Design and optimization of shielding for human exploration missions using FASTRAD software

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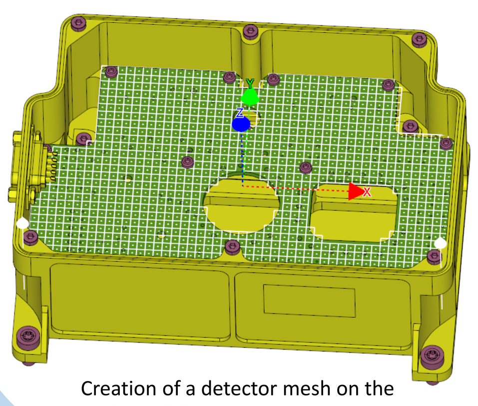
Abstract:

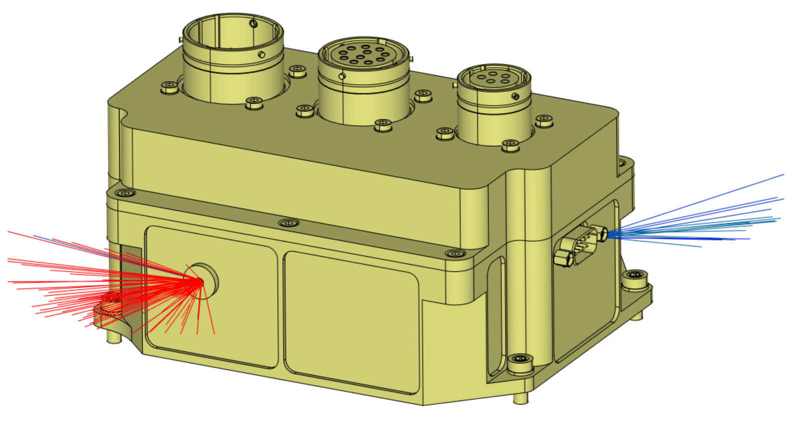
*FASTRAD is a software dedicated to the assessment of radiation effects in space. It is conceived, developed and distributed by TRAD. It contains various tools including **modeling**, calculation (with **Ray-tracing** and GEANT4 physics-based **Monte-Carlo** methods) and **post-processing** tools. We present here the main functionalities available to design, study and optimize the shielding notably in the scope of human exploration missions. Some ongoing developments that will be included in the next version of FASTRAD are also discussed, in particular the integration of Monte-Carlo calculation for heavy ions. We also present some of the current projects for space explorations we're involved in, two PhD theses: one on the use of regolith as a shielding for lunar habitat (by Yulia Akisheva) and another one, on manned missions to Mars, including the development of an environment model as well as a multi-layer shielding optimization (by Gabin Charpentier).*

Identify and locate sneak paths in a model with the Ray-tracing tool

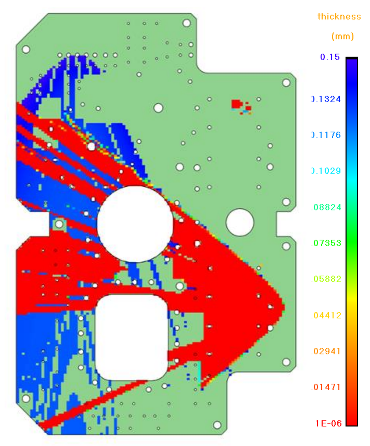
- Use of the ray-tracing method for fast calculations
- Shielding materials managed by equivalent aluminum (simplified approach)
- Create 2D / 3D grids of detectors on sensitive elements
- Estimate the dose and / or the minimum thickness for each detector
- Display results in the 3D view to locate holes and sneak paths



Creation of a detector mesh on the surface of the PCB



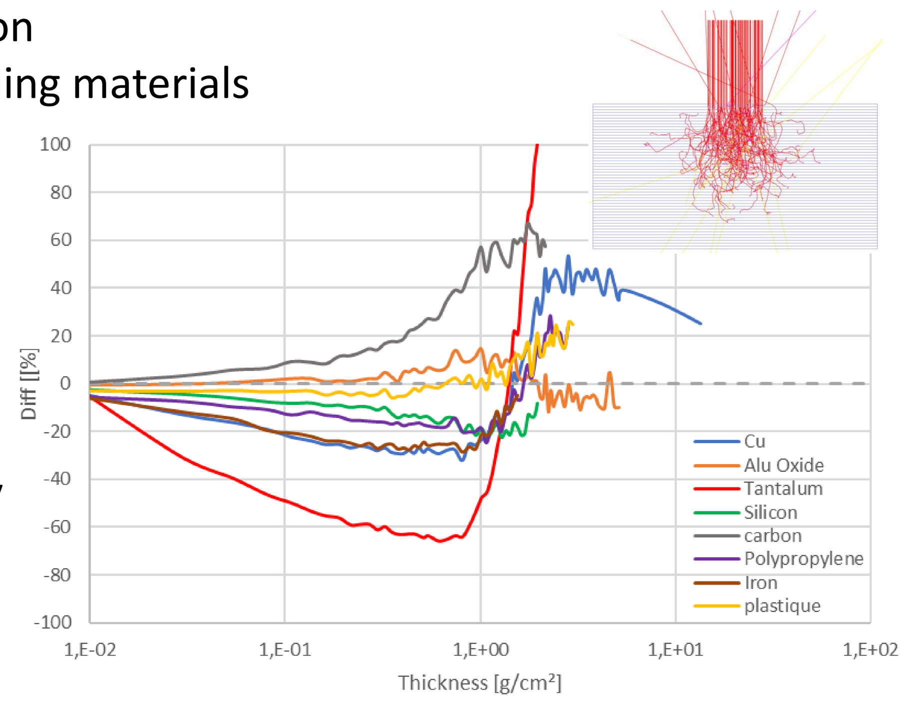
Localization of the holes



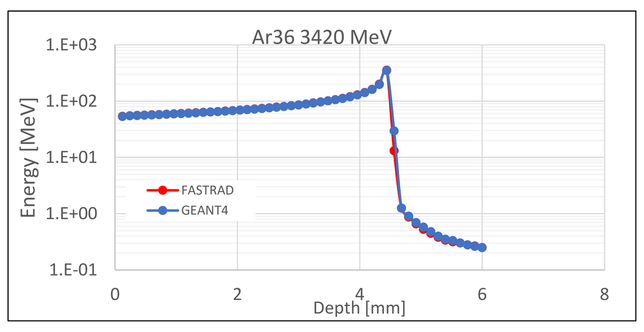
Visualization of the impacted areas

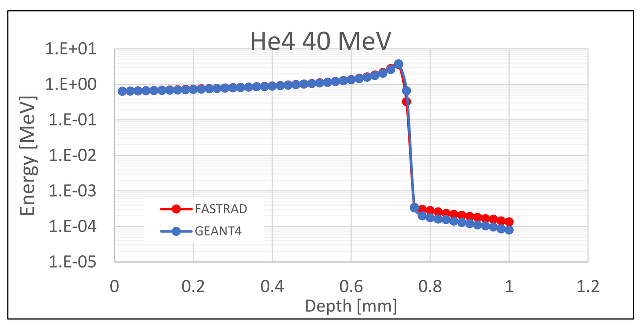
Shielding material effectiveness with the Monte-Carlo tool

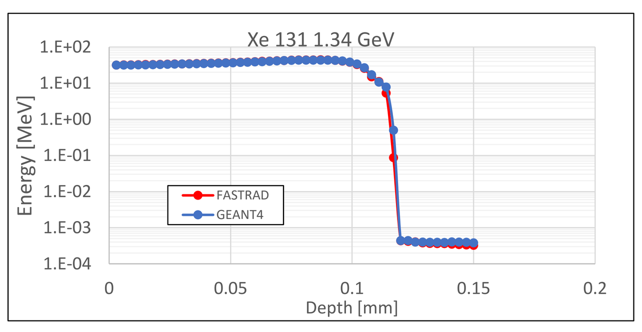
- Use of the Monte-Carlo calculation
- Realistic assessment of the shielding materials
- Create a dose curve (dose as a function of thickness) for each material
- Compare the materials at same thickness (in g/cm²)
- Application to GEO environment
- Results show the dose discrepancy with respect to aluminum
- Negative values indicate a more effective material



Integration of heavy ions for the Forward Monte-Carlo tool (ongoing work)







In the scope of space exploration missions, heavy ion Monte-Carlo is being integrated into FASTRAD.

It will be possible to consider the dose contribution of heavy ions from GCR which is essential for radiation protection.

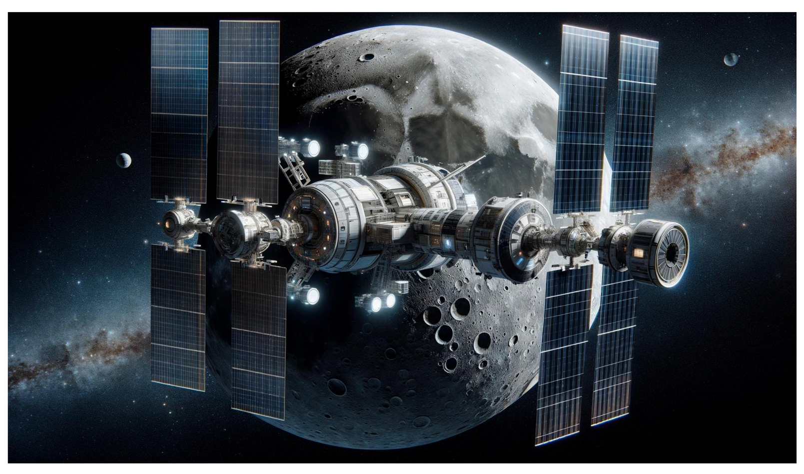
First comparisons (see figures) show good agreements between FASTRAD and GEANT4.

Next steps:

- validation for more ions/energy
- validation of secondary particles generation (photons, neutrons, …)

Radiation protection in space (ongoing work)

- Design of a new tool integrated into FASTRAD for the assessment of radiation protection in space.
- Input of a source for GCR heavy ions.
- Transport of heavy ions
- Creation and transport of secondary particles
- Estimation of new quantities dedicated to radiation protection : equivalent dose, effective dose ….



Use of regolith for lunar exploration

- The dose build-up phenomenon is observed for the total dose equivalent behind EAC-1A type regolith.
- If adding polymers into regolith to make a mixture is compared to building multilayers from equivalent amount of materials, multilayers are far more efficient for radioprotection from Galactic Cosmic Rays
- Globally, for thick regolith shielding, i.e. beyond 43 g/cm², the Solar Particle Event contribution to the total dose equivalent is relatively small. The main dose-contributing components are thus the Galactic Cosmic Rays and secondary emissions produced in the habitat wall.

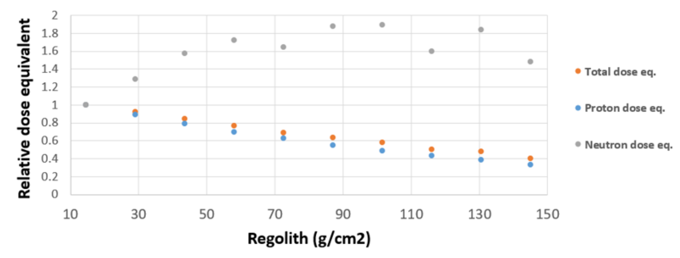


Figure 1. Relative dose equivalent in the ICRU sphere as a function of regolith areal density from GCR protons (ISO-15390 [1] model in SPENVIS [2, 3]). The doses are normalised to the case of 10 cm regolith wall. Simulations done with RayXpert® (v1.9, revision 32322). The uncertainty for all data points is between 0.1% and 3.5%.

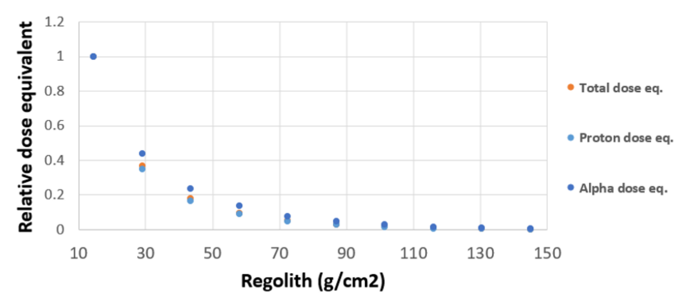


Figure 2. Relative dose equivalent in the ICRU sphere as a function of regolith areal density from Oct89 SPE (worst-week CREME-96 model in SPENVIS [2, 3]). The doses are normalised to the case of 10 cm regolith wall. Simulations done with RayXpert® (v1.9, revision 32322). the uncertainty for all data points is between 0.1% and 7.5%.

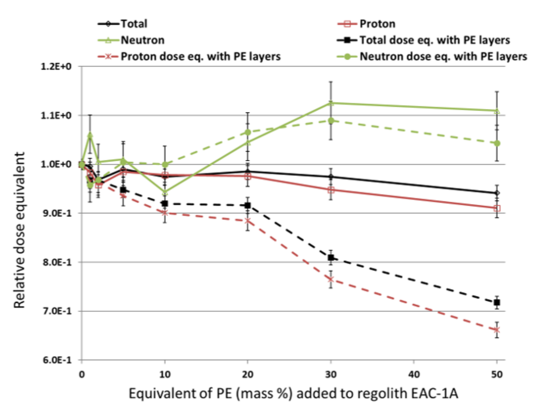


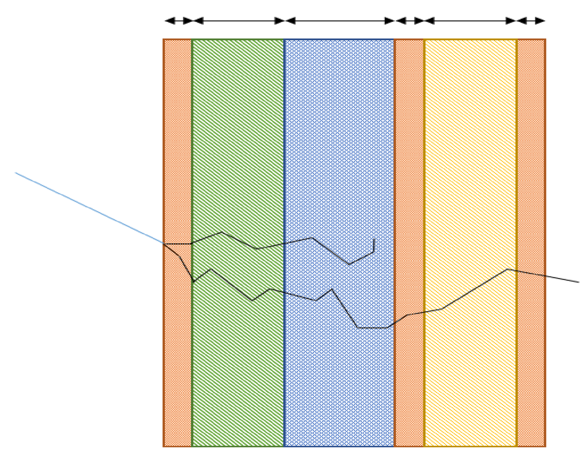
Figure 3. Relative dose equivalent in the ICRU sphere as a function of regolith composition when polyethylene (PE) is added to EAC-1A and for equivalent PE layers behind a 50 cm regolith block, normalised to the dose equivalent in the ICRU sphere behind a bare 50 cm regolith brick. Simulations done with RayXpert® (v1.9, revision 32322). Error bars for all data points are included in the plot.

Highlights from the work on Protective Use of Regolith for Planetary and Lunar Exploration (PURPLE, PhD thesis of Y. Akisheva)

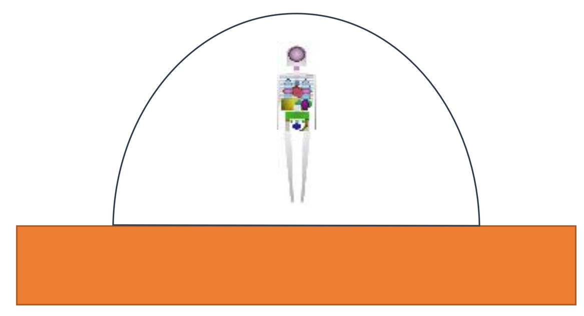
Multi-layer Optimization coupling AI and Monte Carlo:

Multi Layer Shielding Optimization :

- Interface development between NSGAII (Non-dominated Sorting Genetic Algorithm) and Geant4 Monte-Carlo codes
- Dose optimization for habitat shielding on the Martian surface, under different doses and exposures



- Determination of effective doses, organ equivalent doses and risk assessment for comparison with single-layer shielding



- Use of ARAMIS (Atmospheric RAdiation Model for Ionizing spectra on Martian Surface) environment model
- Benchmark of Geant4 and RayXpert/FASTRAD for the selected optimized shielding

Highlights from the work "Radiation protection for manned missions to Mars: environmental modelling, multi-layer optimization, prevention of radiation risks for astronauts" (PhD thesis of G. Charpentier)