Radiation Shielding for Lunar Missions: Regolith Considerations

Tony C. Slaba
NASA Langley Research Center, Hampton, VA, USA

LSIC Crosstalk
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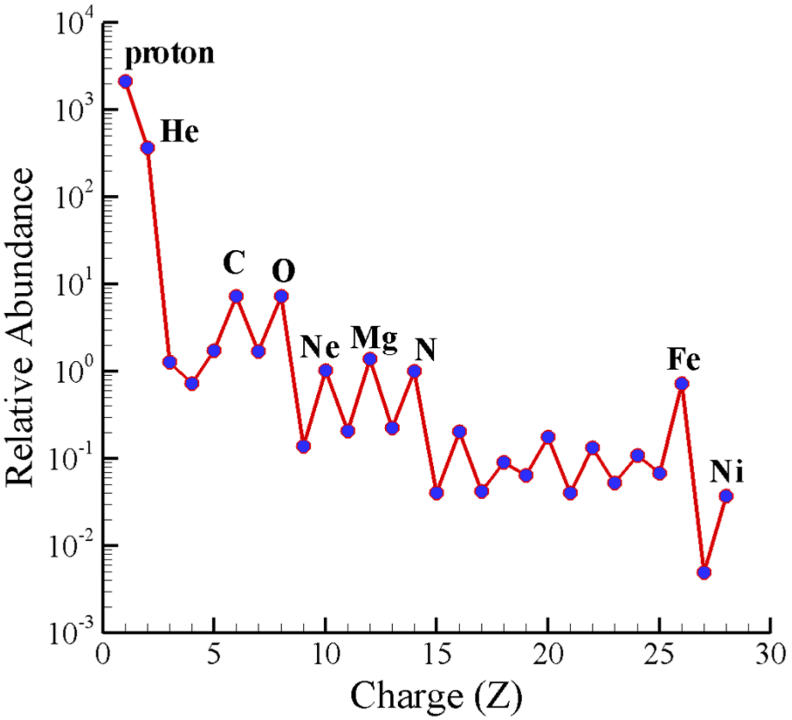
Outline

- Galactic cosmic rays (GCR)
- Mission exposure and risk projections
- Lunar radiation environment
- Shielding
- On-Line Tool for the Assessment of Radiation in Space (OLTARIS)
- Summary

Galactic Cosmic Rays

- GCR include a complex mixture of particles
  - ***VERY*** different than radiation on Earth
  - Includes all ions on the periodic table
  - Continuous low dose-rate exposure in space

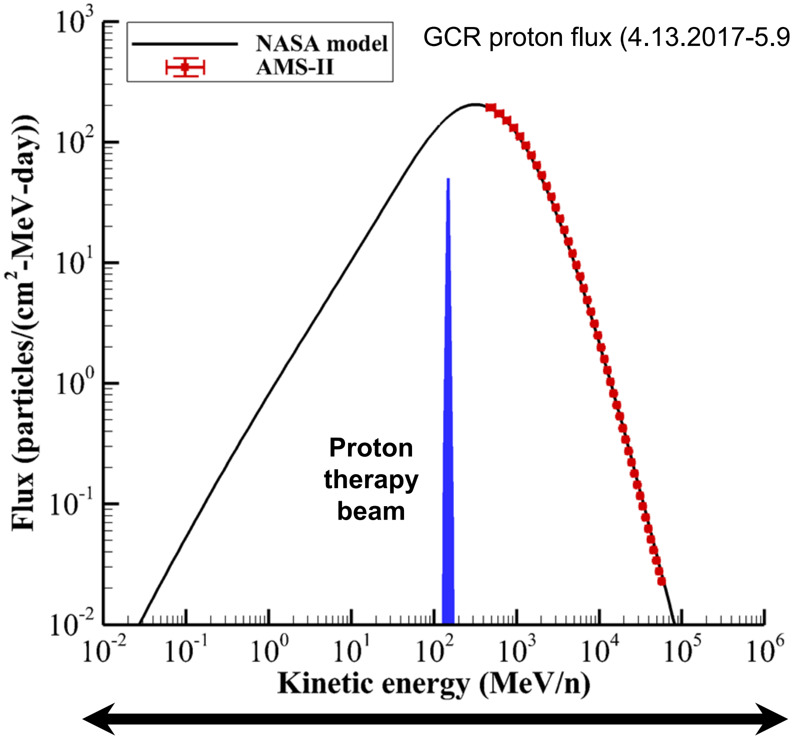


Relative abundance of elements in the 1977 solar minimum GCR environment, normalized to Ne

Galactic Cosmic Rays

- GCR include a broad distribution of particle energies
  - Accelerators and medical applications typically use a single energy (e.g. 150 MeV proton therapy)
  - GCR velocities approach the speed of light
  - Able to penetrate shielding and human tissue
  - Difficult to shield with current technologies
  - **Nuclear interactions with lunar surface give rise to albedo radiation**

GCR proton flux (4.13.2017-5.9.2017)

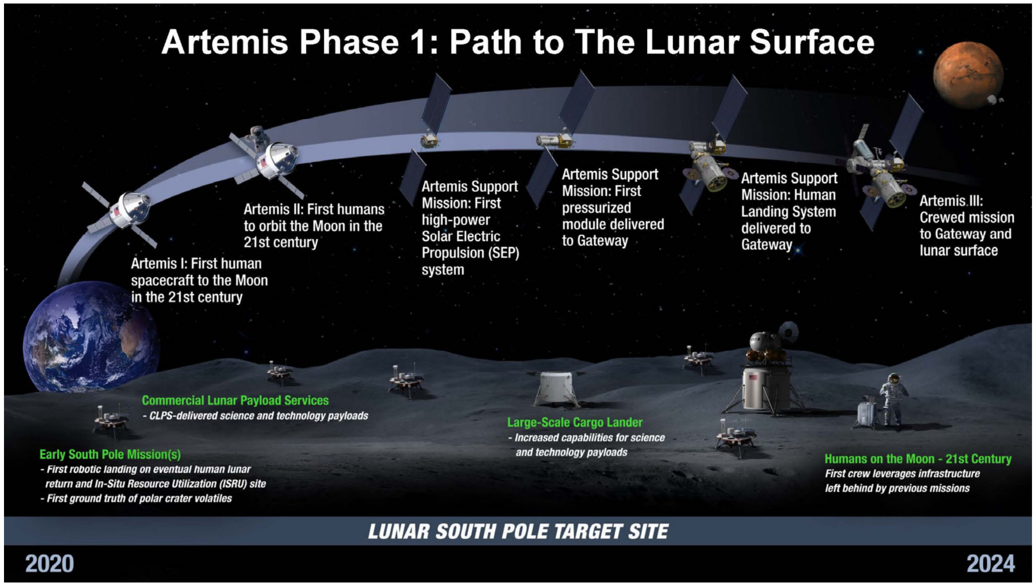


keV/n ↔ x10^3 ↔ MeV/n ↔ x10^3 ↔ GeV/n ↔ x10^3 ↔ TeV/n

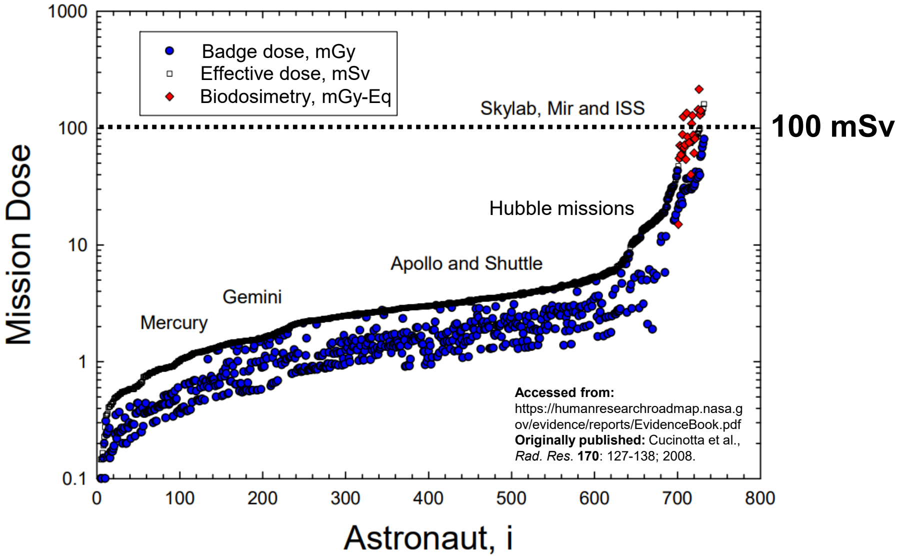
keV/n	MeV/n	GeV/n	TeV/n
Stopped by thinnest shielding (skin)	Able to penetrate some tissue sites	Able to penetrate spacecraft shielding and tissue	Able to penetrate through Earth atmosphere

Projections for Deep Space Missions

https://www.nasa.gov/sites/default/files/atoms/files/america_to_the_moon_2024_artemis_20190523.pdf



Summary of astronaut mission exposures prior to 2008.



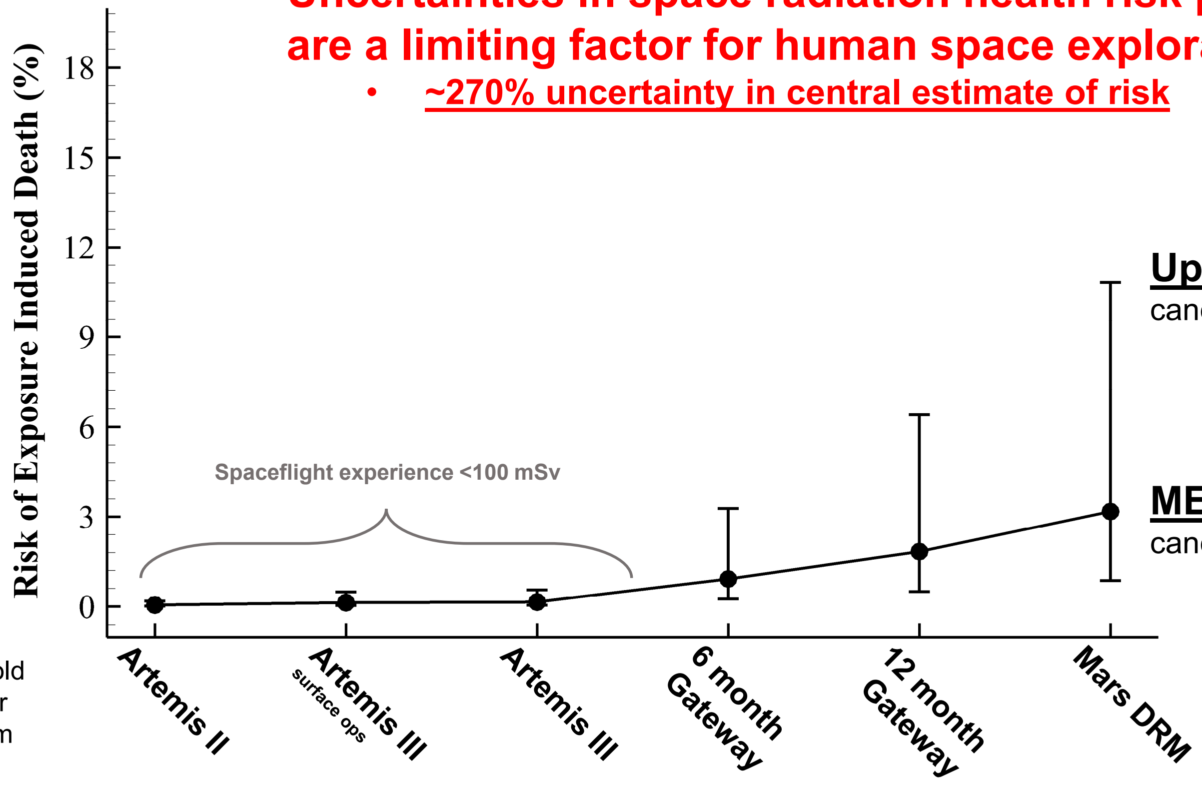
Accessed from: https://humanresearchroadmap.nasa.gov/evidence/reports/EvidenceBook.pdf
Originally published: Cucinotta et al., *Rad. Res.* **170**: 127-138; 2008.

	Artemis II	Artemis III surface ops	Artemis III	6 months Gateway	12 months Gateway	Mars DRM
Duration (days)	10	23.5 + 6.5 surface	30	183	365	621 + 40 surface
Effective dose (mSv)	**10**	**27**	**30**	**182**	**364**	**640**

Projections for Deep Space Missions

Uncertainties in space radiation health risk projections are a limiting factor for human space exploration

- **~270% uncertainty in central estimate of risk**



Upper 95% CL risk from NASA cancer risk model

MEDIAN risk from NASA cancer risk model

Results for 35 year old female never smoker during solar minimum

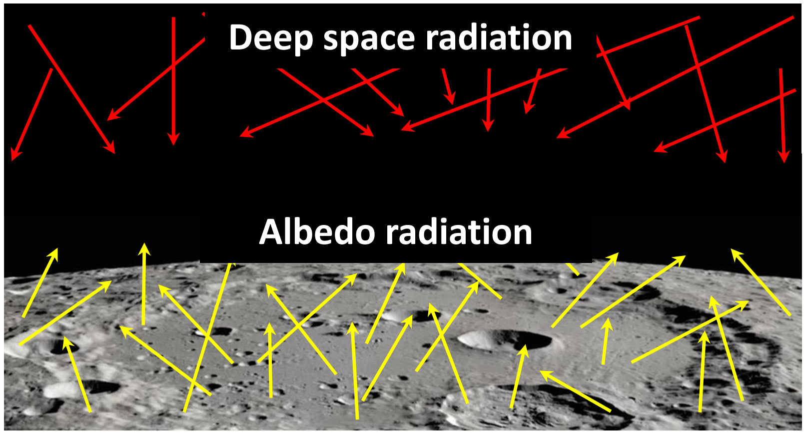
Effevtive dose (mSv)	**10**	**27**	**30**	**182**	**364**	**640**

Lunar Surface Radiation Environment

- Two primary deep space radiation environments
  - **Galactic cosmic rays (GCR): continuous, omnipresent spectrum of highly energetic ions**
  - *Solar particle events (SPE): sporadic and intense bursts of medium energy protons from the sun*
    - *For majority of SPE, lunar albedo environment is small (often ignored in exposure calculations)*

- These environments interact with lunar regolith, yielding albedo radiation
  - Lunar albedo environment is complex
  - Neutrons are the primary health concern

- The lunar surface radiation environment has two main components
  - Ambient deep space radiation → downward directed
  - Induced (albedo) environment → upward directed



Original image: https://moon.nasa.gov/news/155/theres-water-on-the-moon/

Characterization

- **Virtually no direct measurements of lunar surface environment**
  - Neutron spectrum has never been measured over the full range of relevant energies (1)
  - Limited surface dose measurements

- **Knowledge of lunar environment comes mainly from model predictions** (2-4)
  - Validation with ground-based accelerator data and available space flight data
  - Validation with Mars surface measurements
  - Verification through extensive model comparisons

- **Various reports for lunar shielding strategies, shield optimization, and trade studies**
  - Selected publications:
    - Wilson, J.W., et al., Shielding strategies for human exploration, NASA CP 3360; 1997.
    - NASA, NASA's exploration systems architecture study, NASA TM 2005-214062; 2005.
    - Slaba et al., Variation in lunar neutron dose estimates, *Rad. Res.* **176**: 827-841; 2011. (*and references therein*)

(1) Valinia et al. Safe human expeditions beyond low Earth orbit (LEO). NASA TM 20220002905, NESC RP 20-01589; 2022.
(2) Wilson et al., Verification and validation: high charge and energy (HZE) transport codes and future development. NASA TP 2005-213784; 2005.
(3) Hassler et al., Mars science laboratory radiation assessment detector (MSL/RAD) modeling workshop proceedings. *Life Sci. Space Res.* special issue; 2017.
(4) Norbury et al., Advances in space radiation physics and transport at NASA. *Life Sci. Space Res.* **22**: 98-124; 2019.

Regolith Composition Effects

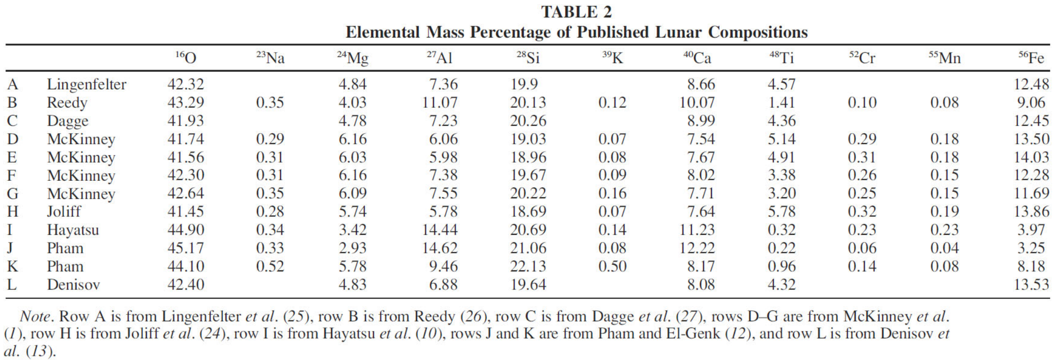
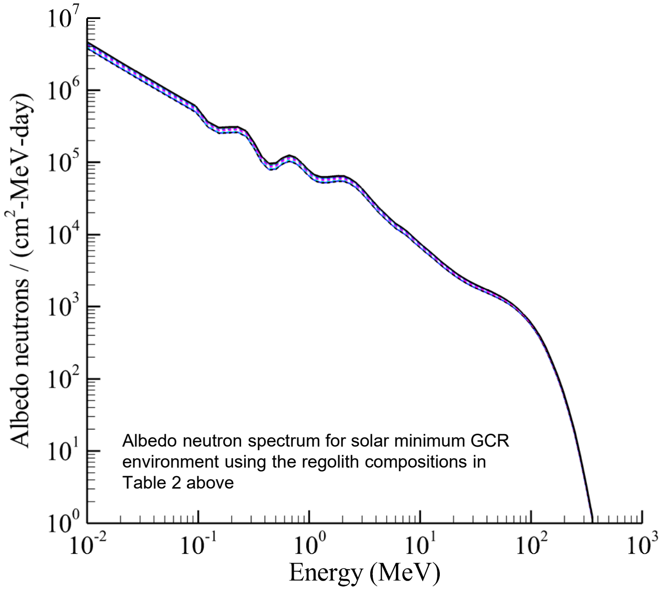


TABLE 2
Elemental Mass Percentage of Published Lunar Compositions

		^{16}O	^{23}Na	^{24}Mg	^{27}Al	^{28}Si	^{39}K	^{40}Ca	^{48}Ti	^{52}Cr	^{55}Mn	^{56}Fe
A	Lingenfelter	42.32		4.84	7.36	19.9		8.66	4.57			12.48
B	Reedy	43.29	0.35	4.03	11.07	20.13	0.12	10.07	1.41	0.10	0.08	9.06
C	Dagge	41.93		4.78	7.23	20.26		8.99	4.36			12.45
D	McKinney	41.74	0.29	6.16	6.06	19.03	0.07	7.54	5.14	0.29	0.18	13.50
E	McKinney	41.56	0.31	6.03	5.98	18.96	0.08	7.67	4.91	0.31	0.18	14.03
F	McKinney	42.30	0.31	6.16	7.38	19.67	0.09	8.02	3.38	0.26	0.15	12.28
G	McKinney	42.64	0.35	6.09	7.55	20.22	0.16	7.71	3.20	0.25	0.15	11.69
H	Joliff	41.45	0.28	5.74	5.78	18.69	0.07	7.64	5.78	0.32	0.19	13.86
I	Hayatsu	44.90	0.34	3.42	14.44	20.69	0.14	11.23	0.32	0.23	0.23	3.97
J	Pham	45.17	0.33	2.93	14.62	21.06	0.08	12.22	0.22	0.06	0.04	3.25
K	Pham	44.10	0.52	5.78	9.46	22.13	0.50	8.17	0.96	0.14	0.08	8.18
L	Denisov	42.40		4.83	6.88	19.64		8.08	4.32			13.53

Note. Row A is from Lingenfelter *et al*. (*25*), row B is from Reedy (*26*), row C is from Dagge *et al*. (*27*), rows D–G are from McKinney *et al*. (*1*), row H is from Joliff *et al*. (*24*), row I is from Hayatsu *et al*. (*10*), rows J and K are from Pham and El-Genk (*12*), and row L is from Denisov *et al*. (*13*).



Albedo neutron spectrum for solar minimum GCR environment using the regolith compositions in Table 2 above

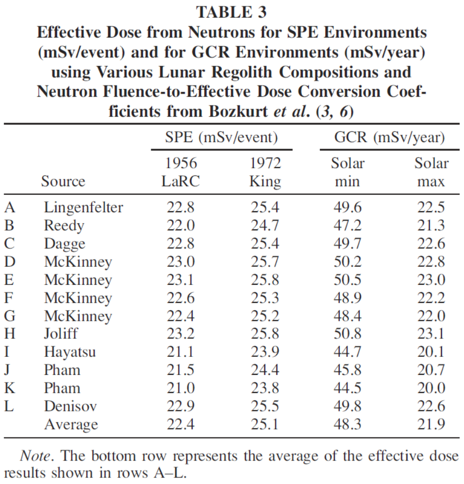


TABLE 3
Effective Dose from Neutrons for SPE Environments (mSv/event) and for GCR Environments (mSv/year) using Various Lunar Regolith Compositions and Neutron Fluence-to-Effective Dose Conversion Coefficients from Bozkurt *et al*. (*3, 6*)

		SPE (mSv/event)		GCR (mSv/year)	
	Source	1956 LaRC	1972 King	Solar min	Solar max
A	Lingenfelter	22.8	25.4	49.6	22.5
B	Reedy	22.0	24.7	47.2	21.3
C	Dagge	22.8	25.4	49.7	22.6
D	McKinney	23.0	25.7	50.2	22.8
E	McKinney	23.1	25.8	50.5	23.0
F	McKinney	22.6	25.3	48.9	22.2
G	McKinney	22.4	25.2	48.4	22.0
H	Joliff	23.2	25.8	50.8	23.1
I	Hayatsu	21.1	23.9	44.7	20.1
J	Pham	21.5	24.4	45.8	20.7
K	Pham	21.0	23.8	44.5	20.0
L	Denisov	22.9	25.5	49.8	22.6
	Average	22.4	25.1	48.3	21.9

Note. The bottom row represents the average of the effective dose results shown in rows A–L.

- **Regolith composition has minimal impact on albedo environment**
  - <10% on neutron albedo exposure (unshielded)
  - ~2% on total exposure (unshielded)
- **Water content in lunar regolith *could* moderately influence albedo environment**
  - More water → bigger impact
  - Note that hydrogen content attenuates mainly lower energy neutrons that make smaller contributions to health risks
  - Albedo environment is a small fraction of the total exposure on the surface

Tables and plot data from: Slaba et al., *Rad. Res.* **176**: 827-841; 2011.

Shielding Comparisons

- Water equivalent thickness or meters-of-water-equivalent
  - Common concepts in terrestrial radiation protection
  - Not often used in space radiation protection

- Shield comparisons are performed on the basis of areal density units (g/cm^2)
  - Areal density (g/cm^2) = Shield length (cm) × material density (g/cm^3)

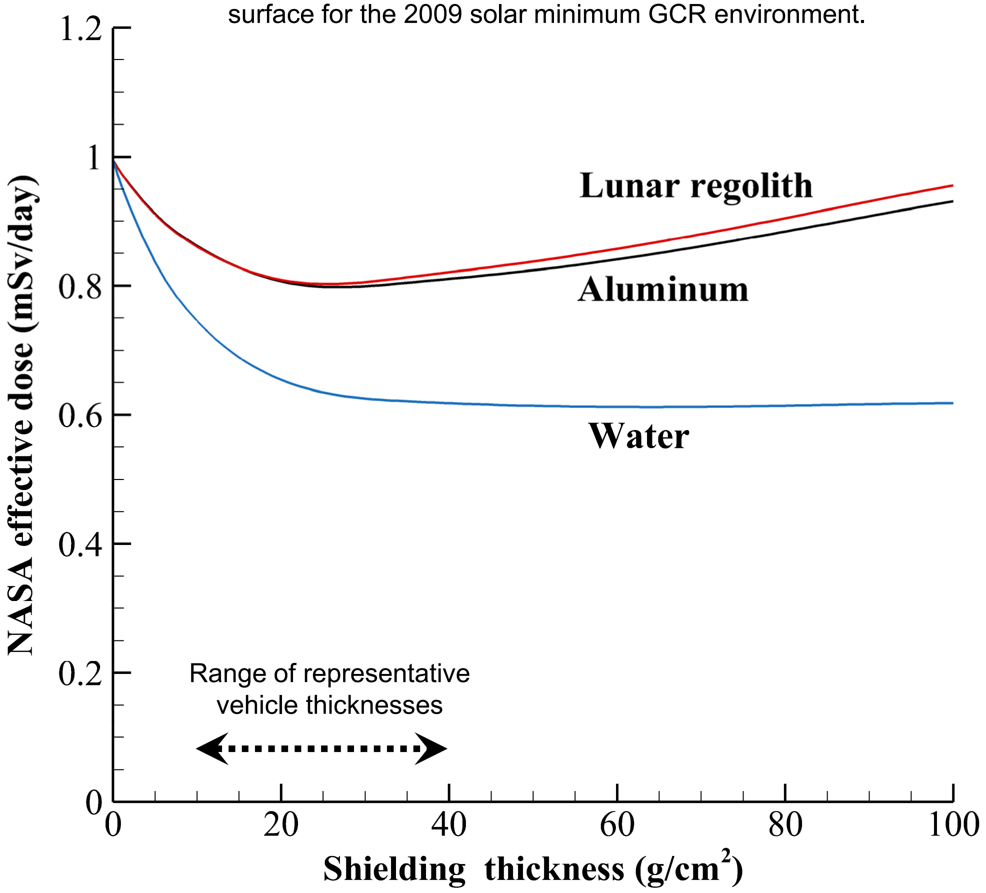
- Density effects have minimal impact on shielding efficiency for space radiation
  - Lunar regolith ($\rho = 1.6\ g/cm^3$)
  - Lunar regolith ($\rho = 3.2\ g/cm^3$)

  } **Same shielding effectiveness at equal g/cm^2**

- NASA radiation standards are not written in terms of shield thickness requirements
  - Universal 600 mSv career limit for all astronauts
  - Exposure limits short and long terms deterministic effects (i.e. non-cancer)
  - Exposure limits set to protect against acute effects from possible solar storms
  - Developing guidance for GCR protection based on exposure levels

  } **See NASA Standard 3001**

Shielding Comparisons

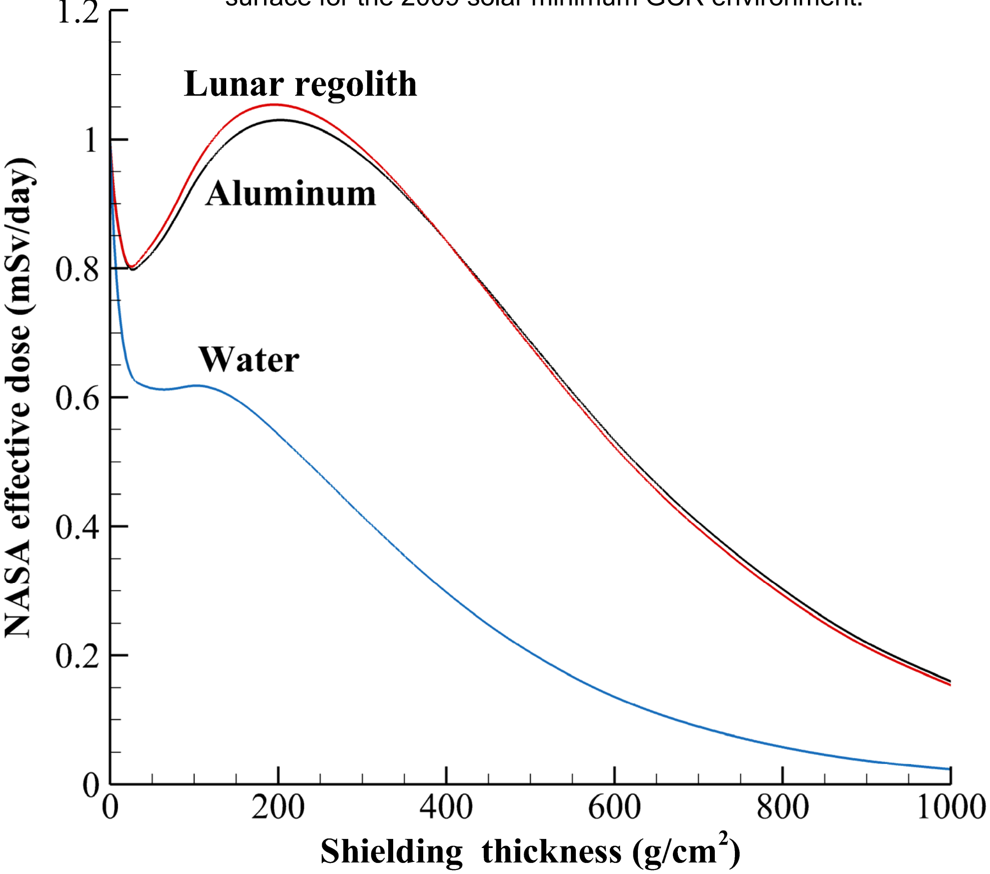


- Lunar regolith performs similar to aluminum shielding
  - Lunar regolith is mainly O, Si, Al, Fe
  - Atomic constituents have similar masses

- Water is a more efficient shield material
  - Hydrogen content limits secondary particle production and attenuates neutrons
  - Polyethylene behaves similar to water

Plot data generated from the OLTARIS website: https://oltaris.nasa.gov

Shielding Comparisons



Effective dose versus shielding thickness on the lunar surface for the 2009 solar minimum GCR environment.

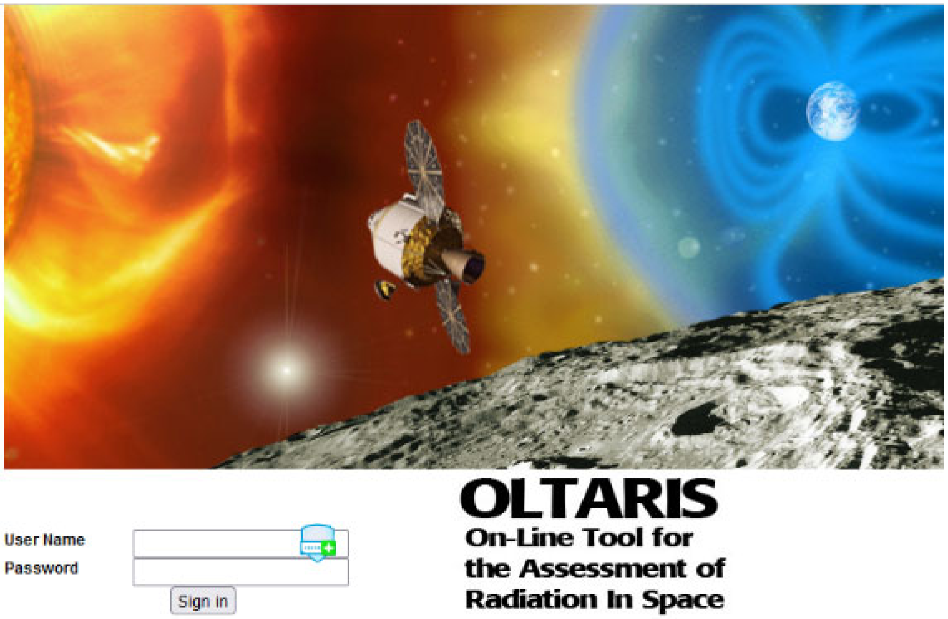
Earth atmosphere thickness

- Beyond ~200 g/cm^2 of shielding, the exposure is dominated by nucleons, pions, muons, and electromagnetic components
  - Same maximum occurs in Earth’s atmosphere
  - Regener-Pfotzer maximum
- At 1000 g/cm^2, the exposure is still higher than “Earth-like” levels

Plot data generated from the OLTARIS website: https://oltaris.nasa.gov

OLTARIS

https://oltaris.nasa.gov



OLTARIS
On-Line Tool for the Assessment of Radiation In Space

- Web-based tool for assessing space radiation exposure and risk
- Based on state-of-the-art NASA models
- Analysis capabilities include:
  - Mission scenarios
    - low Earth orbit
    - deep space (~ 1 AU)
    - ***lunar surface***
    - Mars surface
  - Response functions
    - Absorbed dose in materials
    - Dose equivalent
    - ICRP and ***NASA effective dose***
    - Risk of exposure induced cancer/death
    - Spectral quantities (flux as function of energy or LET)
  - Geometry
    - Slabs
    - Spheres
    - User-defined geometry (ray-trace)
    - Male and female human phantoms

Summary

- Radiation exposure is a significant challenge for human exploration of space
  - Large uncertainties in projecting short- and long-term health risks

- Passive shielding strategies continue to be investigated (good!)
  - High hydrogen content improves shield efficiency
  - Space radiation shielding efficiency for materials is generally well known (high TRL)

- Shield requirements are derived from allowable exposures set forth in NASA Std. 3001
  - Guidance is provided on thickness where possible
  - As low as reasonably achievable (ALARA) principle always applies

- OLTARIS provides a simple and fast on-line tool for assessing space radiation exposures
  - Capabilities support wide range of mission architectures and shielding configuration
  - Easily accessible lunar surface features