15th Geant4 Space Users' Workshop
December 2023 - Pasadena, CA

Advancing Radiation Hazard Simulations in Spacecraft Environments With SPENVIS GEANT4 Tools

M. Laura Sorgi Johann
Research Advisor: Dr. Bereket Berhane
Embry–Riddle Aeronautical University
Daytona Beach, FL

Introduction

Polymer Matrix Composites Interest:

- Several combinations of polymer-based matrix + infills composites have been proposed.
- Composites allows orbit specific mass optimization by selecting the type and percentage of infills based on the radiation hazard.

Undermining Additional Structures:

- Such studies often overlook additional structures like external hulls, racks, and MMODs.
- These structures significantly alter the radiation nature that the shields are designed to counter.

Challenges in Modeling Complex Materials:

- Modeling complex, inhomogeneous materials, including polymer based composites and these additional structures, requires extremely simplified assumptions.

Material Stopping Power

- The rate of electronic energy loss of a heavy charged particle is proportional to the electron number density of the target material (~ρZ/A).
- Above critical energy, radiative energy loss for electrons dominate, so the efficiency of material stopping power scales with Z^2.
- Critical energy is inversely proportional Z.

$$-\left\langle \frac{dE}{dx} \right\rangle_e \propto \rho \frac{Z}{A}$$

e for electronic

$$-\left\langle \frac{dE}{dx} \right\rangle_r \propto \rho \frac{Z^2}{A}$$

r for radiative

Combined Effects in Mixtures

- The combined efficiency of materials is determined by the linear combination of their stopping powers (Bragg additivity) [Martin J. Berger, 1988].
  - Ion stopping power benefits on hydrogen content (high Z/A) and bond strength in material such as polymers.
  - Electron stopping power can be optimized by choosing infills prone to radiative loss processes (high Z).
  - Gamma mass attenuation can be optimized with high Z infills to be more photoelectric prone (~Z^5).

$$\left\langle \frac{dE}{dx} \right\rangle = \sum w_j \left\langle \frac{dE}{dx} \right\rangle_j$$

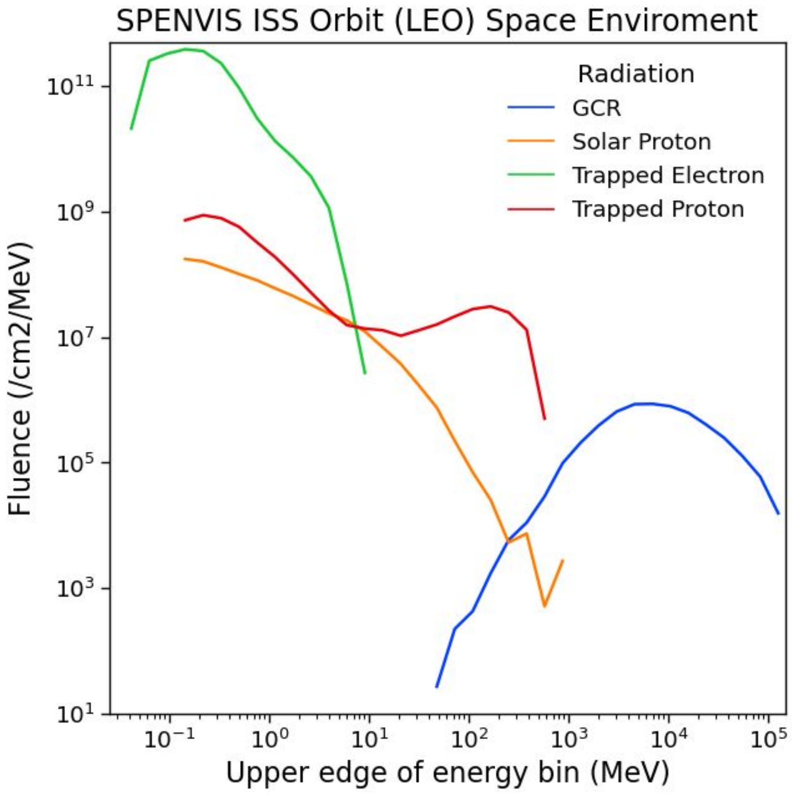
$$\sum w_j \frac{Z_j}{A_j} = \frac{\sum n_j Z_j}{\sum n_j A_j}$$

w_j is the fraction by weight of the j'th constituent

SPENVIS Definitions & Steps to Model Complex Structures

Space Environment in SPENVIS

- Environment definition is provided by SPENVIS in terms of Geant4 General Particle Source (GPS) format:
  - Trapped proton and electron fluence
  - Solar particle mission fluences
  - Galactic cosmic ray (GCR) fluence
- Based on defined mission orbit.



EMBRY-RIDDLE
Aeronautical University

Multi-Layered Shielding Simulation (MULASSIS)

- The integrated GEANT4 tool MULASSIS is used for modeling 1D materials.
- User defined material definition requires chemical composition and density.
- The geometry of materials are limited to homogeneous layers.

Adding new material	
Source:	User defined
Name(*):	
Chemical formula:	separated-by-hyphen (ex: H2-O)
Density [g cm^{-3}]:	
	Add

(*) should include only letters, digits or underscores and start with a letter

Layer number	Material	Thickness (unit)	
Layer 1	Al_6061_T6	2.0	mm
Layer 2	Beta_Cloth	0.2	mm
Layer 3	Dacron_Netting	3.6	mm
Layer 4	G4_KAPTON	2.5	mm
Layer 5	Nextel_312_Af62	8.2	mm
Layer 6	Kevlar29_Style710_Fabric	2.6	mm
Layer 7	Al_2219_T87	4.8	mm

Challenges of Inhomogeneous Materials

- Combining chemical formulas requires dubious assumptions about the material density and dispersion.
- Density variations can render the density correction factor in the Bethe's equation inaccurate, especially for stopping powers dominated by electronic loss, challenging the reliability of Bragg's rule [Martin J. Berger, 1988].

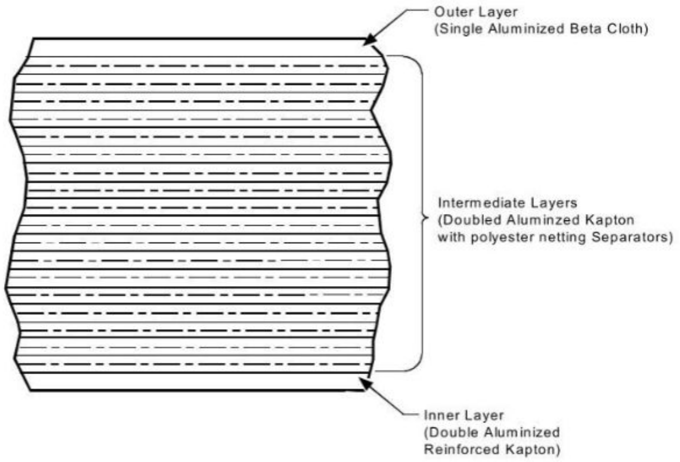
	COLLISION STOPPING POWER ($MeV\text{-}cm^2/g$)		Percent Difference
	Density 1.7 g/cm^3	Density 2.265 g/cm^3	
0.1	3.674	3.671	-0.1
1	1.617	1.609	-0.5
10	1.745	1.730	-0.9
100	1.950	1.928	-1.1

Figure: Density-effect correction and electronic stopping power in graphite of different densities. Adapted from M. J. Berger, 1988.

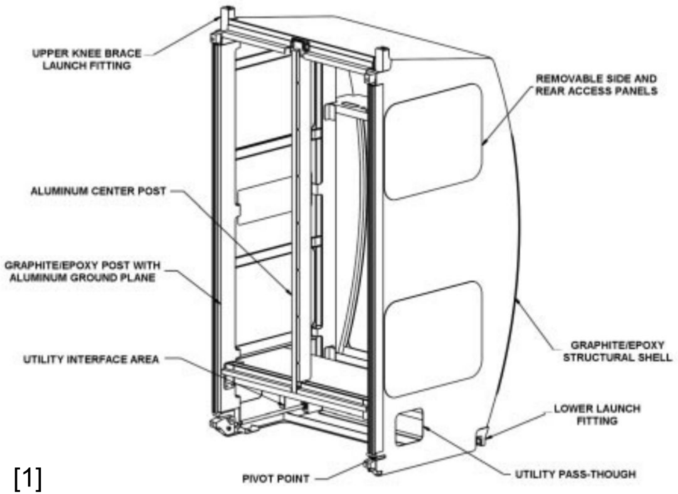
Martin J. Berger. (1988). Monte Carlo Transport of Electrons and Photons. In Ettore Majorana International Science Series (Vol. 38).

Significant External Structures

Multi-Layer Insulation (MLI)

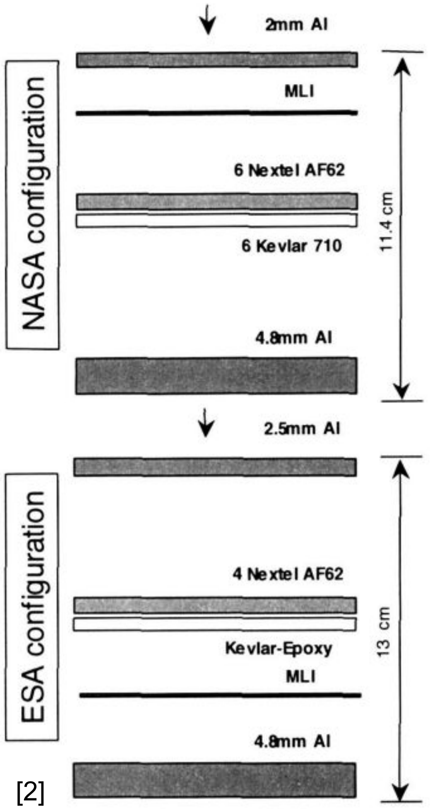


International Standard Payload Racks (ISPRs)



[1]

Micrometeoroids and Orbital Debris shield (MMOD)



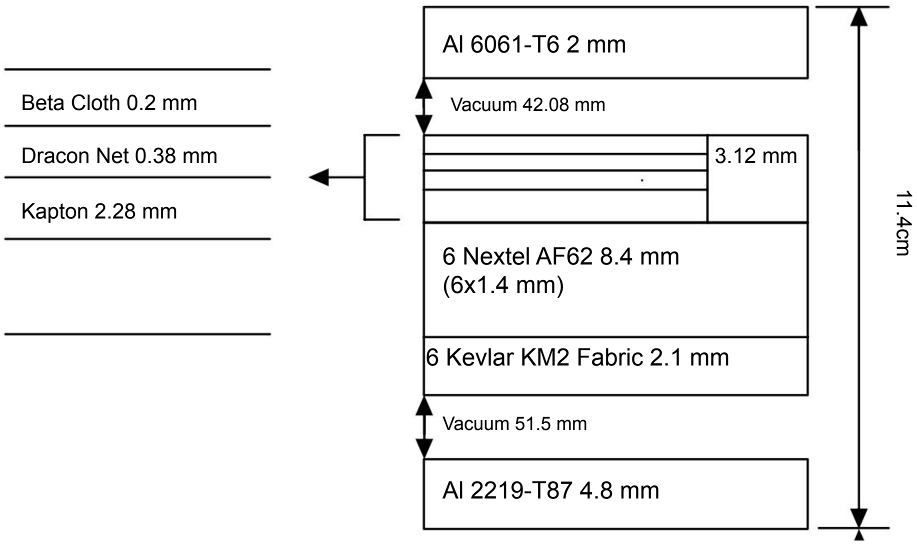
[2]

[1] Copeland, David S., International Space Station Pressurized Payload Accommodation Handbook. March 16, 1999.
[2] Christiansen, E .L. et al., Space Station MMOD Shielding, IAC-06-B6.3.05, 57th International Astronautical Congress, 2006.

EMBRY-RIDDLE
Aeronautical University

Modeling & Benchmarking Effects of External Structures (ISS)

Modeling External Structures: MMOD & MLI



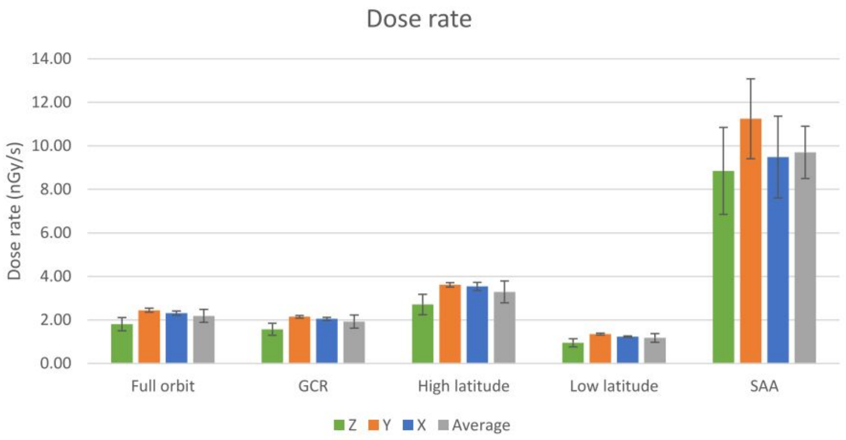
Geometry: User defined

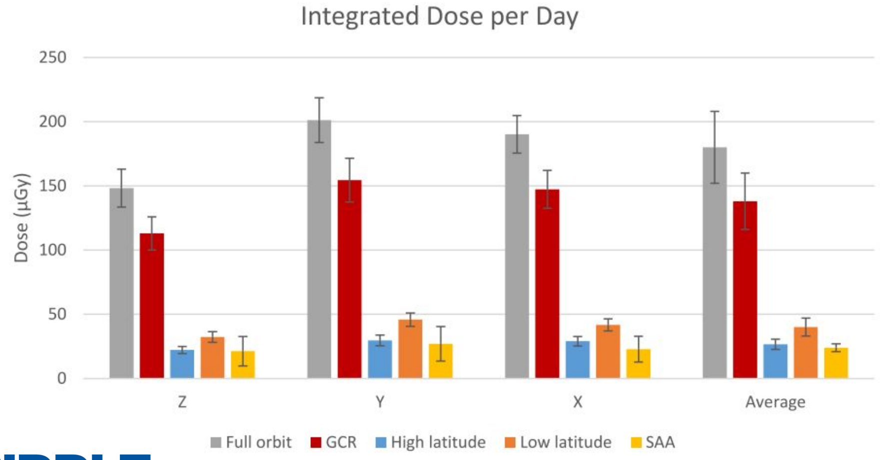
Shape: planar slab — Number of layers: 8

Layer number	Material	Thickness (unit)	Visualisation colour
Layer 1	Al_6061_T6	2.0 mm	grey
Layer 2	Beta_Cloth	0.2 mm	red
Layer 3	Dacron_Netting	3.6 mm	red
Layer 4	G4_KAPTON	2.5 mm	red
Layer 5	Nextel_312_Af62	8.2 mm	blue
Layer 6	Kevlar29_Style710_Fabric	2.6 mm	blue
Layer 7	Al_2219_T87	4.8 mm	dark grey
Layer 8	G4_Si	3.04 mm	white

ISS Dose Survey

- 2020 ISS Columbus module dose assessment [L. Di Fino, 2023]:
  - Average directional daily up to 180 microGy(Si) (540 microGy(Si) for omnidirectional).
  - Peak dose rate of 30 nGy(Si)/s during the South Atlantic Anomaly (SAA) segment.



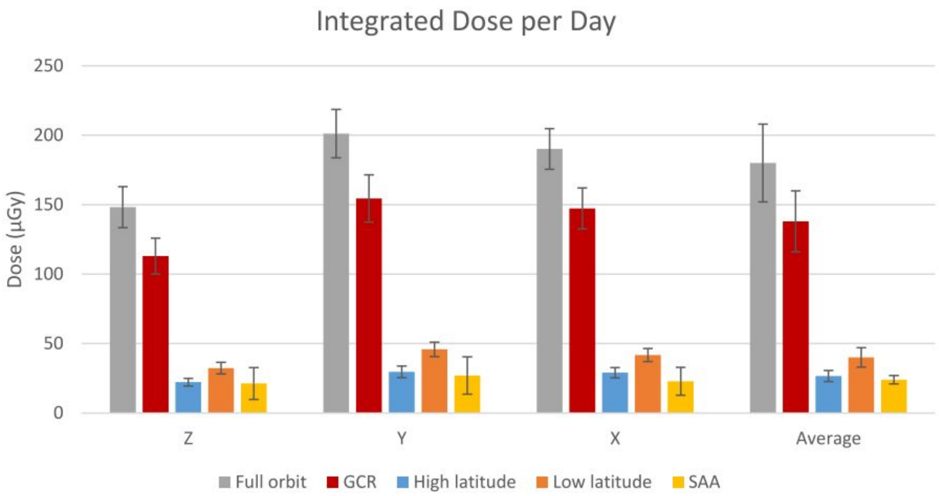


Di Fino, L., et al., Radiation measurements in the International Space Station, Columbus module, in 2020–2022 with the LIDAL detector, Life Sciences in Space Research, 2023.

EMBRY-RIDDLE Aeronautical University

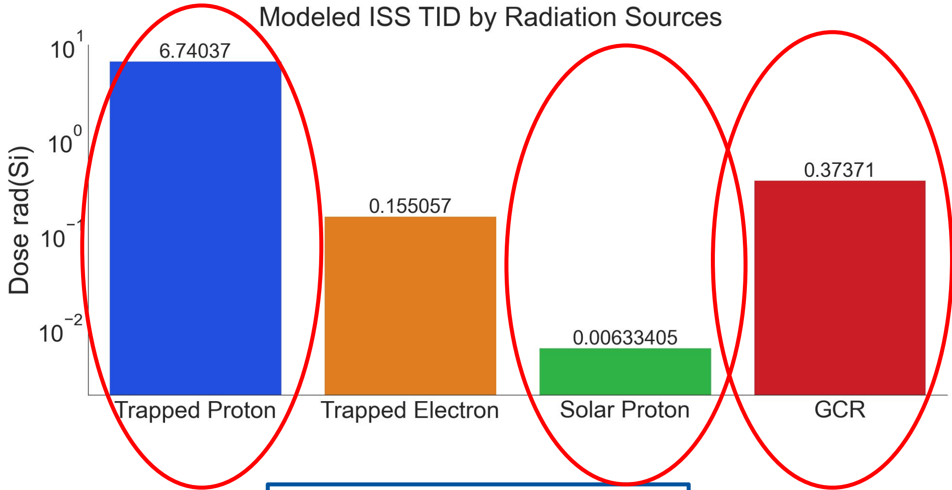
Benchmarking Simulated ISS

Surveyed



0.018 rad(Si)/day = 6.57 rad(Si)/year

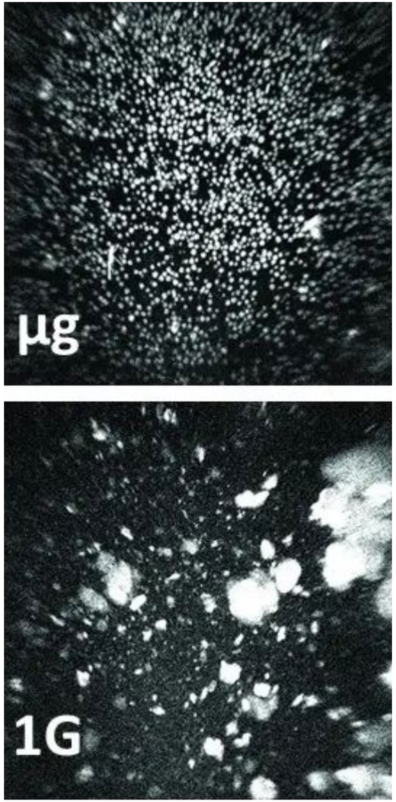
Modeled



7.12 rad(Si)/year

Shielding Efficiency & Dose

- Total energy deposited overlooks critical factors that define the efficiency of shields for multiple purposes.
- Addressing fluence of secondary radiation broadens shield study applicability:
  - Can still shed light on relative biological effectiveness.
  - Benefit the growing interest of in-space production (pharmaceutical, semiconductor, optical manufacturing).

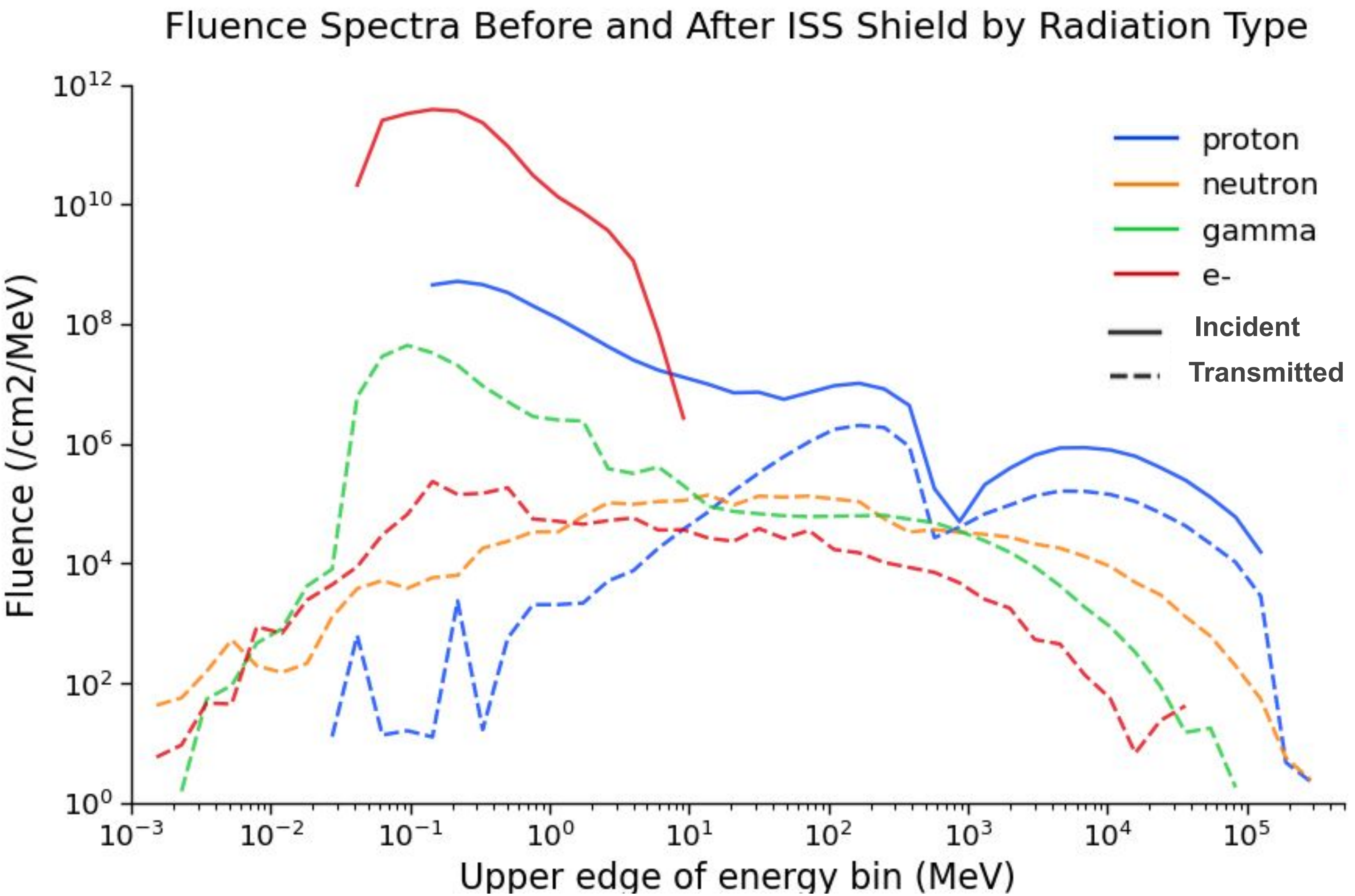


Space Production Applications (InSPA) NASA.gov

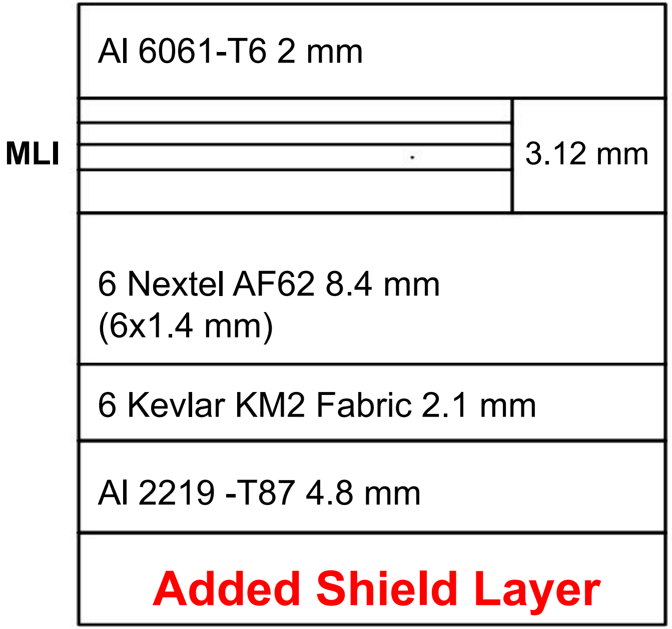
Fluence Assessment for ISS Shields

- Thus, for an all encompassing study, we urge for the use of fluence ϕ(E) (/cm2/MeV).
- In this work:
  - Comparing incident vs transmitted fluence (**𝜹**ϕ(E)) for popular proposed materials to emphasize efficiency declination when existing structures considerations are overlooked.
  - Fluence absorbed fraction (Incident vs transmitted for radiation type over total incident fluence): $(\delta\phi/\phi_i)_{radiation} = (\phi_t - \phi_i)_{radiation} / \sum \phi_i$

EMBRY-RIDDLE
Aeronautical University


Fluence Spectra Before and After ISS Shield by Radiation Type
Fluence (/cm2/MeV)
10^{12}
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
10^{0}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
Upper edge of energy bin (MeV)
proton
neutron
gamma
e-
Incident
Transmitted

Materials Explored

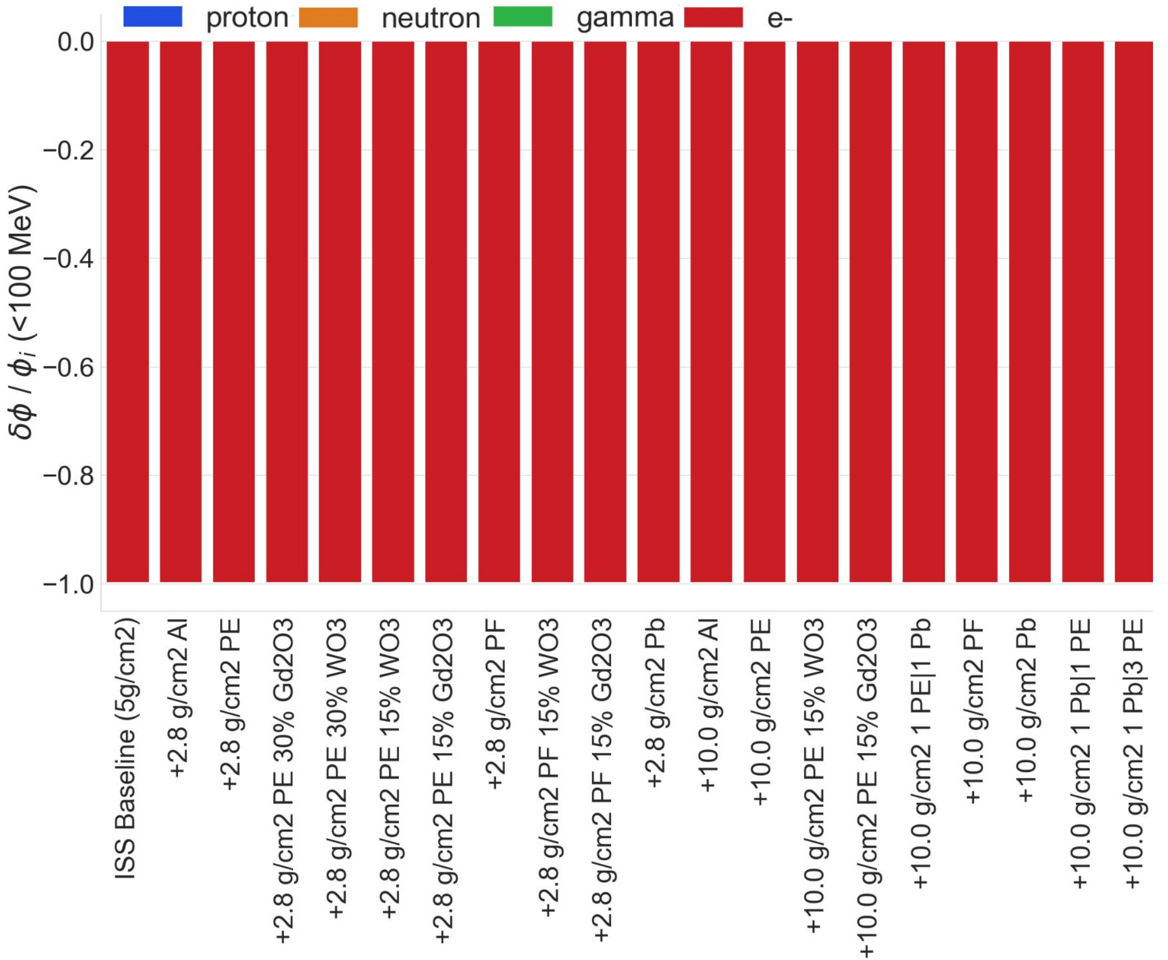


Wt% = particle infil weight percent

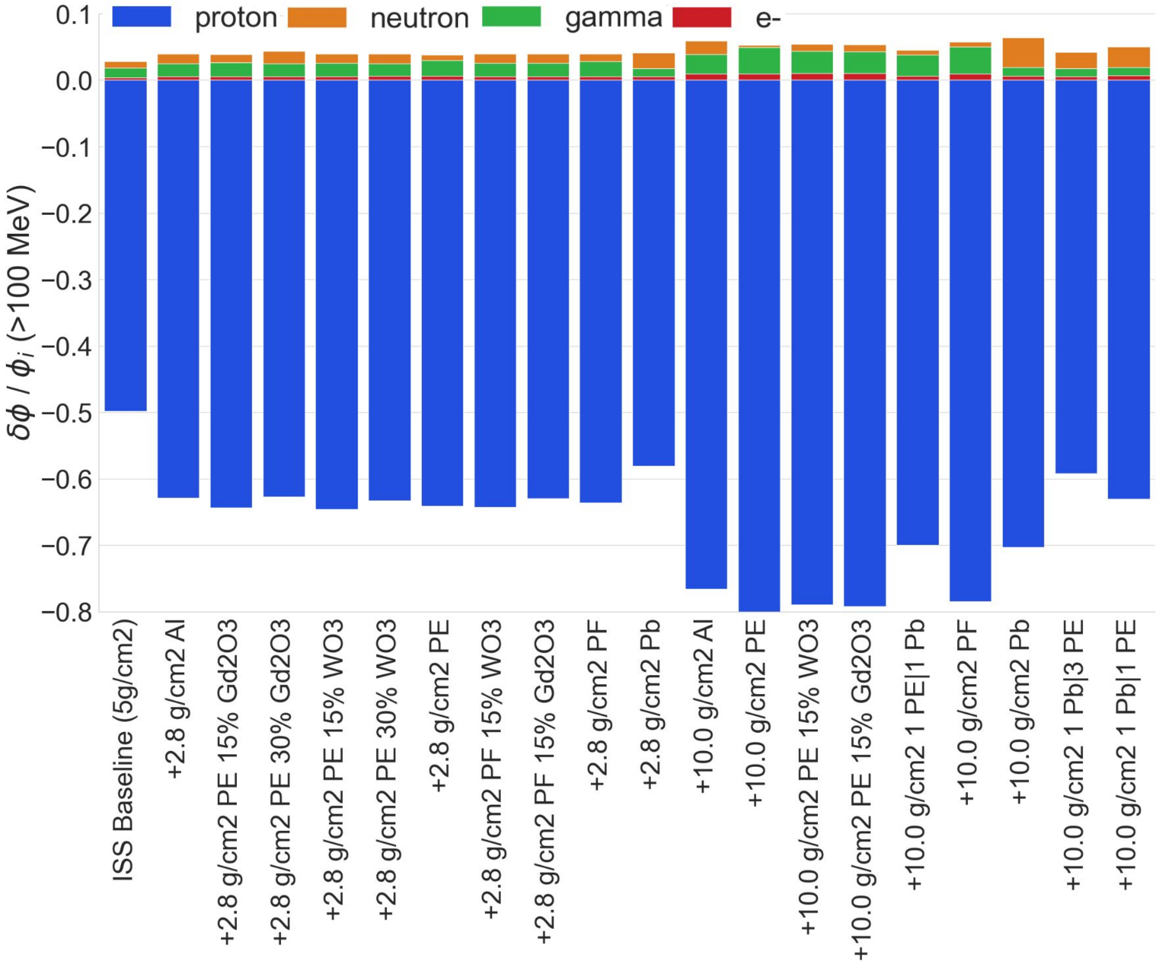
Separated by “ | ” = Layered

Added Areal Density (g/cm2)	Material	Infill Wt% or Layer Ratio	Added Thickness (mm)
-	ISS	N/A	-
2.84	Al	N/A	10.0
	Pb	N/A	2.5
	PE	N/A	30.2
		30% WO3	10.1
		30% Gd2O3	9.9
		15% WO3	15.2
		15% Gd2O3	14.9
	PF	N/A	25.8
		15% WO3	14.1
		15% Gd2O3	13.9
10.00	Al	N/A	35.2
	Pb	N/A	8.8
	PE	N/A	106.4
		15% WO3	53.4
		15% Gd2O3	52.4
	PF	N/A	90.9
	Pb|PE	1:1	57.6
		1:3	77.1
	PE|Pb	1:1	57.6

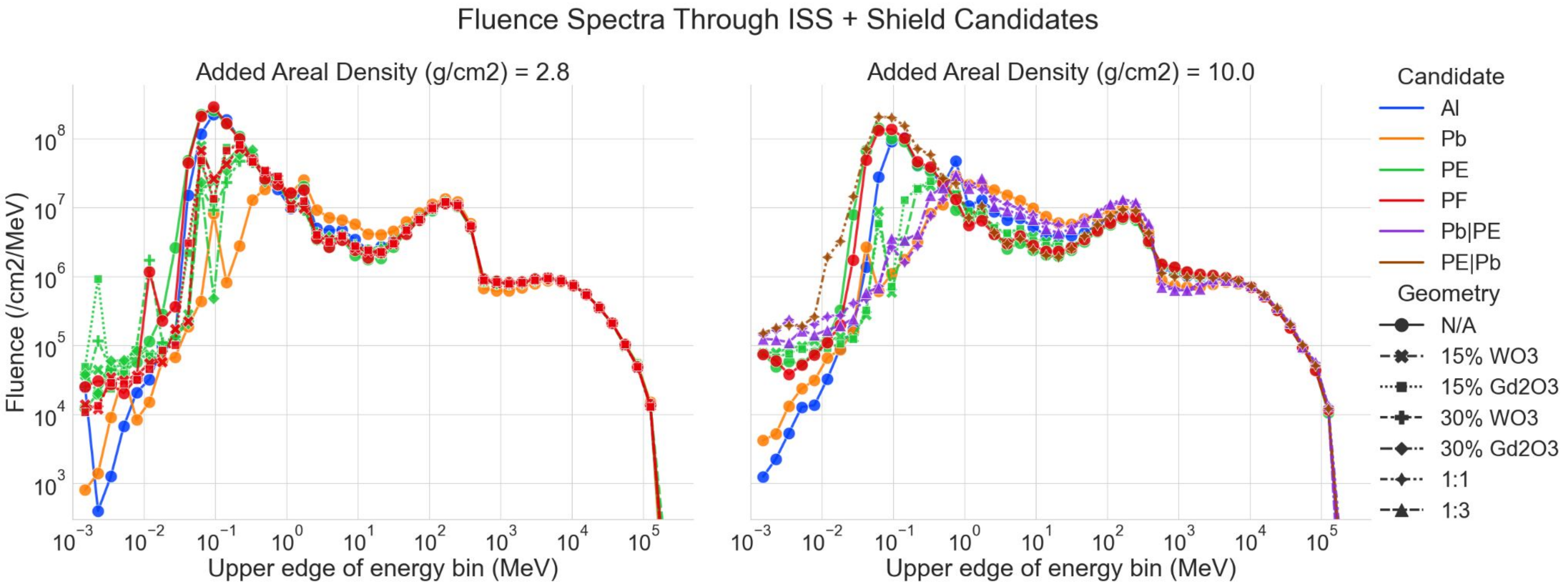
- No additional shielding for low-energy (<100 MeV) protons beyond the ISS baseline demonstrated enhancements.
- Equal improvement in low-energy electron shielding observed across all candidates.
- Low-energy secondary product fraction minimal across.

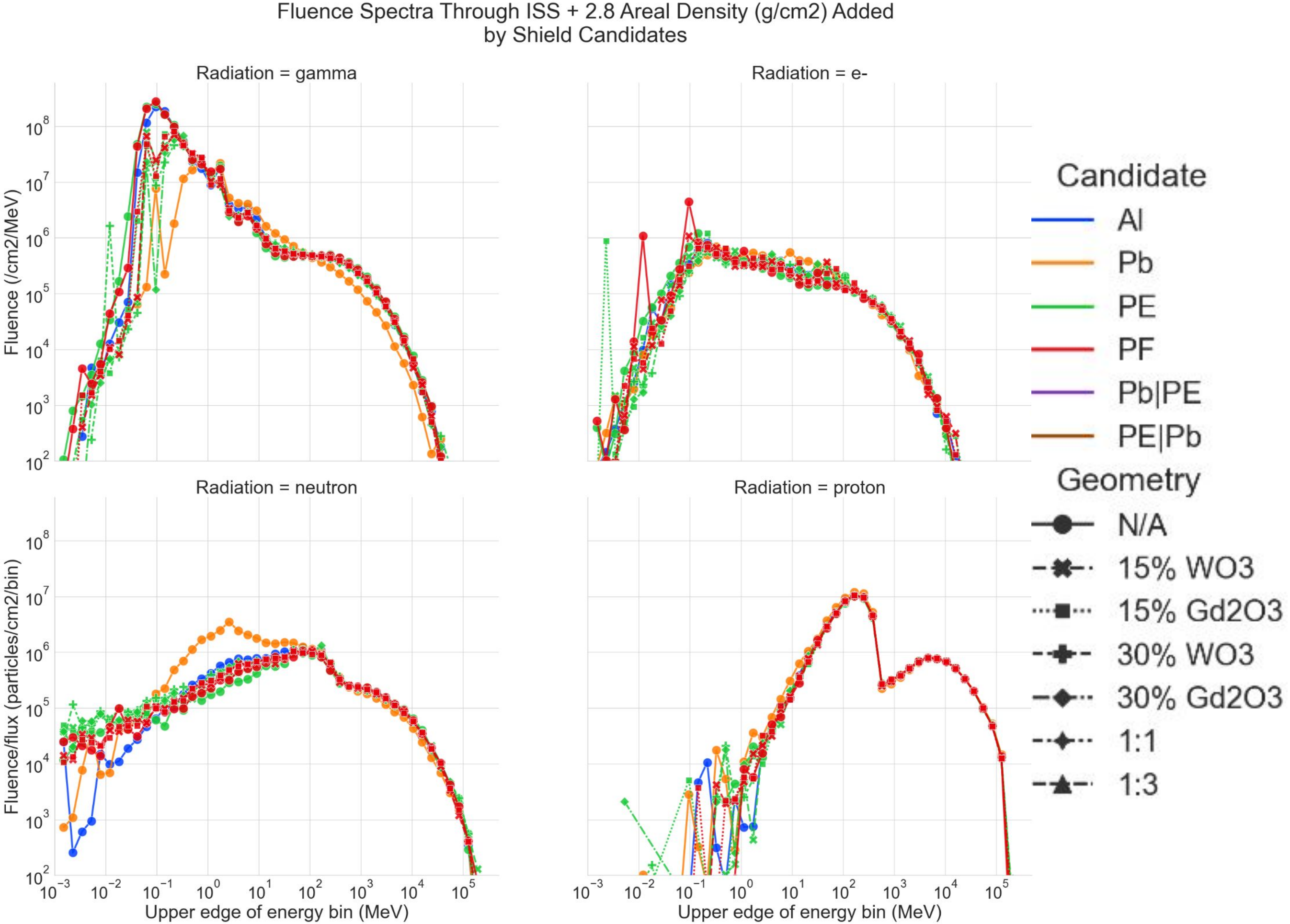


- Improvements for high-energy (>100 MeV) proton shielding could include as little as 2.8 g/cm^2 of added areal density.
- Increased areal density and/or atomic number (Z) in materials lead to higher production of secondary neutrons and gamma particles.

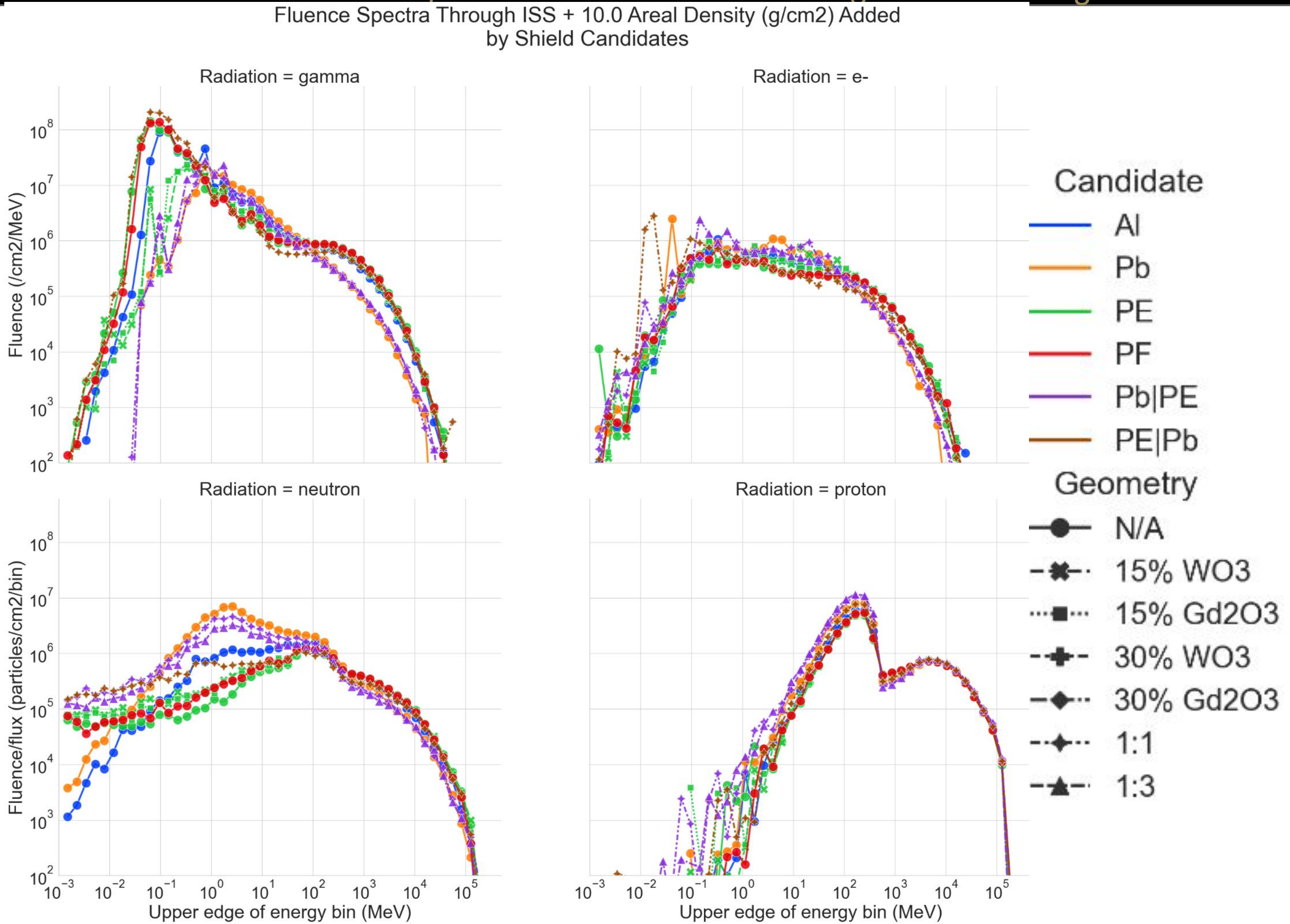


EMBRY-RIDDLE Aeronautical University


Fluence Spectra Through ISS + Shield Candidates
Added Areal Density (g/cm2) = 2.8
Added Areal Density (g/cm2) = 10.0
Fluence (/cm2/MeV)
Upper edge of energy bin (MeV)
Upper edge of energy bin (MeV)
Candidate
Al
Pb
PE
PF
Pb|PE
PE|Pb
Geometry
N/A
15% WO3
15% Gd2O3
30% WO3
30% Gd2O3
1:1
1:3



EMBRY-RIDDLE
Aeronautical University



EMBRY-RIDDLE
Aeronautical University

Thank you!

M. Laura Sorgi Johann (Laura Johann):
sorgijom@my.ERAU.edu

Berhane Bereket: bereket.berhane@ERAU.edu

EMBRY-RIDDLE
Aeronautical University