RADIATION EXPOSURE AND SHIELDING EFFECTS ON THE LUNAR SURFACE

Daniel Matthiä, Thomas Berger

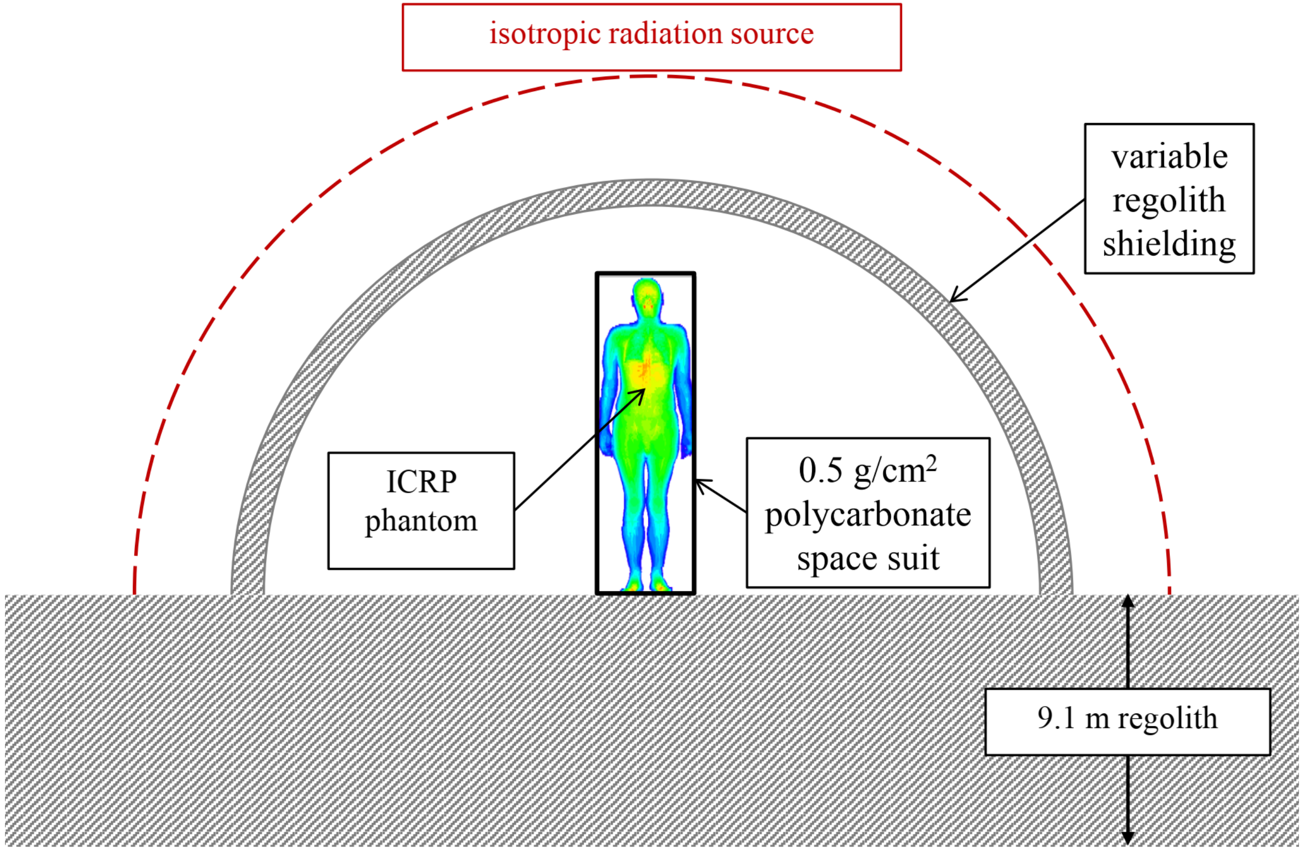
Institute of Aerospace Medicine, German Aerospace Center (DLR), Cologne

DLR

Introduction

- Calculation of dose / dose equivalent / gray equivalent for lunar surface
  - Solar particle events: Aug. 1972, Oct 1989 (NASA design reference event)
  - Galactic cosmic radiation, solar minimum
- Unshielded (“space suit”) and various amounts of regolith shielding (dome)
  - Direct calculation with ICRP voxel phantom and fluence-to-dose conversion coefficients
- Comparison to model and experimental data from literature
- Matthiä & Berger, Radiation exposure and shielding effects on the lunar surface, Space Weather, 2024, doi: 10.1029/2024SW004095

Model setup



Polycarbonate “space suit“ cylinder + regolith dome ($1 g/cm^2$ to $180 g/cm^2$)

on regolith block 20m·20m·9.1m

Isotropic primary particle source + transport with Geant4.11.00.p04 (QGSP_INCLXX_HP_EMZ)

Dose calculation with voxel phantom

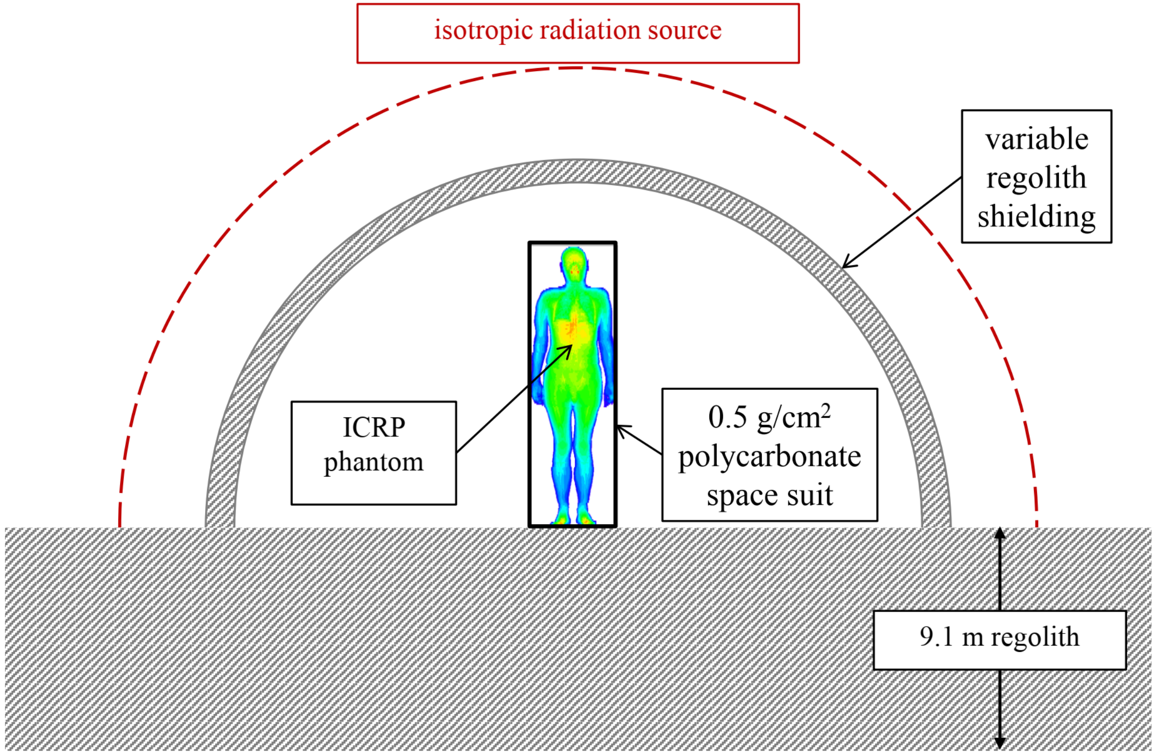
- Energy deposition is recorded per voxel, weighted by

- *Q*(LET) for dose equivalent
- or RBE for Gray-equivalent

→ organ dose / dose equivalent

- weighted sum for effective dose

equivalent



Dose calculation with fluence-to-dose conversion coefficients (only GCR)

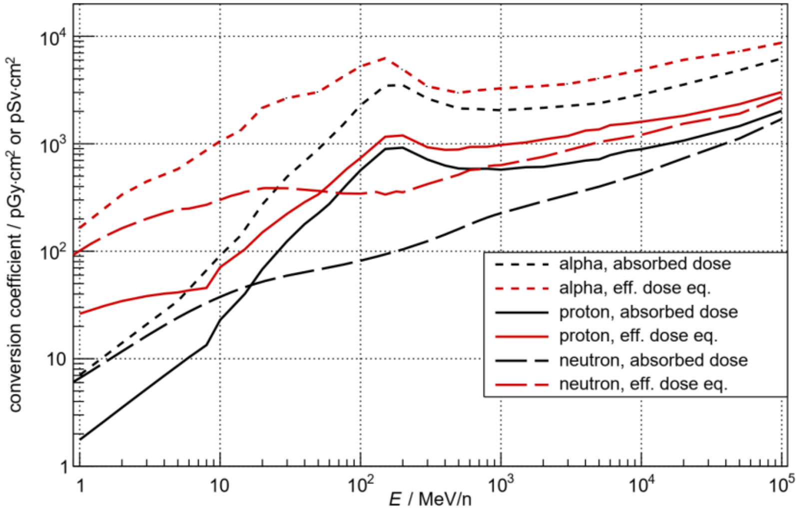
- ICRP phantom removed

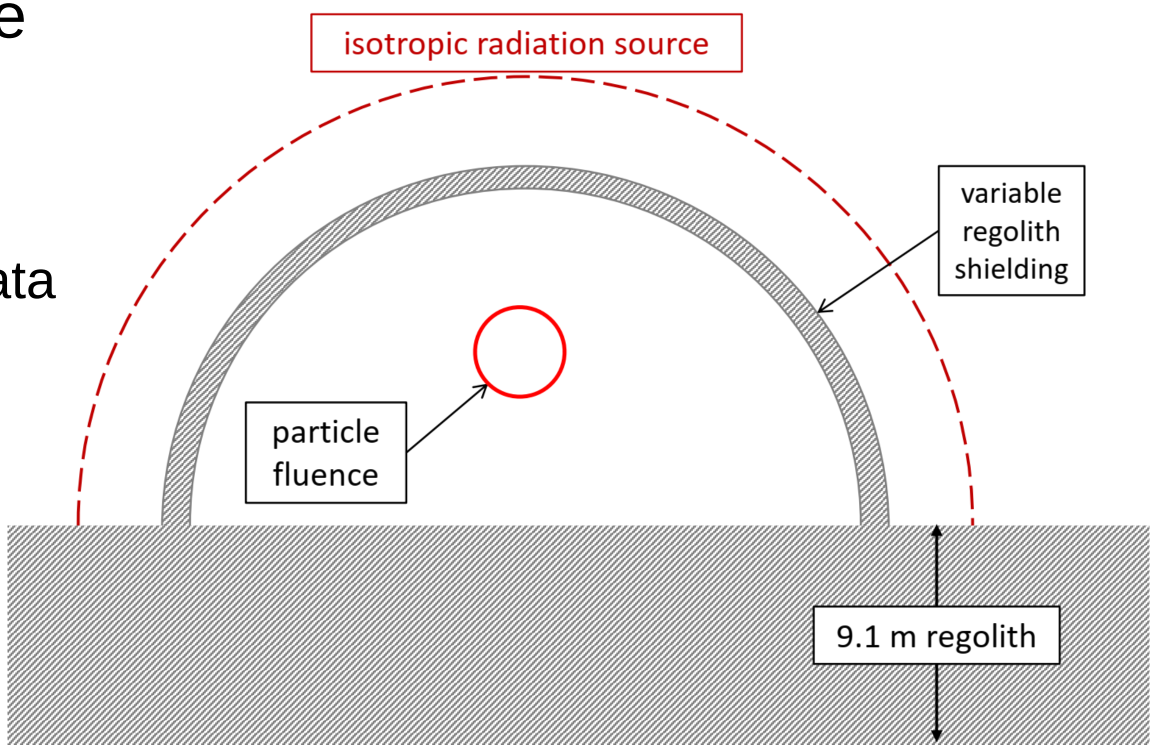
→ calculated particle fluence through sphere

→ folded with conversion coefficients

  - ICRP for organ/whole body dose
  - pre-calculated response for benchmark with data

ICRP fluence-to-dose conversion





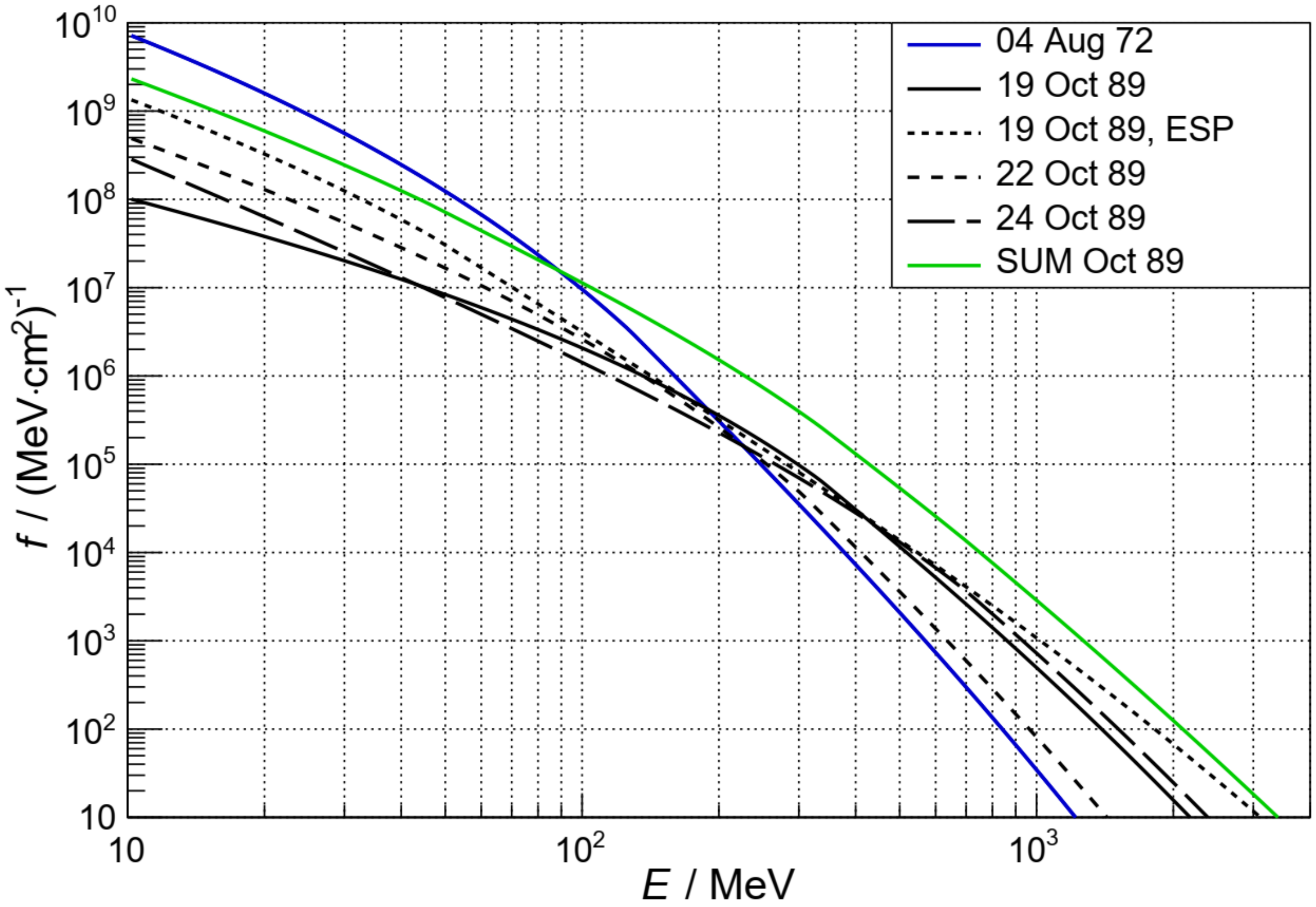
Solar energetic particle events

- Primary protons

10 MeV ≤ E ≤ 20 GeV

- Sum of Oct 89 events:

NASA design reference



Townsend et al. (2018), Life Sciences and Space Research, 17, 32–39. https://doi.org/10.1016/j.lssr.2018.02.002
Tylka et al. (2010), 2010 fall AGU meeting.

Skin – total dose from solar particle events

- >10 Gy-Eq unshielded
- below limit for > 4g/cm^2

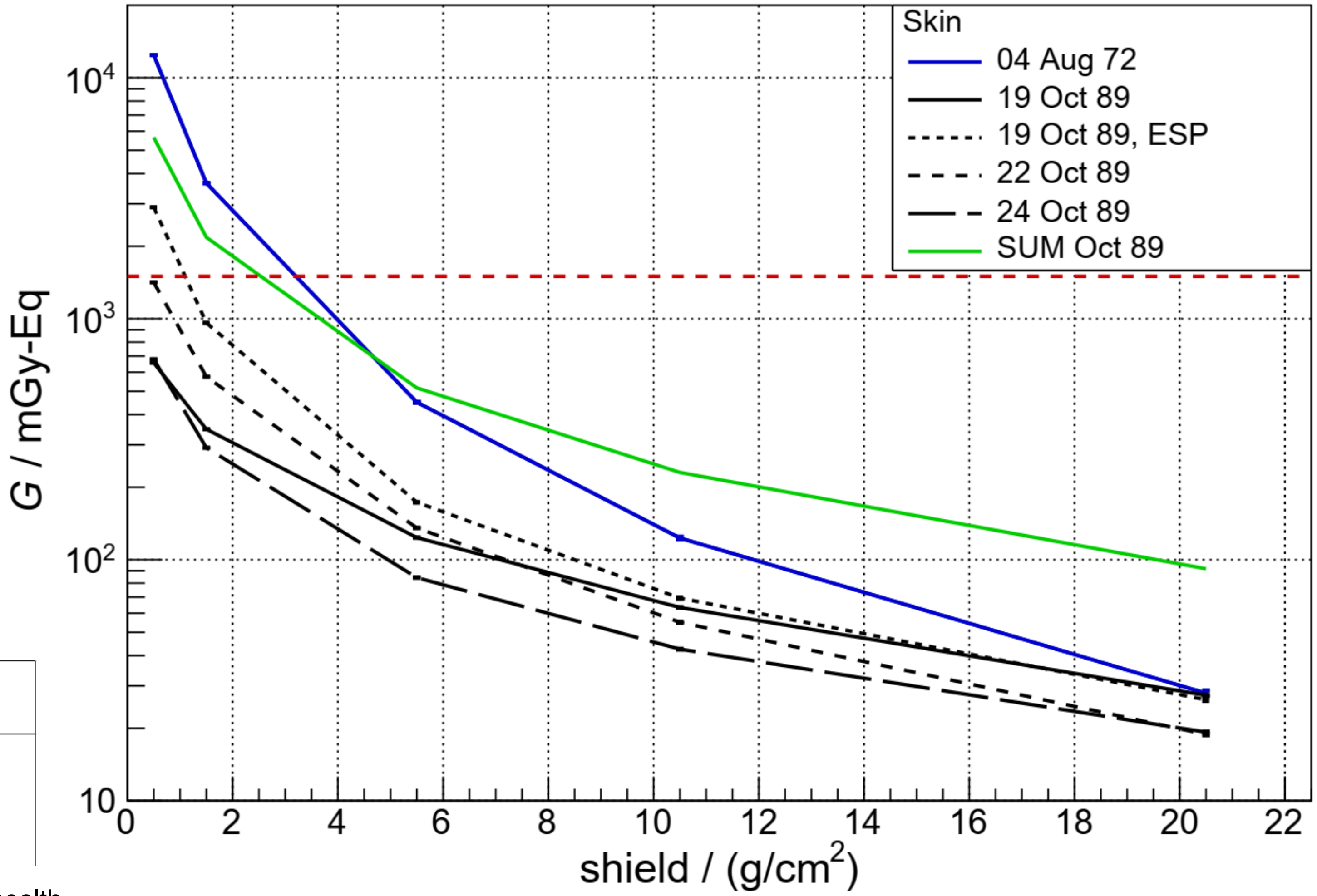
Table 1
NASA 30-Day Limits for Non-Cancer Risks (NASA, 2022)

Organ	30-Day limit (mGy-Eq)
Lens	1,000
Skin	1,500
Blood Forming Organs (BFO)	250
Circulatory System	250

Note. Data is taken as excerpt from Table 4.8–1 in NASA (2022).

Table 4.8-4—Recommended Shielding Guidelines for SPEs

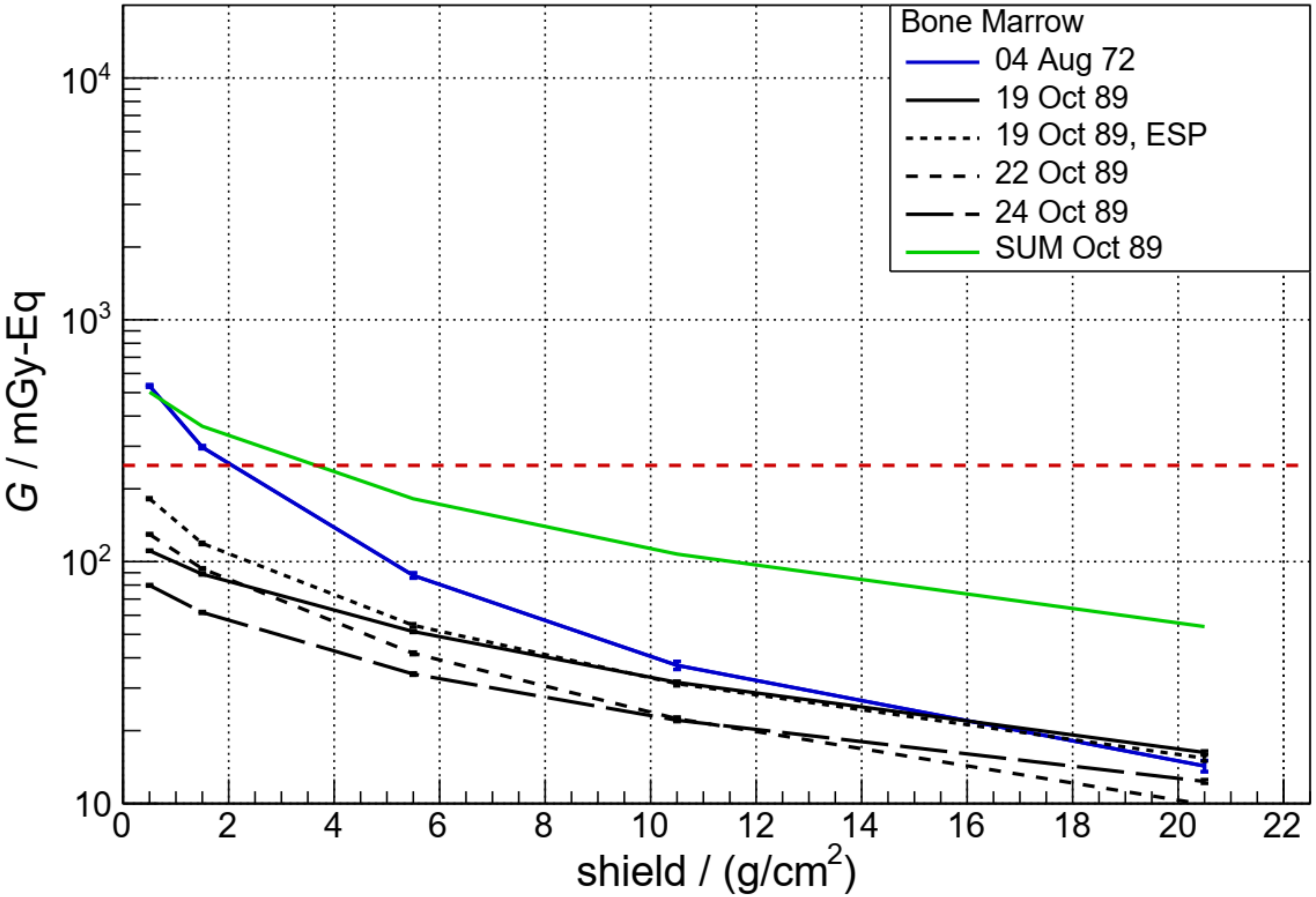
Mission Location and Duration	*Shielding**	*Type(s) of Shielding*	*Comments*
Celestial surface, any duration	*10 cm (or g/cm^2) water equivalent surrounding the crewmember. Considers celestial surface shielding contribution*	*Reconfigurable shielding already within the vehicle*	*Timeline of SPEs allows for reconfiguration*



NASA. (2022). NASA space flight human-system standard volume 1: Crew health.

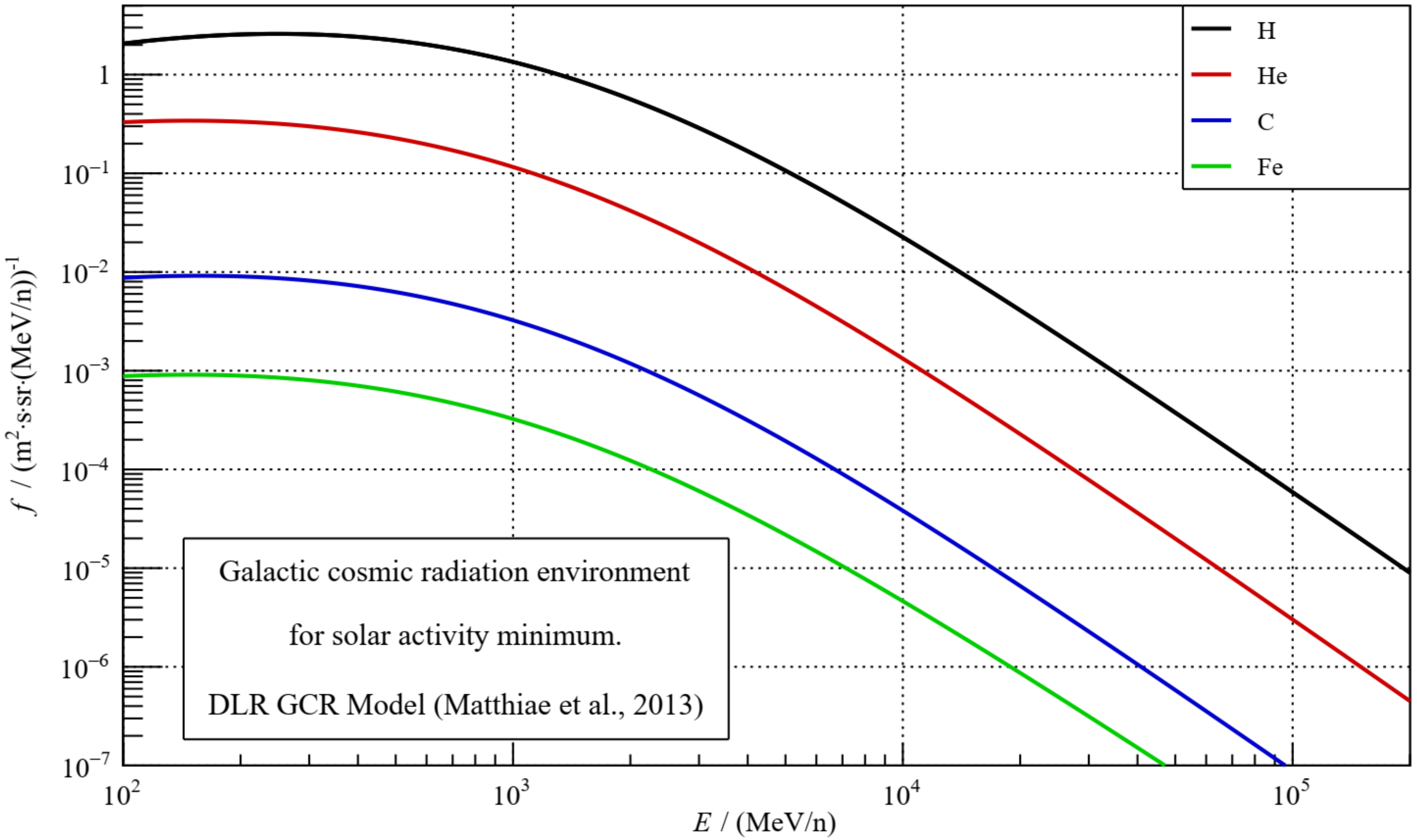
Bone marrow – total dose from solar particle events

- ~0.5 Gy-Eq unshielded
- below limit for > 4g/cm²



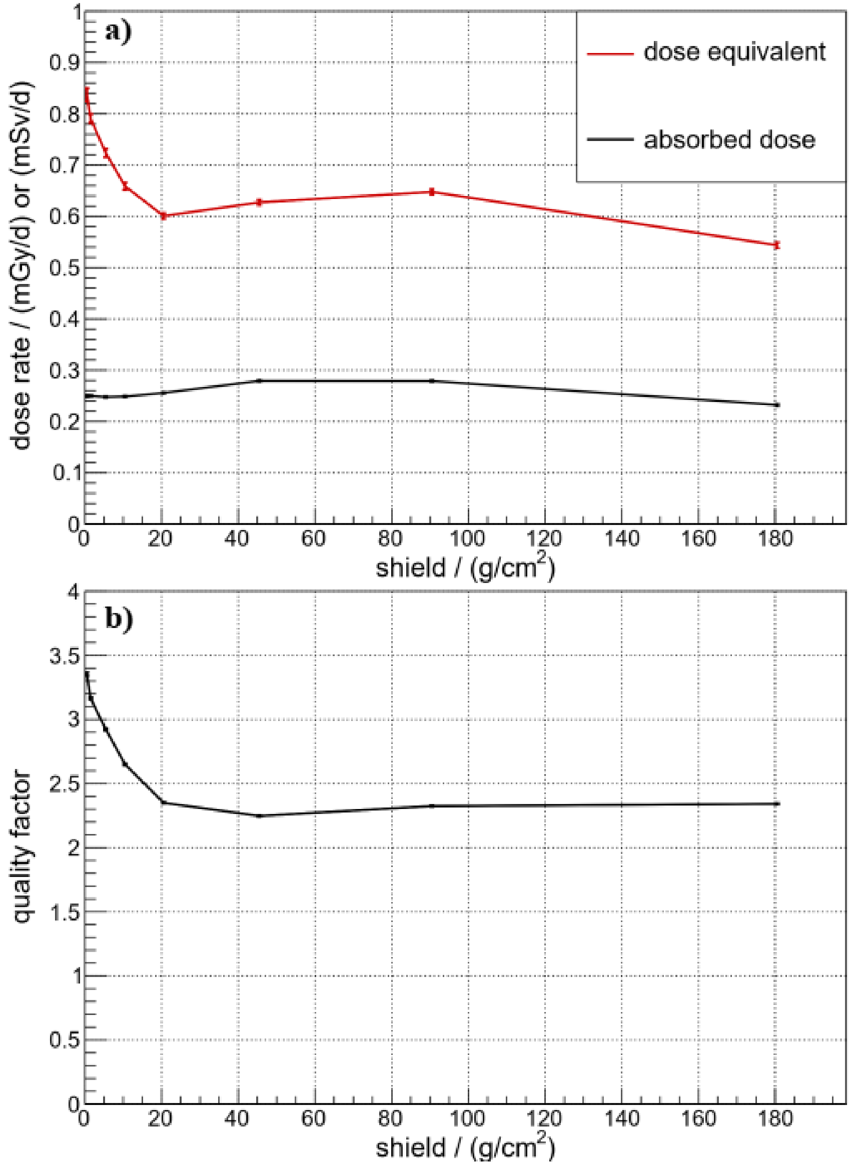
Galactic cosmic radiation – Solar Minimum

- H to Fe
- 10 MeV/n ≤ *E* ≤ 200 GeV/n

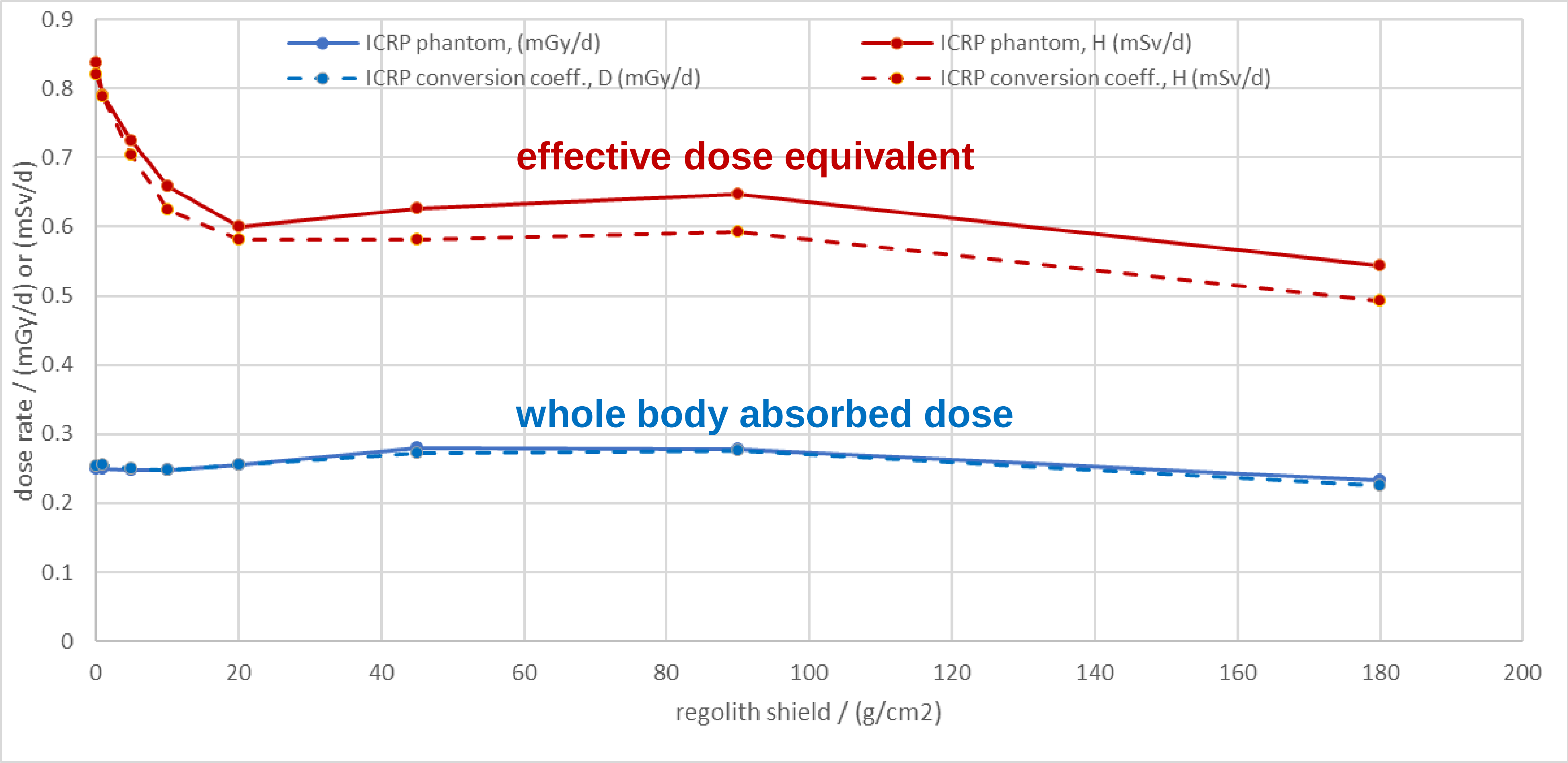


Galactic cosmic radiation – Solar Minimum
Effective dose equivalent and absorbed dose

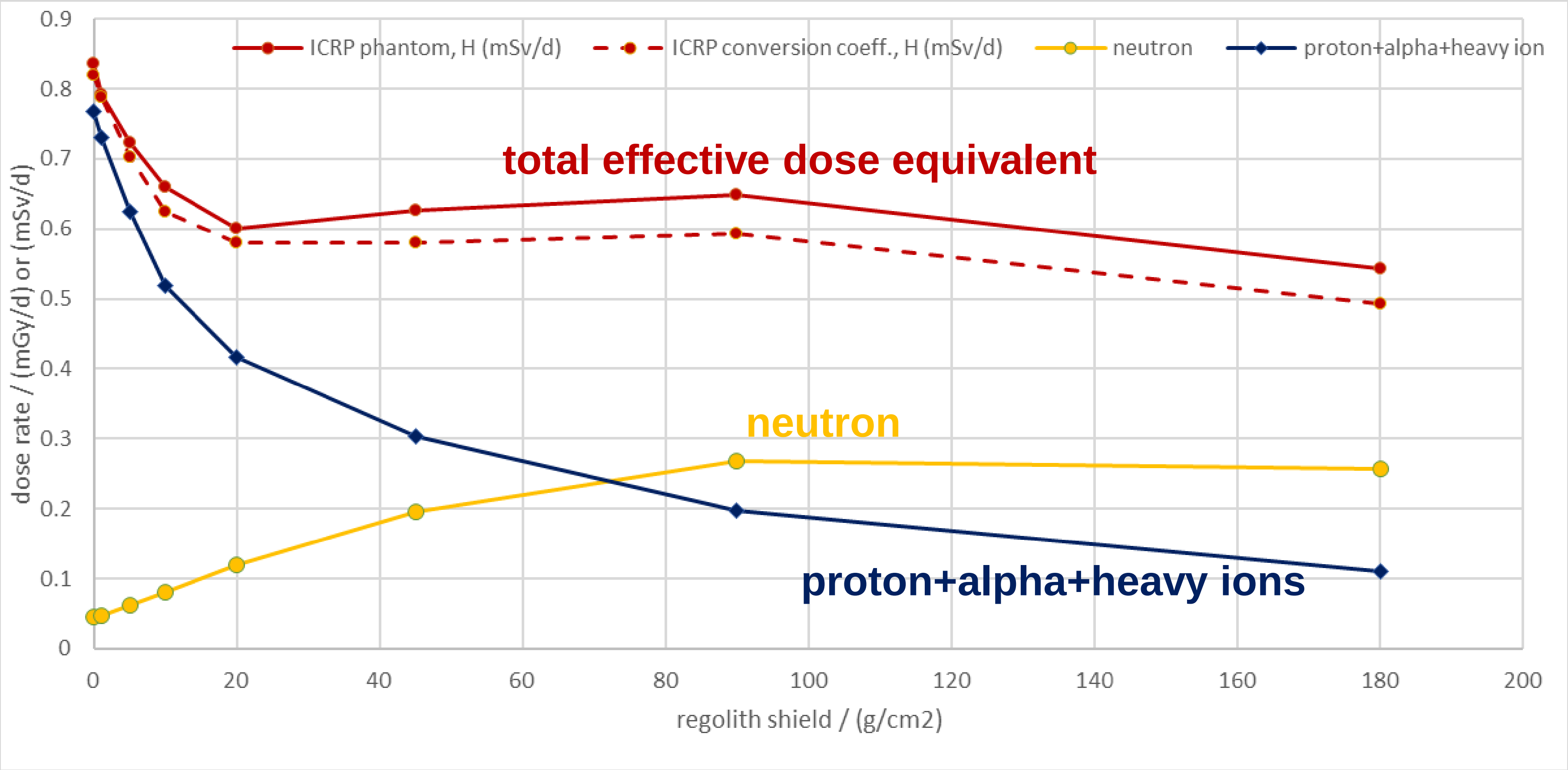
- ICRP numerical voxel phantom
- $H_E \approx$ 850 mSv/d to 550 mSv/d
- $Q \approx$ 3.5 to 2.3



Galactic cosmic radiation - comparison of ICRP voxel phantom and fluence-to-dose conversion coefficients

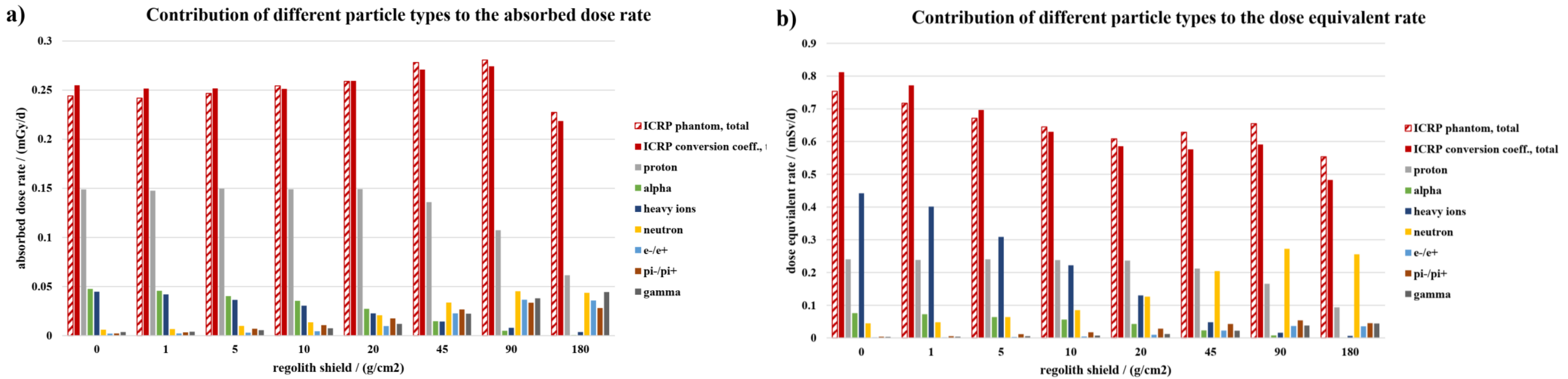


Galactic cosmic radiation – contribution of neutron and proton/heavy ions to the effective dose equivalent



- neutron: 5% to 50%
- proton+alpha+heavy ions: 90% to 20%

Galactic cosmic radiation – contribution of different particle types



Comparison to model data from literature
(selected, more in the paper)

Literature data					This work	
Ref.	**Source**	**Shielding**	**Quantity/unit**	**Value**	**Quantity/unit**	**Value**
Burahmah and Heilbronn (2023), Table 2, Lunar surface, male	GCR solar min.	1 cm Al (2.33 g/cm2)	Effective dose rate (µSv/d)	762.1	Effective dose equivalent rate (µSv/d)	768 ± 8
Shavers et al. (2023), Table 5 for GCR, Table 6 for GCR + Reference SPE, JAXA male, NASA male, RSA	GCR, Jan. 2013	5 g/cm2 Al	30-day total effective dose / mSv (JAXA/ NASA/RSA)	19.1/14.8/15.8	30-day total effective dose equivalent mSv	15.8 ± 0.1
	GCR, Jan. 2013 + Reference SPE	5 g/cm2 Al	30-day total effective dose / mSv (JAXA/ NASA/RSA)	173/ 207/328		238 ± 1

Model data from this work was rerun for Jan 2013 and interpolated to match the shielding.

Burahmah and Heilbronn (2023), *Aerospace*, *10*(11), 970. https://doi.org/10.3390/aerospace10110970
Shavers et al. (2023), Zeitschrift für Medizinische Physik, 34(1), 31–43. https://doi.org/10.1016/j.zemedi. 2023.10.005

Comparison to model data from literature, continued
(selected, more in the paper)

Literature data					This work	
Ref.	**Source**	**Shielding**	**Quantity/unit**	**Value**	**Quantity/unit**	**Value**
Naito et al. (2020), Table 2	GCR solar min.	none	Effective dose equivalent rate/ (mSv/yr)	416 ± 18	Effective dose equivalent rate/ (mSv/yr)	299 ± 6
Dobynde and Guo (2024), Figure 1	GCR solar min.	1 g/cm2 Al; 10 g/cm2 Al; 30 g/cm2 Al; 60 g/cm2 Al;	Dose equivalent rate in spherical phantom (mSv/yr)	411 349 311 322	Effective dose equivalent rate (µSv/d), regolith shielding	288 ± 6 228 ± 4 212 ± 3 213 ± 2

Naito et al. (2020), Journal of Radiological Protection, 40(4), 947– 961. https://doi.org/10.1088/1361-6498/abb120
Dobynde and Guo (2024). Nature Astronomy, 8(8), 991–999. https://doi.org/10. 1038/s41550-024-02287-8

Comparison to measurements from literature

Literature data				This work	
Ref.	**Source**	**Quantity/unit**	**Value**	**Quantity/unit**	
Dachev et al. (2011)	GCR, solar min. (Mai 2009–Oct 2009)	Dose rate in Si µGy/h	10.7	Dose rate in Si µGy/h	13.4 ± 0.1
Spence et al. (2010); https://crater-web.sr.unh.edu	GCR, solar min. (December 2009)	Dose rate in Si µGy/h	9.86 ± 0.02	Dose rate in Si µGy/h	9.3 ± 0.1
Zhang et al. (2020)	GCR, low solar modulation (Jan/Feb 2019)	Dose rate in Si µGy/h	10.2 ± 0.9 (charged) 3.1 ± 0.5 (neutral)	Dose rate in Si µGy/h	9.2 ± 0.1 (charged) 0.0730 ± 0.0003 (neutral)
	GCR, low solar modulation (Jan/Feb 2019)	Dose equivalent rate in water µSv/h	57.1 ± 10.6 (charged)	Dose equivalent rate in tissue µSv/h	64.7 ± 0.8 (charged)

Model data was calculated from particle fluence with corresponding conversion coefficients for Si and tissue slabs.

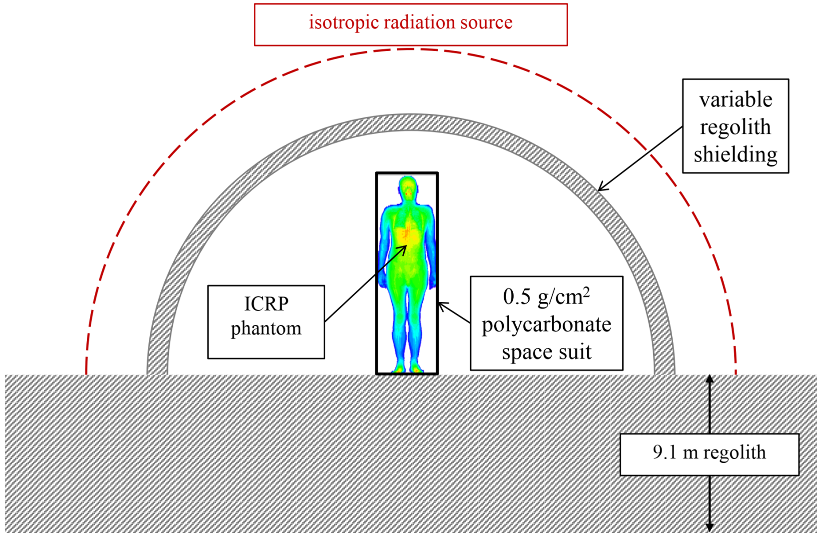
Dachev et al. (2011), *Advances in Space Research*, *48*(5), 779–791. https://doi.org/10.1016/j. asr.2011.05.009
Spence et al. (2010), Space Science Reviews, 150(1), 243–284. https://doi.org/10.1007/s11214- 009-9584-8
Zhang et al. (2020), *Science Advances*, *6*(39), eaaz1334. https://doi.org/10.1126/sciadv.aaz1334

Neutrons on the Lunar Surface

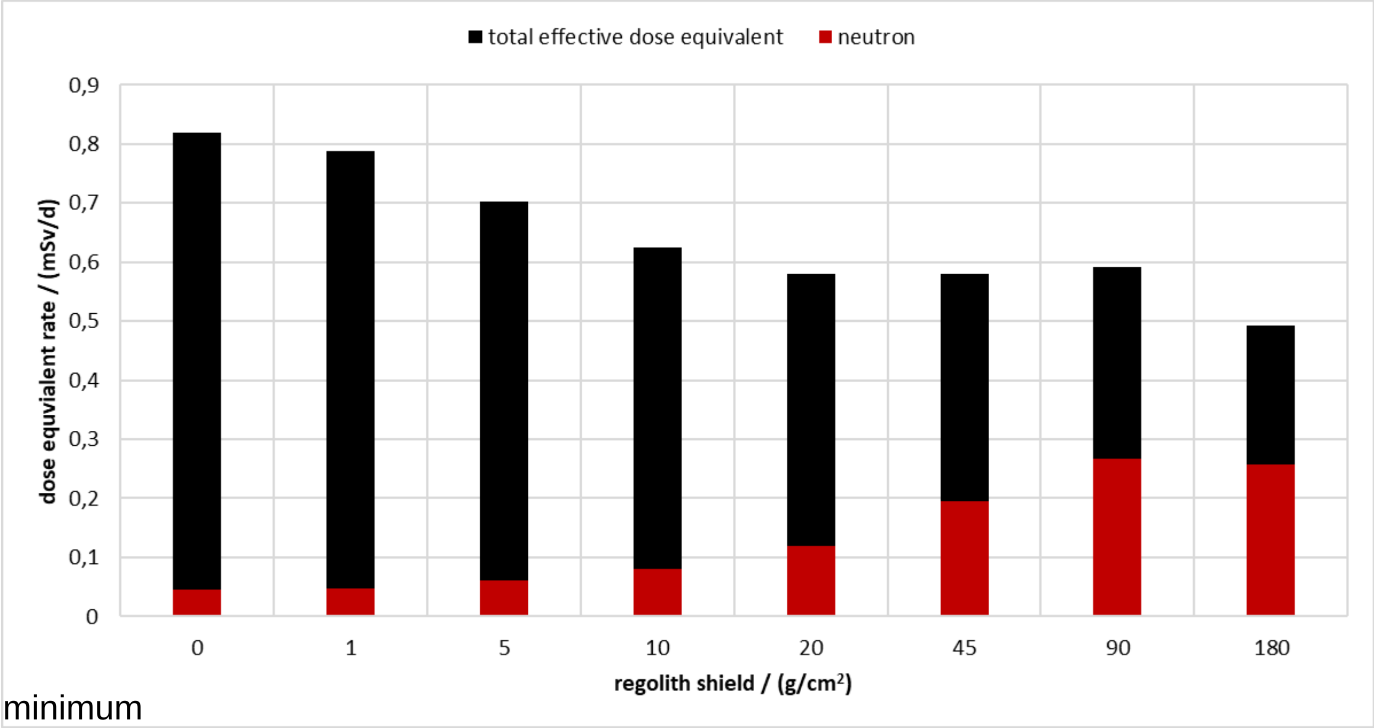
- GCR, solar energetic particles
- Albedo neutrons from interactions with regolith, potentially habitats

Matthiä & Berger, Radiation exposure and shielding effects on the lunar surface, Space Weather, 2024, doi: 10.1029/2024SW004095

Neutrons on the Lunar Surface



- GCR, solar energetic particles
- Albedo neutrons from interactions with regolith, potentially habitats
- GCR (space suit)*
  - total ~ 0.8 mSv/d
  - neutrons ~ 0.05 mSv/d (6%)
- Neutron contribution up to ~50%

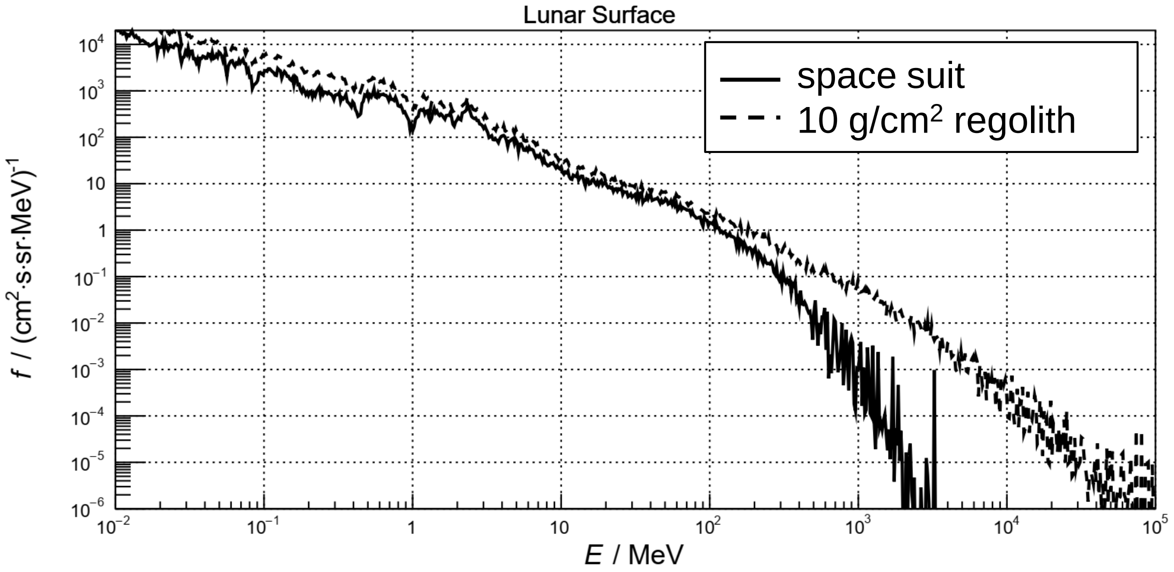


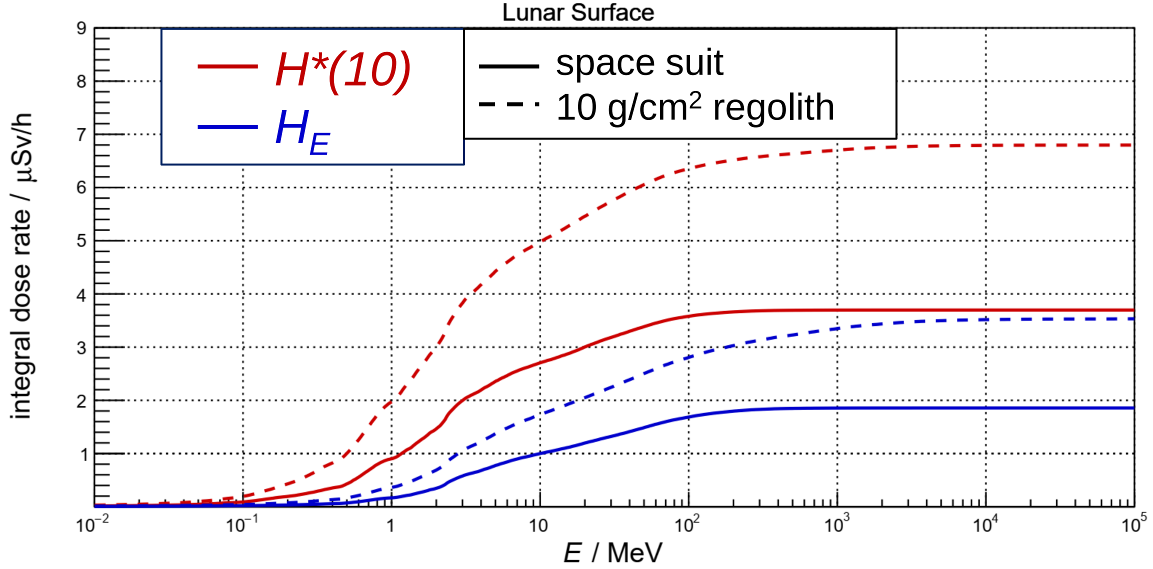
*model calculations of the total effective dose equivalent for solar minimum

Neutron spectra on the Lunar Surface (model)

- Space Suit:
  - ~ only albedo neutrons
  - energies ~0.1MeV – 100 MeV
  - ambient dose eq. *H*(10)*: ~4 µSv/h
  - effective dose equivalent H_E: ~2 µSv/h

- Habitat (10g/cm^2 regolith):
  - energies ~0.1MeV – few GeV
  - ambient dose eq. *H*(10)*: ~7 µSv/h
  - effective dose equivalent H_E: ~3.5 µSv/h





Summary

- Solar particle events: Aug. 1972, Oct 1989 (NASA design reference event)
  - "space suit": both events well above the 30 day limit for both skin and bone marrow
  - ~4g/cm^2 required to reduce the doses below the limit

- Galactic cosmic radiation, solar minimum
  - Absorbed dose: ~250 to 300 µGy/d, little impact of shielding
  - Effective dose equivalent: ~850 to 550 µSv/d (decrease of *Q* from ~3.5 to 2.3)

- Comparison to model data from literature: mostly ok

- Comparison to experimental data from literature:
  - Good agreement for charged particles (in silicon)
  - ? for neutrons

- Matthiä & Berger, Radiation exposure and shielding effects on the lunar surface, Space Weather, 2024, doi: 10.1029/2024SW004095
- More neutron stuff (aviation and ISS), IAEA workshop at https://conferences.iaea.org/event/410/sessions/3309/attachments/20676/34876/3..2025-07-07-DLR-ME-SBA-Matthi%C3%A4_nBHEAM_Vienna.pdf

Impressum

Thema: Radiation Exposure from Neutrons in Spaceflight and Aviation

Datum: 2025-09-01

Autor: Daniel Matthiä

Institut: Institut für Luft- und Raumfahrtmedizin

Neutrons in Aviation

- GCR (and rarely high energy solar particles)
- Secondary neutrons from interactions with the atmosphere
- Total dose rates up to 10µSv/h
  - 40% - 60% from neutrons

EURADOS, “Cosmic Radiation Exposure of Aircraft Crew”, Final report of the EURADOS WG 5, 2004.

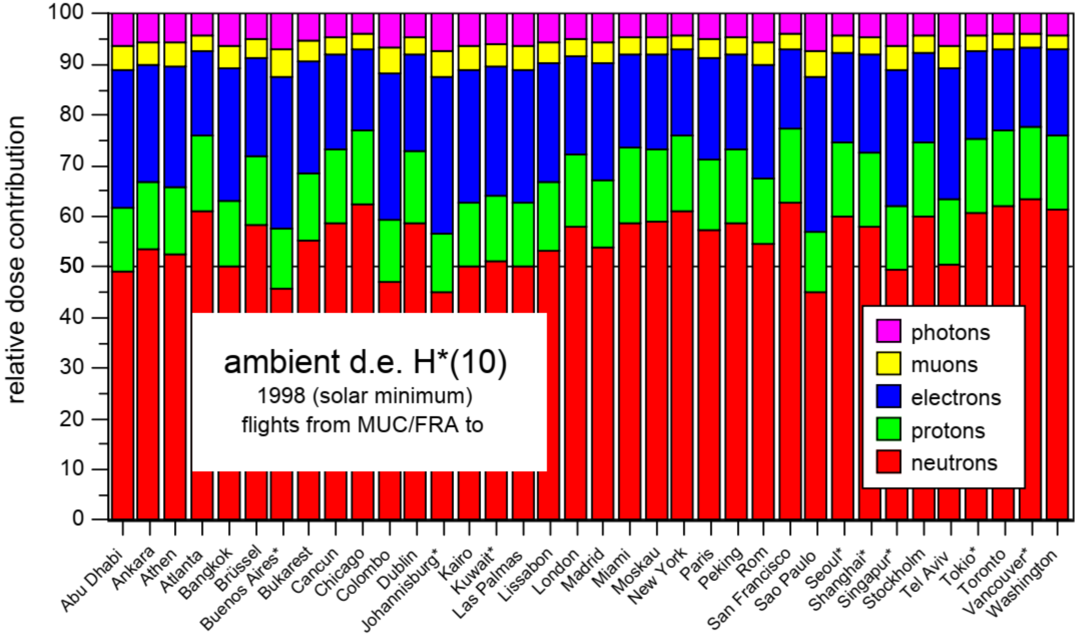
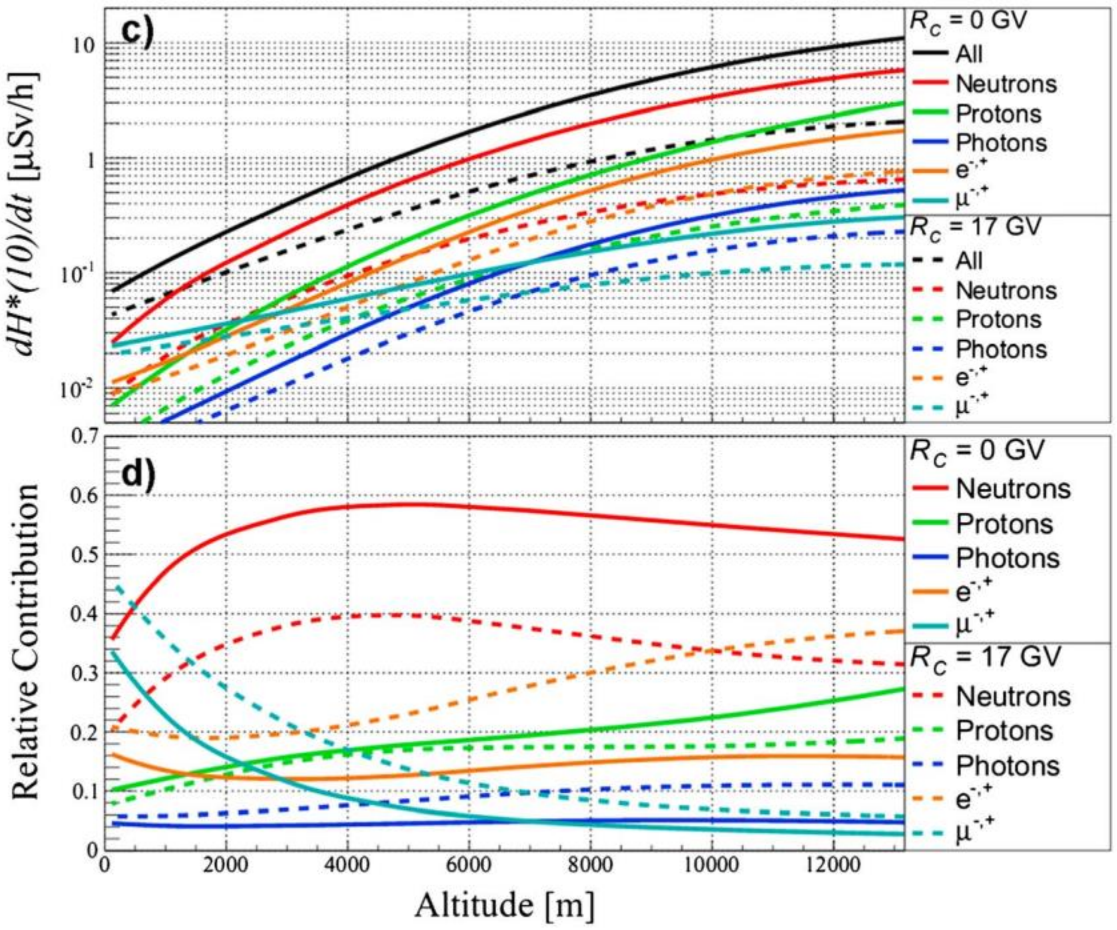


Figure II.6 Relative contribution to ambient dose equivalent for various destinations near solar minimum condition (1998) for 37000 ft flight altitude.

Neutrons in Aviation

- GCR (and rarely high energy solar particles)
- Secondary neutrons from interactions with the atmosphere
- Total dose rates up to 10 µSv/h
  - 40% - 60% from neutrons
- Neutron contribution decreases
  - with increasing altitude
  - with increasing magnetic shielding

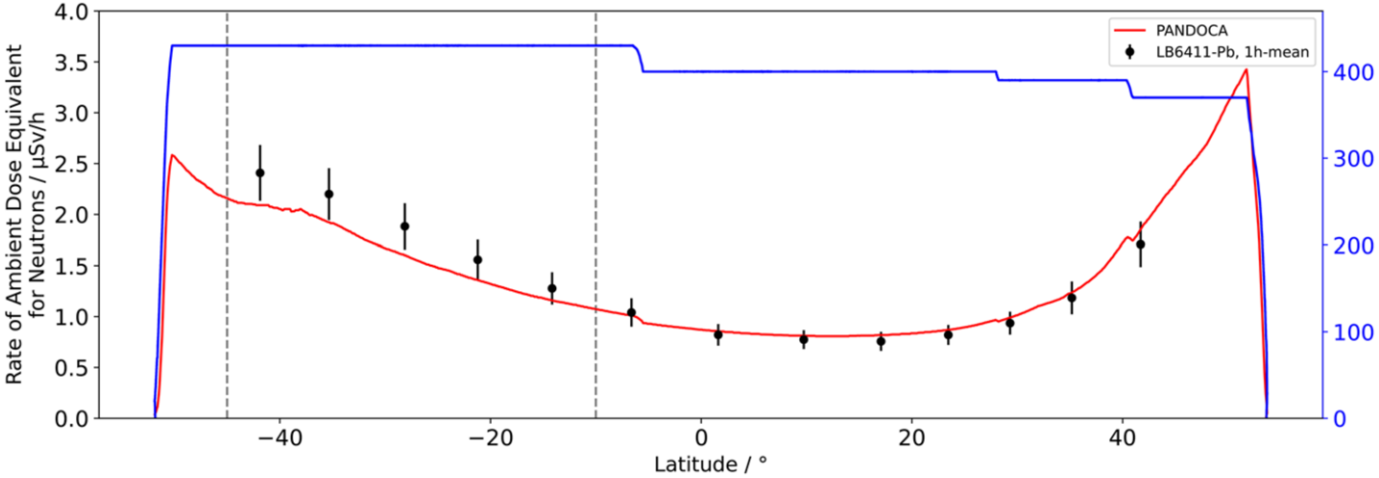
Matthiä et al., Numerical calculation of the radiation exposure from galactic cosmic rays at aviation altitudes with the PANDOCA core model, Space Weather, 2014, [doi: 10.1002/2013SW001022](https://doi.org/10.1002/2013SW001022)



Neutrons in Aviation – Measuring flight to Falkland Islands Ambient dose equivalent *H*(10)*

- Measurement *H*(10)*:
  - total: 51±3 µSv
  - neutron: 23±2 µSv (45%)
- Model/PANDOCA *H*(10)*:
  - total: 54 µSv
  - neutron: 22.5 µSv (42%)

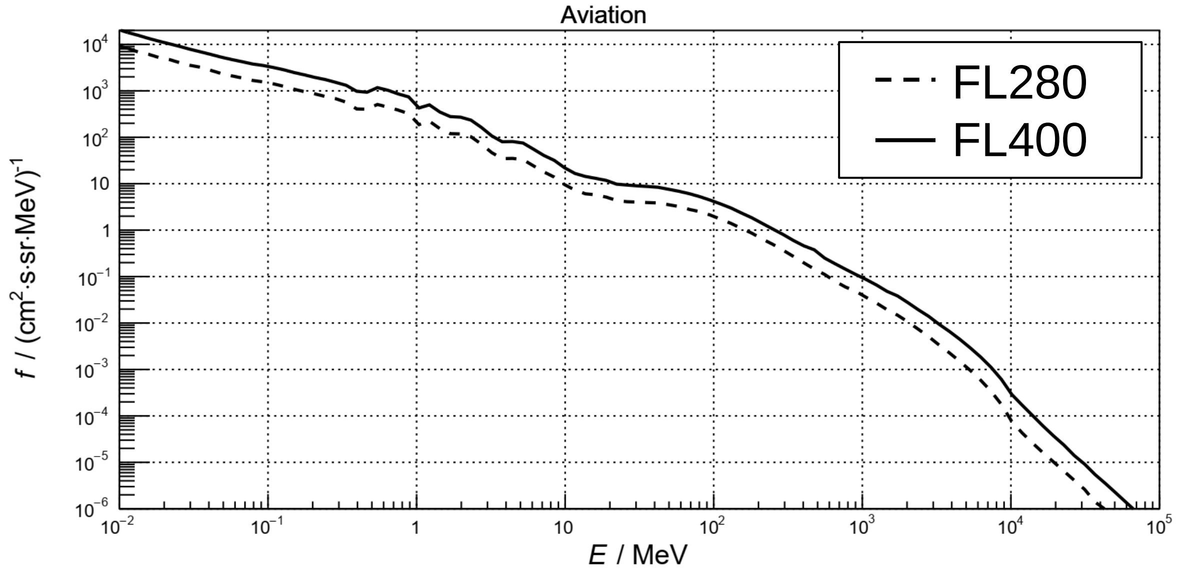
Meier et al., Impact of the South Atlantic Anomaly on radiation exposure at flight altitudes during solar minimum. Scientific Reports, 2023, doi: 10.1038/s41598-023-36190-5

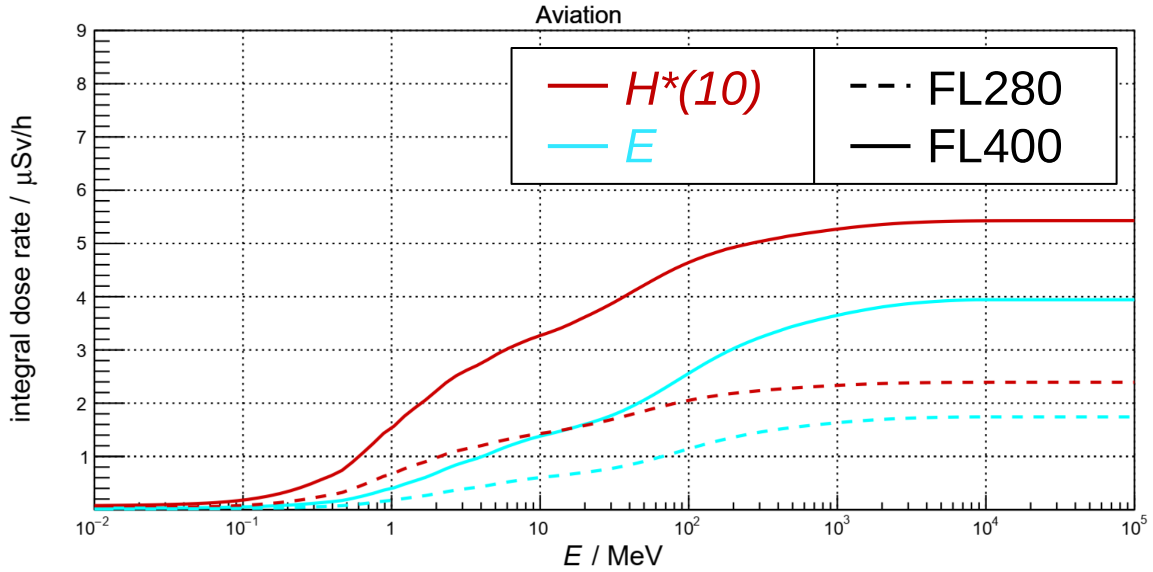


Ambient dose equivalent rate vs. latitude measured with neutron dose rate monitor LB6411-Pb

Neutrons in Aviation – Neutron spectra at different altitudes (model)

- Energies ~ 0.1MeV – few GeV contribute
- Ambient dose eq. *H*(10)*: 2.5 – 5 µSv/h
- Effective dose *E*: 2 – 4 µSv/h

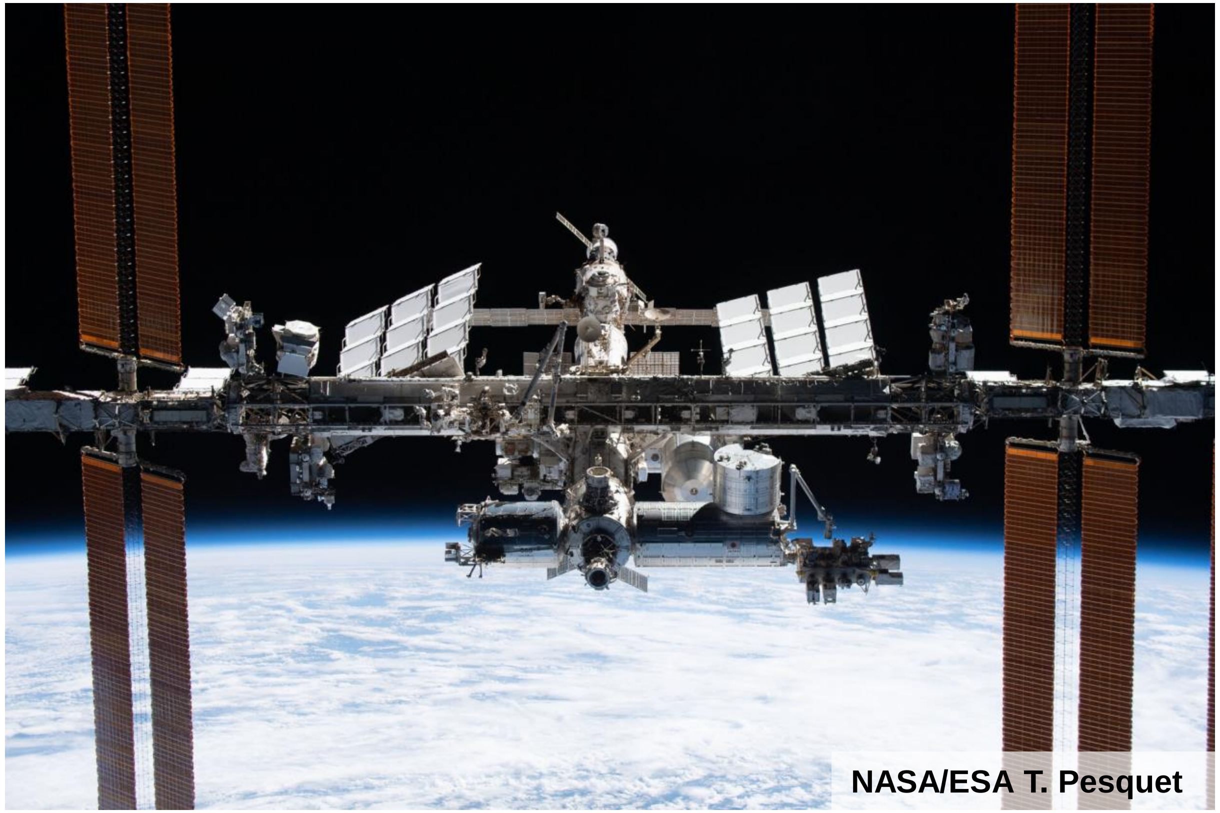




Neutrons in Low Earth Orbit
International Space Station (ISS)

- GCR, trapped particles (radiation belts)

- Neutrons from interactions with ISS, cargo etc.


NASA/ESA T. Pesquet

Neutrons in Low Earth Orbit International Space Station (ISS)

- GCR, trapped particles (radiation belts)

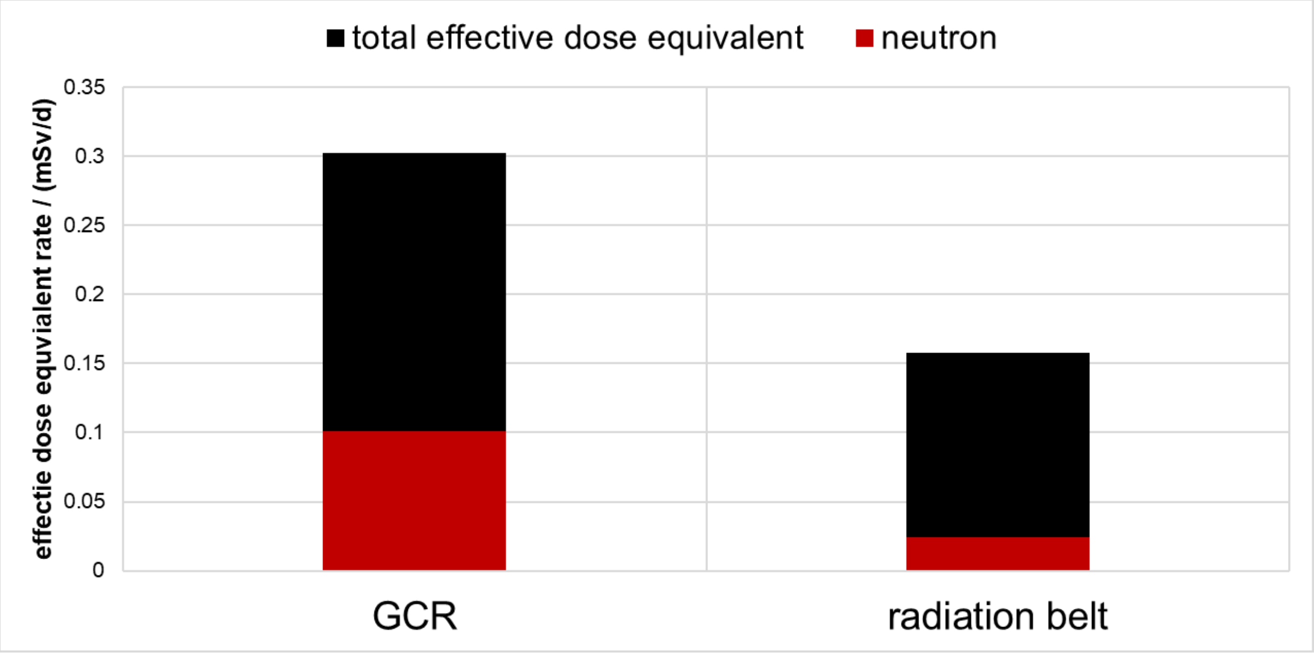
- Neutrons from interactions with ISS, cargo etc.

- GCR (COLUMBUS lab.)*
  - total ~ 0.3 mSv/d
  - neutrons ~ 0.1 mSv/d (33%)

- Radiation belt (COLUMBUS lab.)*
  - total ~ 0.16 mSv/d
  - neutrons ~ 0.02 mSv/d (12%)

*model calculations of the total effective dose equivalent for solar minimum

Berger et al., Long term variations of galactic cosmic radiation on board theInternational Space Station, on the Moon and on the surface of Mars, JSWSC, 2020, doi: 10.1051/swsc/2020028



Neutron spectra in Low Earth Orbit International Space Station (model)

- Radiation Belt:
  - energies ~0.1MeV – 100 MeV
  - ambient dose eq. *H*(10)*: ~2 µSv/h
  - effective dose equivalent H_E: ~1 µSv/h

- GCR:
  - energies ~0.1MeV – few GeV
  - ambient dose eq. *H*(10)*: ~9 µSv/h
  - effective dose equivalent H_E: ~4 µSv/h