehicle habitats are currently under study for future interplanetary manned missions. Among them a novel vehicle concept was proposed consisting of an Inflatable Habitat; this model represents a new and alternative vehicle design with respect to traditional hard shell habitats [4]. A simplified Inflatable Habitat model (SIH) was studied in this project; it consists of a multilayer structure, including:

- an external thermal protection blanket, made of layers of betacloth and mylar;
- a meteoroid and debris protection, consisting of layers of nextel (bullet proof material) and open cell foam;
- a structure made of kevlar;
- a rebundant bladder, consisting of layers of polyethylene, polyacrylate, EVOH, kevlar, nomex.

This structure is complemented by a shielding layer against GCR and an additional shielding structure with the role of a shelter against SPE. The simulation study considered different shielding materials and thicknesses to be optimized to limit the astronaut harmful exposure to GCR radiation. The vehicle concept under study is shown in figure 1.

Possible configurations of planetary surface habitats were also under study. This simulation considered a surface habitat exploiting the local planetary soil as construction and shielding material(figure 2). This configuration was studied in the moon radiation environment. The Moon is considered as an intermediate base for the planetary exploration. Its radiation environment was considered as more harmful than the Mars environment.

4 SOFTWARE PROCESS

The adoption of a rigorous software process allows to develop robust and reliable software applications. The software development of the Geant4 simulation followed an iterative and

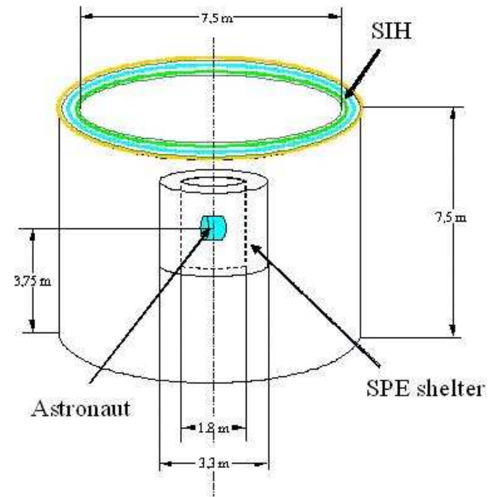

Figure 1: Vehicle concept: model of the SIH and SPE shelter of the Inflatable Habitat Module.

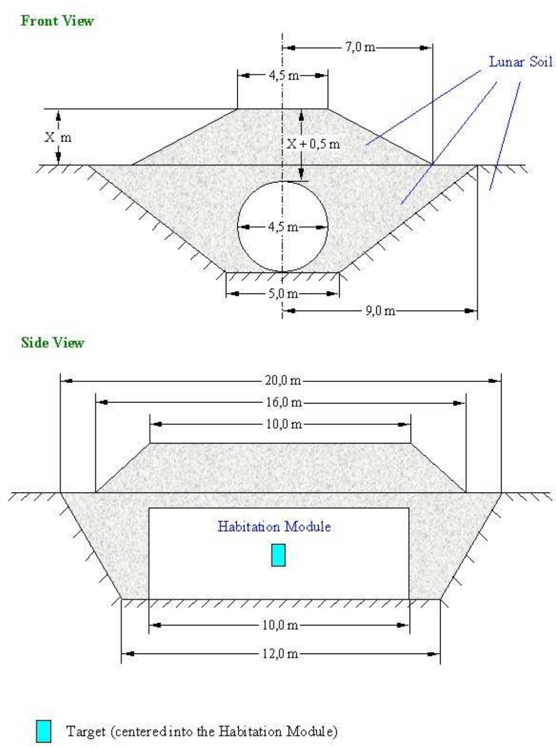

Figure 2: Example of planet surface habitat concept set on the Moon.

incremental approach, based on the Unified Software Development Process (USDP) [5]. The Rational Unified Process (RUP) [6], mapped onto ISO 15504 [7], was adopted as process framework, tailoring the process to the specific characteristics of the project.

The application development passed through all the phases of life-cycle; the User Requirements were identified and documented, the software architecture was designed, the code was implemented and tested [8].

5 STRATEGY OF THE SIMULATION

Geant4 [9] was chosen as Simulation Toolkit for its advanced capability addressed to Medical Physics domain [10].

The dosimetric effect of GCR and SPE was quantitatively studied in the set of simplified experimental configurations chosen, with proposed shielding solutions.

For a better understanding of the dependence of the dosimetric results from the physics processes undertaken by particles, in a first moment the dosimetric effect of electromagnetic processes was studied, then the hadronic physics processes were activated in the simulation on top of the electromagnetic processes to evaluate their contribution to the dosimetric results.

Individual simulations were performed for each GCR and SPE particle component.

6 GEANT4 REMSIM SIMULATION MODEL

6.1 Simulation components

The Geant4 REMSIM simulation encompasses various components, that have different responsibilities and cooperate to achieve the goals of the application defined in the User Requirement Document.

The primary particle component manages the generation of primary particles; they can be protons, α particles, ions, with a defined energy or following an energy spectrum. At this stage of the study the primary particles were generated from a fixed vertex, with a defined direction.

The geometry component has the responsibility of the definition of the experimental set-up in terms of geometry and material composition. The geometrical models of vehicle concepts and surface habitats and the phantom representing the astronaut are defined in this component.

The phantom is a water box where the energy deposited by primary and secondary particles is collected. The energy deposit was analysed with respect to the depth in the phantom.

The physics component has the responsibility of activating the physics processes. It has been modularised in sub-components: each of them controls the activation of processes related to a type of particle.

The user can define interactively the physics processes to activate, the number of events to be generated, the primary particles to generate in terms of particle type and energy, the geometrical configuration.

The Geant4 REMSIM simulation is interfaced to the external visualisation tools OpenGL, DAWN, VRML and to the external analysis tools AIDA 3.2 [11] and PI 1.2.1 [12].

6.2 Experimental set-ups

Figure 3 shows the experimental set-up modeled in the Geant4 simulation as a simplified configuration of the SIH and its shielding layer. The GCR components impinge on the SIH model orthogonally.

For this first dosimetric study 10. cm and 5. cm thick water or polyethylene layers were evaluated as shielding solutions.

A second dosimetric study was performed replacing the Inflatable multilayer structure with a layer of aluminum; the two solutions were compared from a radioprotection point of view.

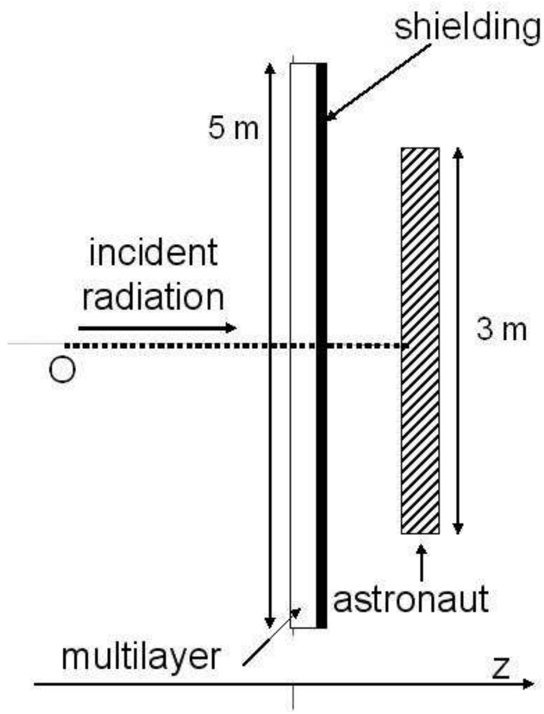

Figure 3: Geant4 model of the Simplified Inflatable model complemented by a shielding layer; multilayer refers to the SIH structure.

The same configuration, with an additional shielding layer of 75 cm of water, representing the SPE shelter, was studied; in this configuration the effect of SPE was evaluated (figure 4).

Figure 5 shows the experimental set-up adopted for the Moon surface habitat configuration; both GCR and SPE dosimetric effects were considered.

6.3 Modeling of the physics processes

The Geant4 electromagnetic Low Energy package [13], [14], [15], was adopted to model the electromagnetic processes of photons, electrons, protons, α particles, ions. The Geant4 electromagnetic Standard package [9] was chosen to model the electromagnetic processes of positrons.

Hadronic physics processes were modeled for protons and α particles as incident particles.

Geant4 offers alternative and complementary hadronic models in the energy range of interest to this simulation; two alternative approaches were considered to model the proton inelastic scattering; the nuclear de-excitation and Precompound models were activated in the lower energy range up to 100 MeV, two alternative options for intra-nuclear transport (the Bertini or the Binary [22] cascade models) up to 3.2 GeV and 10 GeV respectively, the Low Energy Parameterized

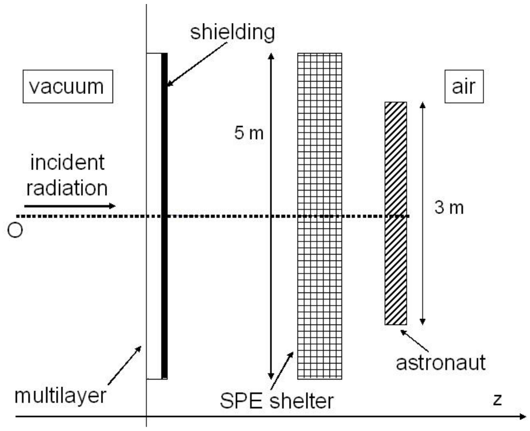

Figure 4: Geant4 model of the SIH model complemented by a shielding layer and an additional SPE shelter; multilayer refers to the SIH structure.

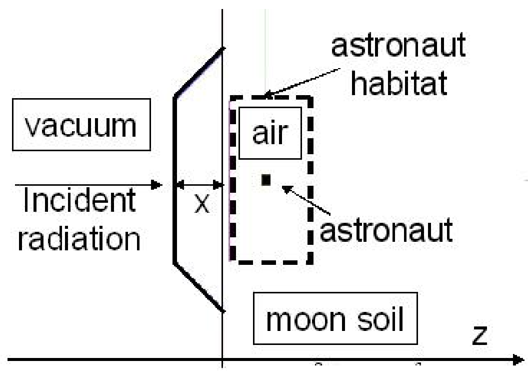

Figure 5: Geant4 model of the Moon surface habitat concept.

model at intermediate energies, the Quark Gluon String model beyond 20 GeV. For α particles the hadronic inelastic process was modeled through the Geant4 Low Energy Parameterized (LEP) model for energies lower than 100. MeV and the Geant4 Binary Ion model in the energy range between 80. MeV and 40. GeV. No models for the hadronic interactions for α particles are available for energies higher than 40 GeV.

The overlapping energy ranges of the definition of the complementary hadronic models allow the smooth blending of different hadronic models.

The validation of the electromagnetic and hadronic models selected for this simulation are documented in [16] and [17] respectively.

7 RESULTS

The study was focused on the evaluation of the relative shielding properties of different materials and thicknesses of the proposed shielding structures. For this purpose relative energy deposits and equivalent doses were calculated in the phantom. It should be noted that, given the approximated geometrical configuration and the simplified angular distribution of the primary particles generated, only relative calculations are meaningful while the calculation of absolute doses would not produce realistic results.

7.1 Vehicle concept: SIH

The dosimetric effect of the selected set of Galactic Cosmic Rays was studied, complementing the SIH concept with the following shielding options:

- no shielding,
- 5. cm and 10. cm polyethylene layer,
- 5. cm and 10. cm water layer.

Figure 6 shows the energy deposit of GCR protons in the phantom representing the astronaut with respect to the depth; 100 K events were generated, the electromagnetic physics processes were activated only.

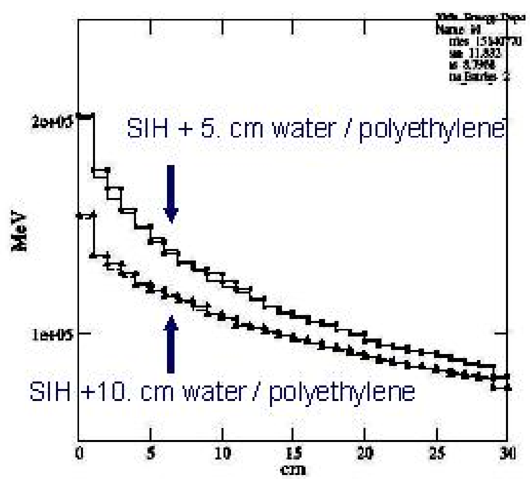

Figure 6: Energy deposit in the astronaut concept resulting from GCR protons, in the experimental set-up shown in figure 3, in different shielding configurations (indicated by the arrow in the figure); the energy deposit is calculated with respect to the depth in the astronaut concept.

Polyethylene and water have an equivalent shielding behavior.

7.2 Vehicle concept: SPE shelter

The effect of both GCR and SPE was studied in the configuration shown in figure 4, in which the SPE shelter complements the SIH and 10 cm water GCR shielding structure. Generating 100 K events, only 4 SPE protons reach the astronaut while SPE α particles are completely stopped by the SPE shelter. A more detailed study was performed to evaluate the effect of the high energy tail of solar event protons and α particles in a dedicated simulation production.

7.3 Moon surface habitat concept

The dosimetric effect of GCR and SPE was calculated in the experimental set-up shown in figure 5 with respect to the thickness x of the Moon soil roof put on top of the surface habitat. The energy deposit of the GCR and SPE decreases with thicker roofs.

8 CONCLUSIONS

A Geant4 simulation was developed and used to perform a first quantitative dosimetric study of the effects of Galactic Cosmic Rays and Solar Particle Events in vehicle concepts and Moon surface habitats under study for interplanetary manned missions. The habitats were modeled with simplified geometrical structures, retaining the essential characteristics for a first dosimetric study.

From this study, it is possible to infer that a Simplified Inflatable Module offers a similar radioprotection behavior from GCR with respect to traditional aluminum structures. In the Simplified Inflatable Module water and polyethylene have an equivalent shielding behavior.

The Geant4 REMSIM simulation shows that a water SPE shelter is a possible solution to limit the exposure of the astronauts to the harmful effects of SPE.

In this study Geant4 demonstrated its capability to address the study domain of radioprotection in manned space missions.

This work represents the first approach in the European AURORA programme to estimate quantitatively a crucial issue: the radioprotection of astronauts in the manned exploration of the Solar System.

9 ACKNOWLEDGMENTS

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