Monte Carlo based shielding efficiency evaluation against GCR and SPE in deep space using light materials

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Joris Gackowski (Electrabel ENGIE) dr. Alessio Parisi (SCK CEN) dr. Olivier Van Hoey (SCK CEN) **Alberto Ottonello (Tractebel ENGIE)**

TE - Core and Fuel studies Group

Portfolio

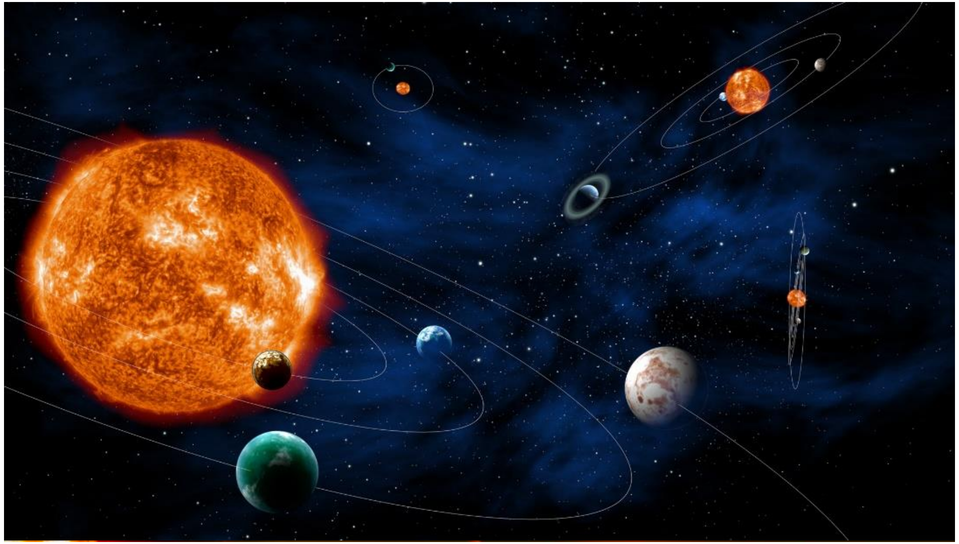
- Owner's Engineer of the Belgian Utility with independent capacities from Fuel vendors
  - —Fuel cycle & In-Core Fuel Management
  - —Fuel Safety Evaluation
  - —Reload Verification & Accident Analysis
  - —Core Monitoring & Operation
  - —Fuel Storage
  - —Shielding/Criticality/Activation
- Support Engie Group Int'l development
- Consultancy and Assistance for Int'l customers
- Training

UNIT	In operation since	NSSS	Number of assemblies	Assembly lattice	Fissile height [ft]	Thermal power [MW]	Power uprate programs
Doel 1	1975	W	**121**	**14*14**	**8**	**1192** *-> 1311 (+10%)*	***PU+SGR in 2009***
Doel 2	1975	W	**121**	**14*14**	**8**	**1192 -> 1311 (+10%)**	**PU+SGR in 2004**
Doel 3	1982	FRA	**157**	**17*17**	**12**	**2775 -> 3054 (+10%)**	**PU+SGR in 1993**
Doel 4	1985	W	**157**	**17*17**	**14**	**2988**	**SGR in 1996**
Tihange 1	1975	FRA	**157**	**15*15**	**12**	**2655 -> 2865 (+8%)**	**PU+SGR in 1995**
Tihange 2	1982	FRA	**157**	**17*17**	**12**	**2775 -> 2895 (+4.3%)**	**PUCE in 1995**
						-> 3054 (+10% tot)	**PU+SGR in 2001**
Tihange 3	1985	W	**157**	**17*17**	**14**	**2988**	**SGR in 1998**

PU = power uprating SGR= steam generator replacement
PUCE = Power Uprate and Cycle Extension

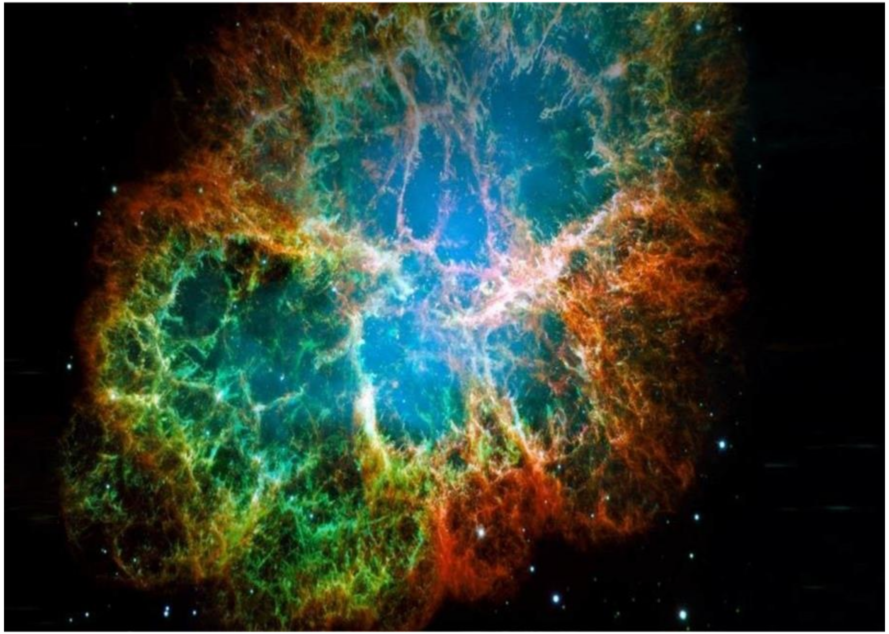
Introduction

- Current space missions **inside** magnetosphere
  - Astronauts partly shielded
  - Shielding not top priority
- Future deep space missions **outside** magnetosphere
  - No “natural protection”
  - Shielding = top priority



Radiation environment in space

- Sources of radiation is space
  - **Primary sources**
    - Galactic Cosmic Radiation (GCR)
    - Solar wind
    - Solar Particle Event (SPE)
    - Trapped radiation belts
  - **Secondary sources**



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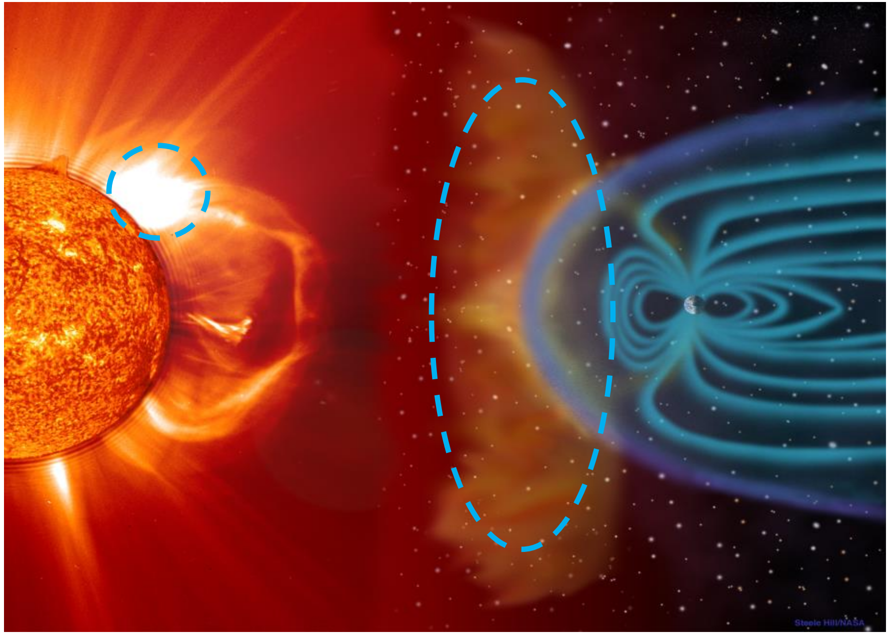

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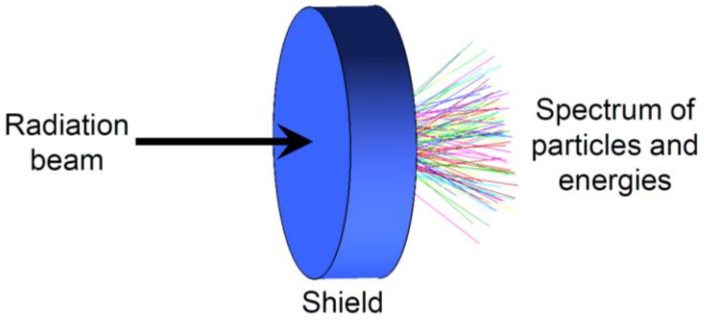


Introduction

- Work objectives
  1. Identify materials for optimum shielding (physics)
  2. Evaluate shielding efficiency (transport codes)
- Delineation of scope
  - Location at 1 AU
  - Passive shielding

- But first …. We need to benchmark the calculational methodology

Radiation protection in space

- ALARA
  - Earth → time, distance, shielding
  - Space → shielding
- Current materials in LEO → aluminium

➔ In deep space → Al = **good** for **SPE** but **not optimal** for **GCR**

- Recommended materials → light materials

➔ Optimal shielding against (heavy) ions

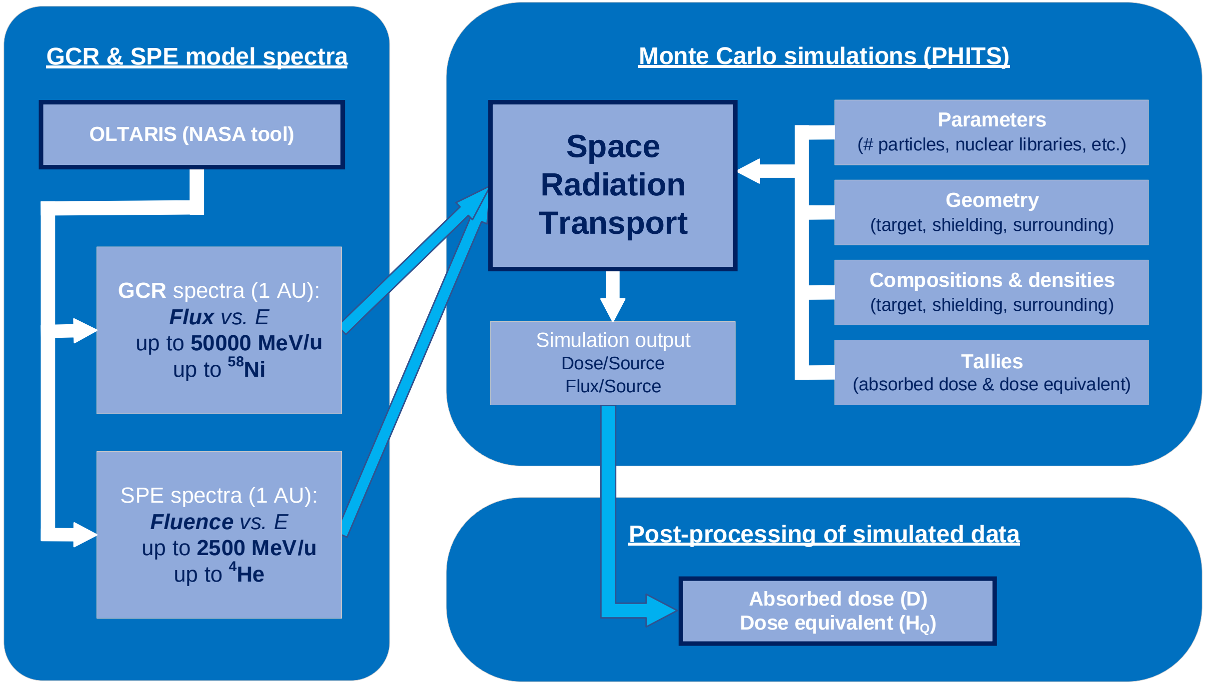
Methodology and data for dose assessment

- Dose assessment in space
  1. Radiation transport calculations (validated models)
  2. Measurements

  ➔ **Recommended = transport calculations**
- Reliable dose calculations → accurate spectral data (source term)
  - GCR → analyzed models & compared to measurements ➔ Solar Min 2010
  - SPE → analyzed historical data on Solar outbursts ➔ 1972 King

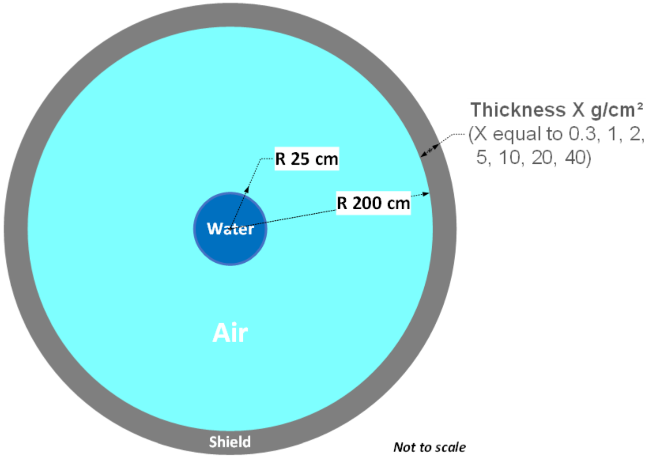
  ➔ **Selected based on intensity & energy distribution**

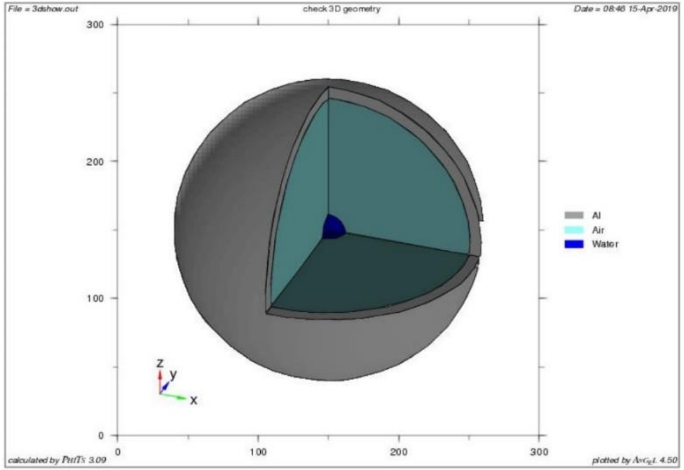
Methodology and data for dose assessment



Methodology and data for dose assessment

- Modelling input parameters (PHITS)
  - Geometry





Benchmarking

- GCR

  Solar Min 2010

  — Estimation of galactic cosmic ray exposure inside and outside the Earth's magnetosphere during the recent solar minimum between solar cycles 23 and 24, Mrigakshi et al. 2013b, Advances in Space Research, Volume 52, Issue 5, p. 979-987, 2013

- SPE

  August 1972 LaRC

  — D → benchmarked to 1D (MULASSIS) & 3D (GRAS) dose calculations tools

  — Results for 1972 King SPE spectral data generated by OLTARIS & SPENVIS

Conclusions on the benchmarking

- A calculation methodology based on the Monte Carlo code PHITS and OLTARIS was established.
- Confidence in this methodology was gained following the satisfactory benchmark results both for GCR and SPE.
- Best results for unshielded configurations because of increasing statistical uncertainties with growing shield thickness in the results against which PHITS and OLTARIS were tested.
- Next step: optimisation of a passive shield:

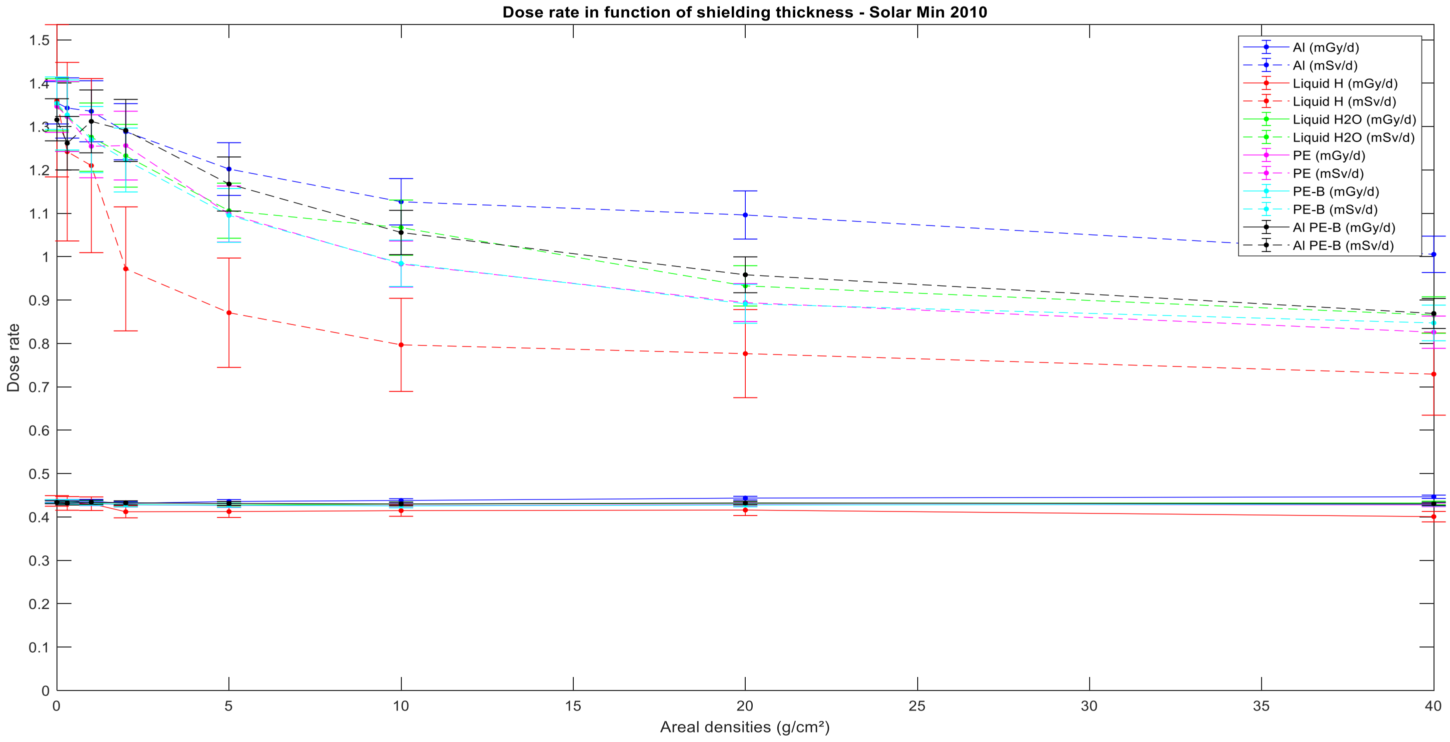
  — candidate materials: hydrogenated compounds using Al as reference.

Results

- Analyzed data
  - GCR
    - Solar Min 2010 → bounding
    - Solar Max 2001
  - SPE
    - August 1972 LaRC
- Dose results → absolute doses, dose reduction factors, shielding efficiencies

Results

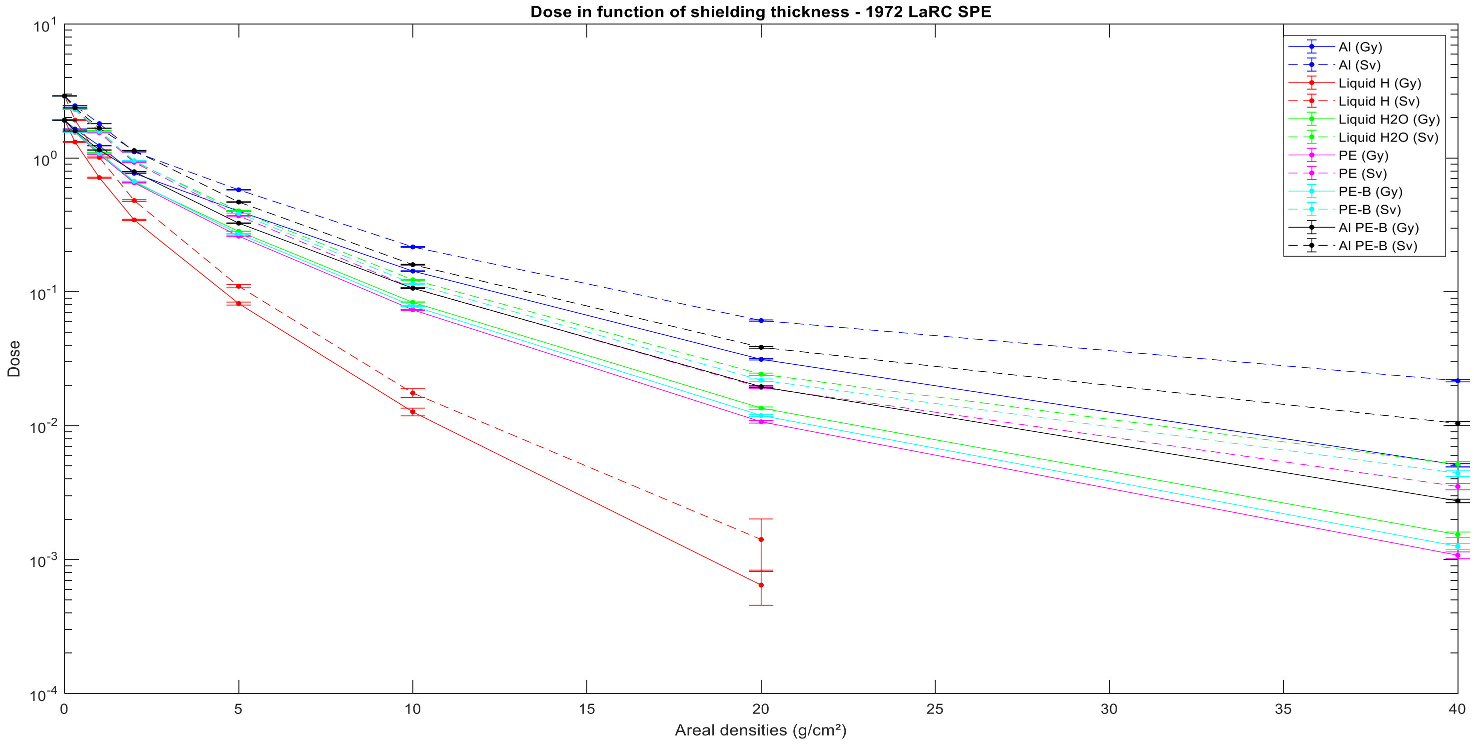
- GCR



Dose rate in function of shielding thickness - Solar Min 2010
Dose rate
Areal densities (g/cm²)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
1.5
0
5
10
15
20
25
30
35
40
Al (mGy/d)
Al (mSv/d)
Liquid H (mGy/d)
Liquid H (mSv/d)
Liquid H2O (mGy/d)
Liquid H2O (mSv/d)
PE (mGy/d)
PE (mSv/d)
PE-B (mGy/d)
PE-B (mSv/d)
Al PE-B (mGy/d)
Al PE-B (mSv/d)

Results

- SPE



Dose in function of shielding thickness - 1972 LaRC SPE
Dose
Areal densities (g/cm²)
10^1
10^0
10^-1
10^-2
10^-3
10^-4
0
5
10
15
20
25
30
35
40
Al (Gy)
Al (Sv)
Liquid H (Gy)
Liquid H (Sv)
Liquid H2O (Gy)
Liquid H2O (Sv)
PE (Gy)
PE (Sv)
PE-B (Gy)
PE-B (Sv)
Al PE-B (Gy)
Al PE-B (Sv)

Conclusions

- Main outcomes

1) Light materials → superior shielding characteristics (GCR & SPE)

2) Liquid H → best shielding efficiency (D & H)

3) Adding B to PE → overall counter effective (D & H)

4) SPEs → much easier to shield than GCR

5) Dose reduction → strongest for lower solar activities

6) Bounding shielding design → most intensive solar minimum

Future work

- Source terms
  - Use spectral data from other GCR models (e.g. BON2014 & SINP) & historical SPEs (e.g. 04/11/2003)
- Geometries & materials
  - Use mathematical (voxel) models of human body & novel shielding materials (e.g. CNT, BNNT)
- Simulations
  - Increase # source particles (decrease errors) and optimize VRT
  - Analyze dose contribution of primary/secondary particles & dose depth distributions in target

Thank you for your attention