Geant4 Simulations to Characterise Silicon Microdosimeters for the Radiation Protection of Astronauts in a Lunar Mission

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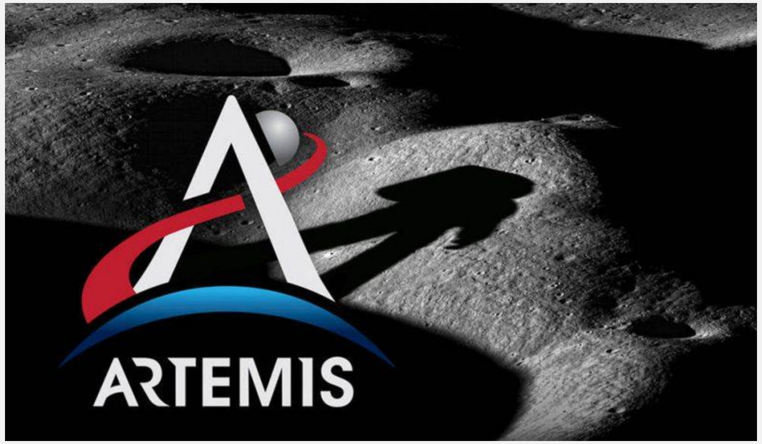
Overview

Why the Moon?

Revitalised interest in space industry aiming to return humans to the Moon
- Eg: Australian Space Agency, NASA's Artemis Missions

Understanding of lunar radiation environment is essential in assessing the safety of future missions returning astronauts to the Moon



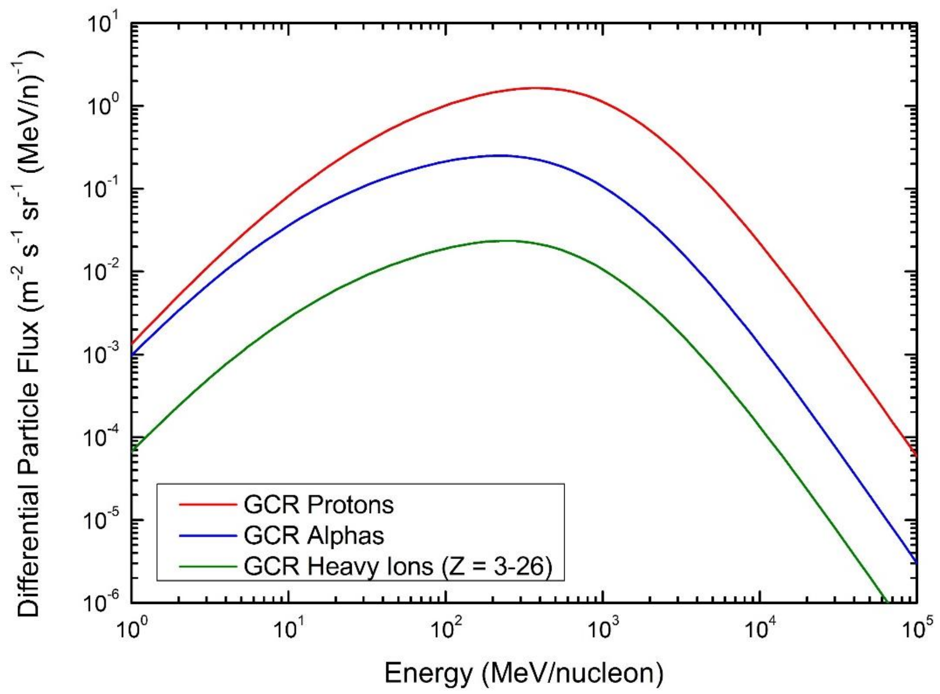
Improved radiation protection measures for astronauts in space:

1. Radiation transport simulations representing space radiation environments and exposures with increased accuracy
2. Development and characterisation of detectors/microdosimeters for real-time dosimetry and environment monitoring in space

Primary GCR Spectra

Calculated via SPENVIS (4.6.10 – released May 4, 2018)

- Near-Earth Interplanetary Space (1 AU from Sun)
- GCR model: ISO-15390 (standard)
- Solar activity data: Solar Minimum (late 2009)
  - Calculated within SPENVIS using 12-Month averaged Wolf Number of 4.8)
- GCR spectra generated from incident Protons to Fe ions
  - Generated for particle energies from 10^0 to 10^5 MeV/nucleon with a resolution of 20 points per decade



Geant4 Modelling

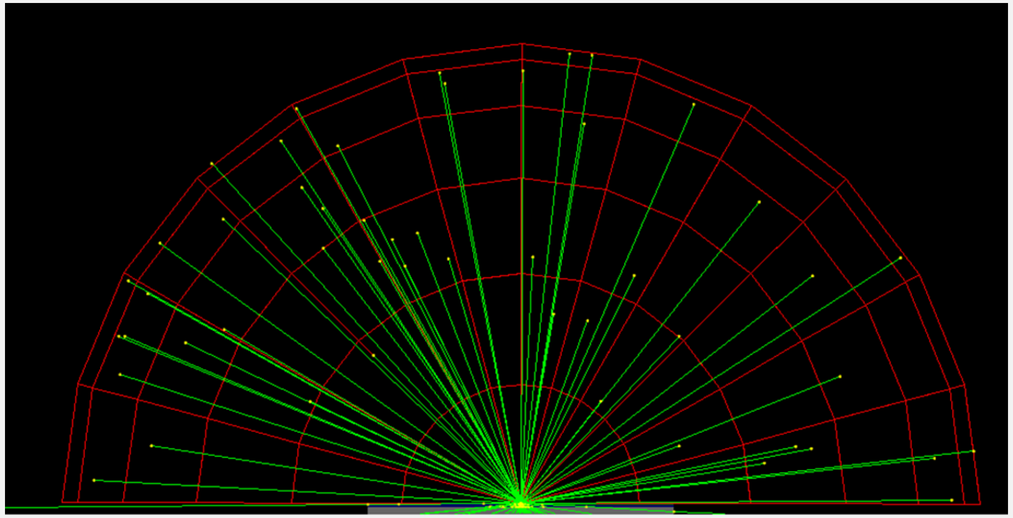
- Geant4 (version 10.07.p02 – released 11 June 2021)
- Built-in physics list FTFP_BERT_HP adopted to model particle propagation, interaction and energy deposition within lunar soil. Physics list includes:
  - Fritiof model (particle energies > 10 GeV)
  - Bertini cascade model (particle energies < 10 GeV)
  - High Precision neutron model (G4NDL4.6 – neutron energies < 20 MeV)
- Primary GCR Protons and Alpha particles incident on lunar surface
  - Incident energies in range 1-10^5 MeV/n
  - Account for 99% of GCR falling incident on the Lunar surface

Agostinelli, S. et al. (2003). GEANT4: A simulation toolkit. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 506(3), 250–303. https://doi.org/10.1016/s0168-9002(03)01368-8

Simulation Geometry

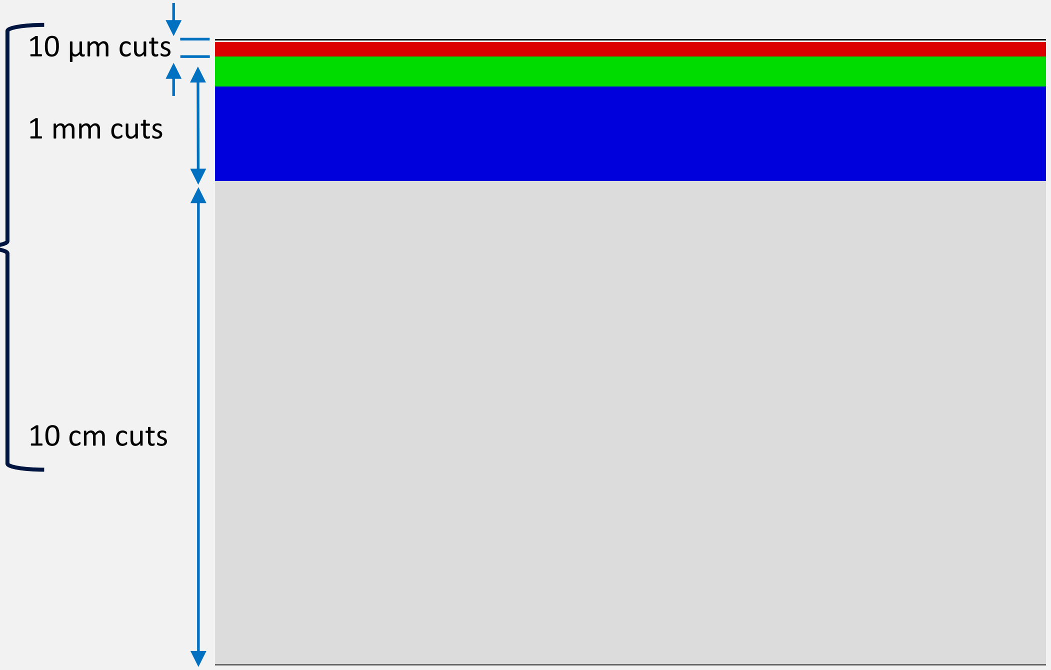
TABLE: Elemental composition of the Lunar Surface as implemented in Geant4. Layer compositions are presented as mass percentages, based on LNPE Borehole data following the works of McKinney *et al.* (2006) and Mesick *et al.* (2018).

	Layer 1	Layer 2	Layer 3	Layer 4
Depth:	0 – 22 cm	22 – 71 cm	71 – 224 cm	>224 cm
Density:	1.76 g/cm^3	2.11 g/cm^3	1.78 g/cm^3	1.79 g/cm^3
O	41.739%	41.557%	42.298%	42.636%
Si	19.026%	18.955%	19.668%	20.218%
Fe	13.496%	14.030%	12.277%	11.688%
Ca	7.541%	7.668%	8.020%	7.707%
Al	6.061%	5.977%	7.384%	7.598%
Mg	6.162%	6.026%	6.156%	6.091%
Ti	5.144%	4.905%	3.380%	3.198%
Na	0.292%	0.313%	6.026%	0.346%
Cr	0.287%	0.309%	0.264%	0.255%
Mn	0.176%	0.178%	0.152%	0.146%
K	0.067%	0.074%	0.086%	0.109%
Gd	0.004%	0.004%	0.004%	0.004%
Sm	0.003%	0.003%	0.003%	0.003%
Th	0.001%	0.000%	0.001%	0.001%
Eu	0.001%	0.001%	0.001%	0.000%



"Cuts" = Minimum/threshold traversal length of secondaries in that medium

If secondary traversal < cut length, secondary particle will not be generated



Isotropic Source Modelling with Directional Biasing

- G. Santin* describes the need for the emission of particles from surface of a sphere to follow a cosine-law angular distribution to simulate an isotropic radiation field at a desired target.

- The dose per particle can then be normalised to a dose per unit time in the "real world"

- Integrate over 2π emission angle with cosine biasing

$$\int_0^{2\pi} d\varphi \int_0^{\pi/2} d\theta cos\theta sin\theta = \pi$$

- Number of particles per unit "real time" from hemisphere ($2\pi R^2$ surface)

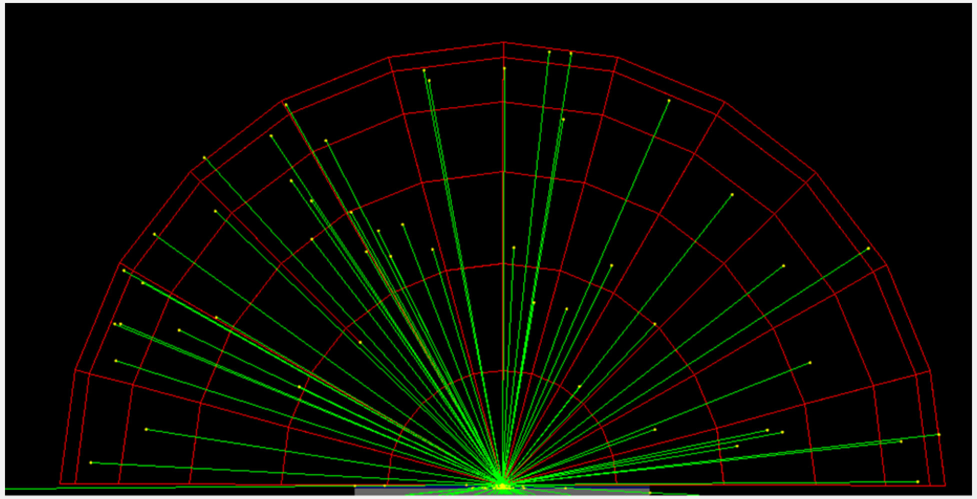
$$N_r = \Phi * 2\pi R^2 * \pi,$$ Φ = integral flux ($cm^{-2}\ s^{-1}\ sr^{-1}$)

- With directional biasing ($\theta_{min} < \theta < \theta_{max}$)

$$N_r = \Phi 2\pi^2 R^2 (\sin^2\theta_{max} - \sin^2\theta_{min})$$

- Dose per unit "real time":

$$D_r = D_s\left(\frac{N_r}{N_s}\right)$$



R = 1000m ; $\theta_{max} = 0.0573^O$

*Santin, G. (2007). *Normalisation modelling sources* [PowerPoint presentation]. Geant4 tutorial, Paris, 4-8 June 2007. URL: http://geant4.in2p3.fr/2007/prog/GiovanniSantin/GSantin_Geant4_Paris07_Normalisation_v07.ppt

Albedo (Secondary) Particles from the Lunar Surface

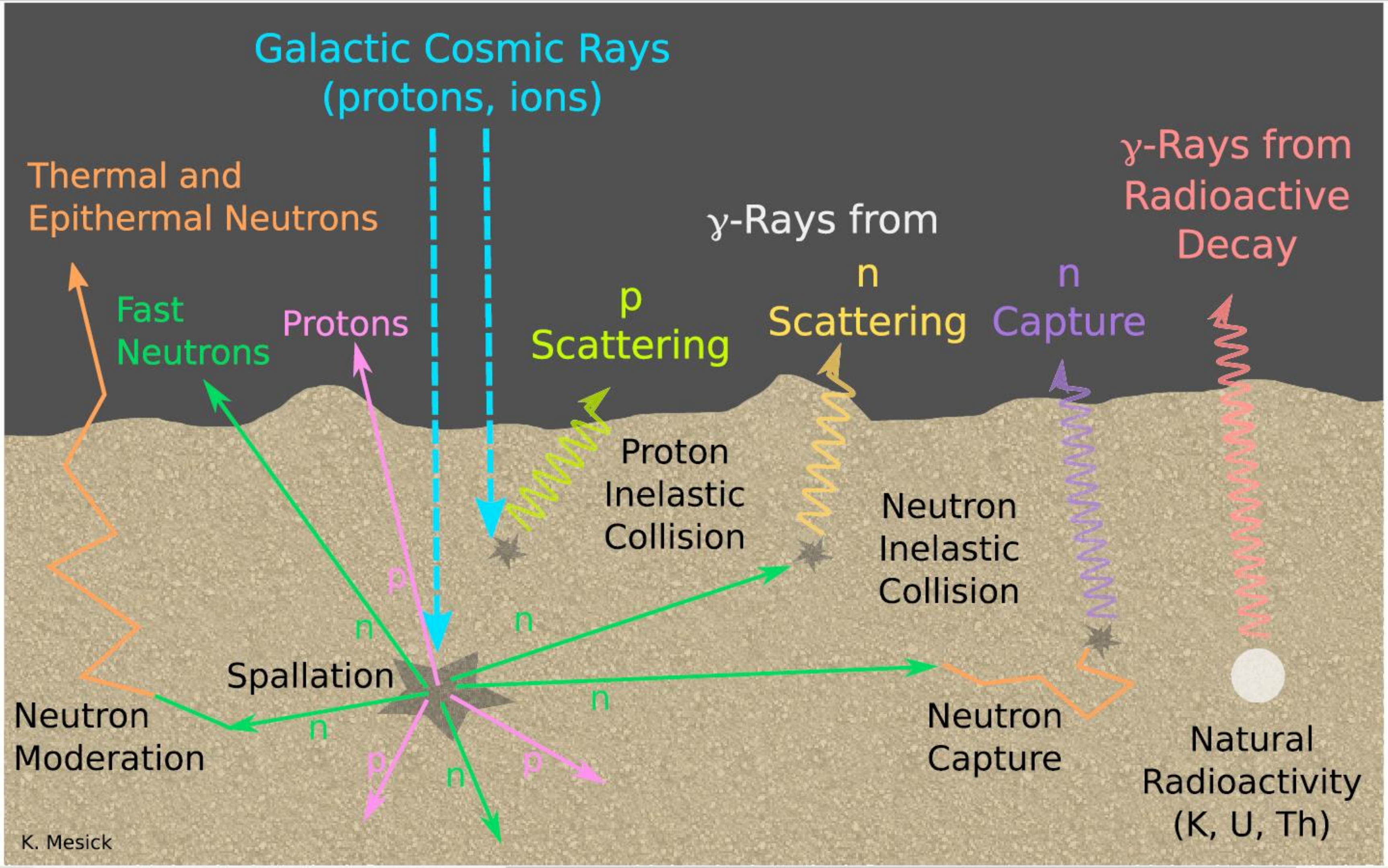
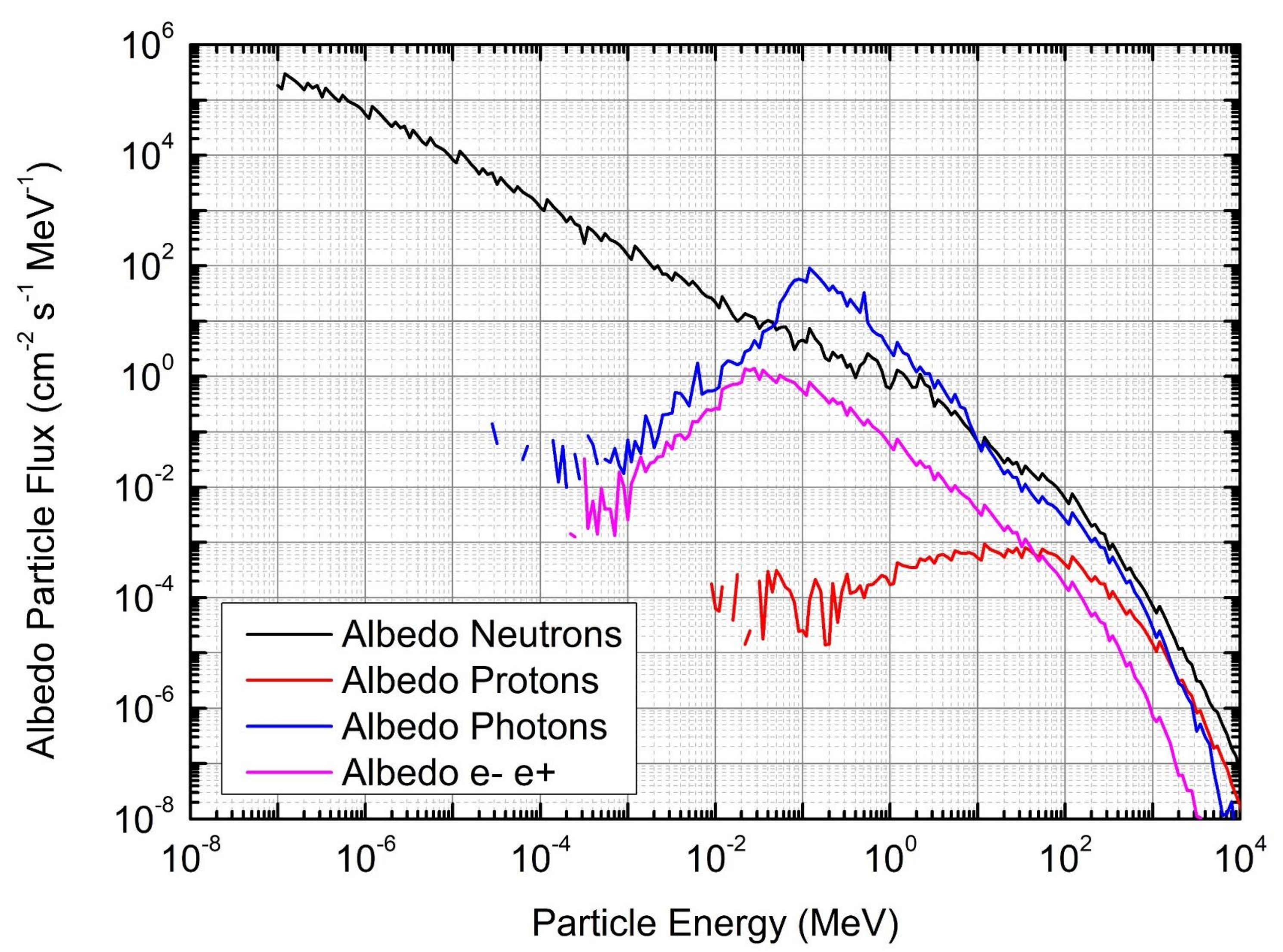
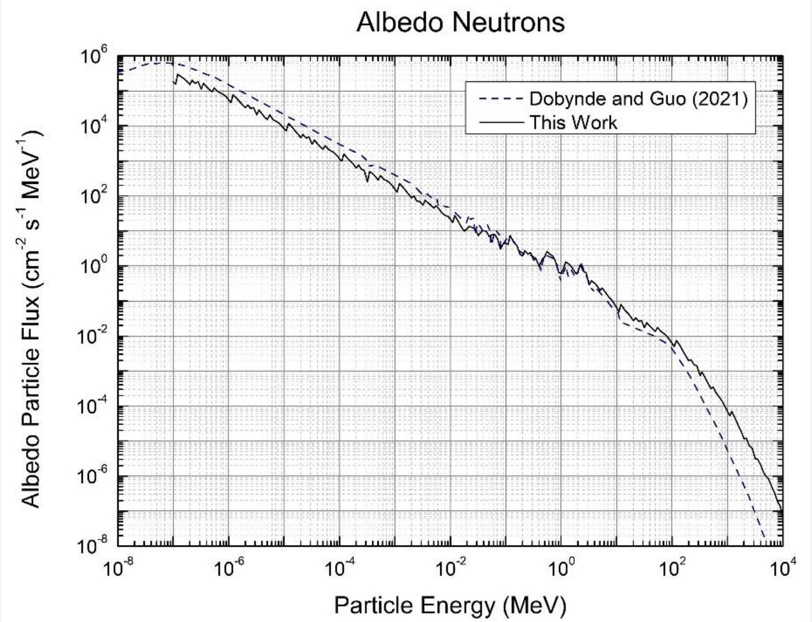


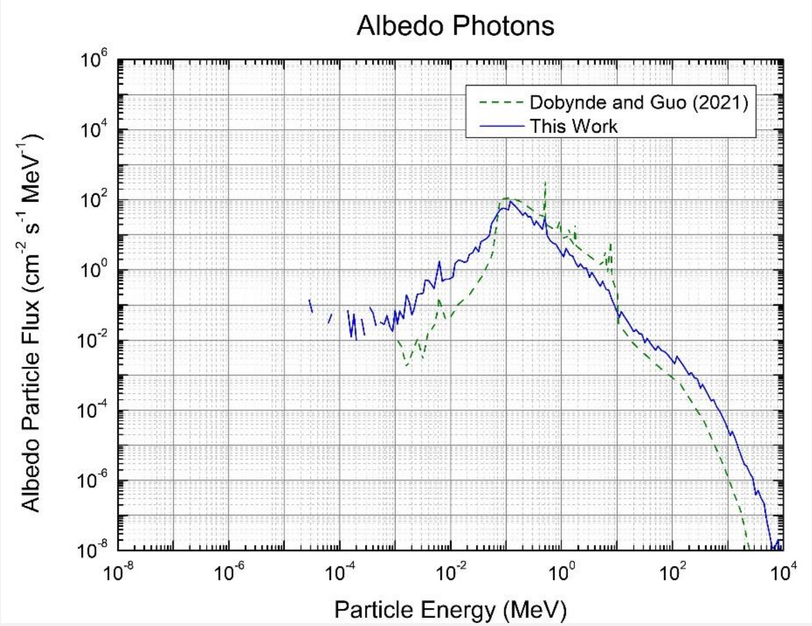
Image from Mesick, K.E., Feldman, W.C., Coupland, D.D.S. and Stonehill, L.C., 2018. Benchmarking Geant4 for simulating galactic cosmic ray interactions within planetary bodies. Earth and Space Science, 5(7), pp.324-338.

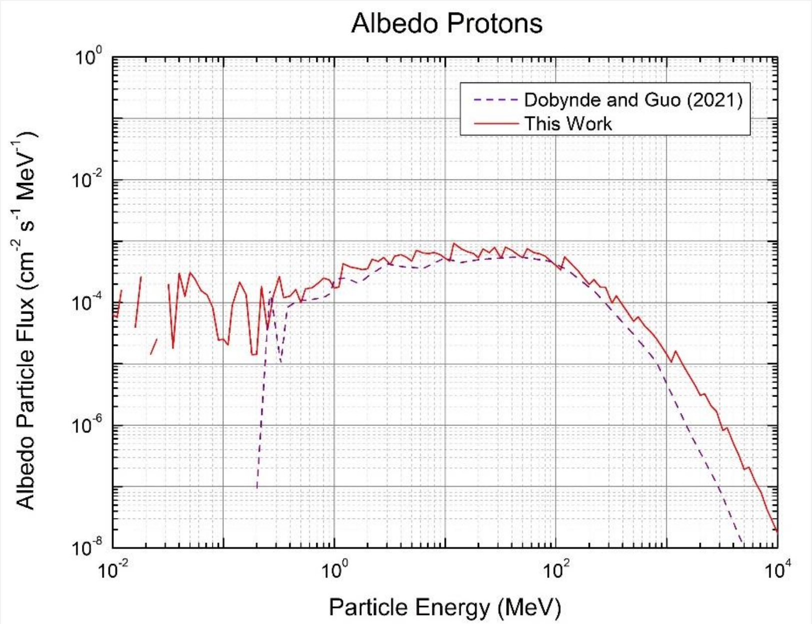
Results – Albedo Particles from GCRp and GCRα

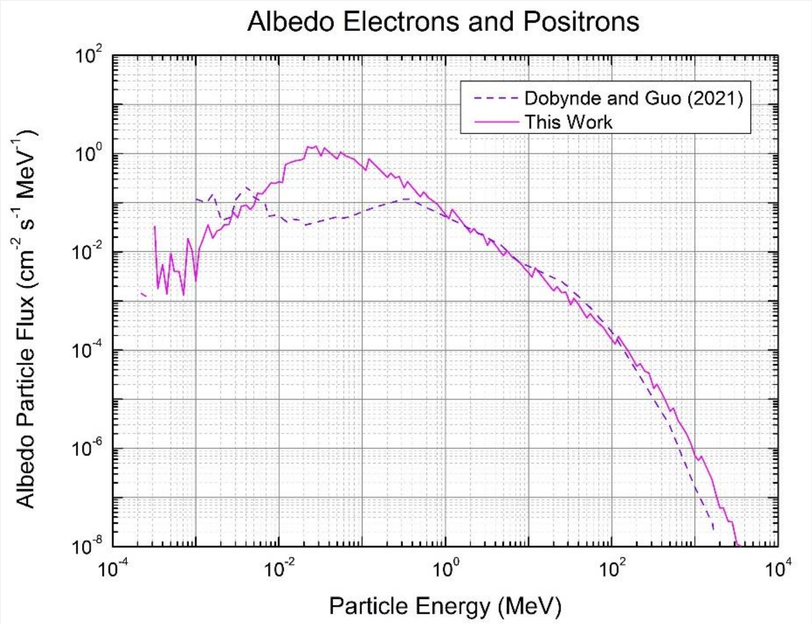


- Albedo particles recorded as all secondary particles exiting the lunar surface in an upwards direction
- Observation volume is 5x5 m^2 surrounding the focus of the incoming GCR particles
- Albedo e- e+ shows combined flux of albedo electrons and positrons









- Results benchmarked against the work of Dobynde and Guo (2021) showing good agreement overall
- Largest discrepancy is in an over-estimation of e-/e+ flux in the energy range 10^{-2} to 10^{0} MeV

Dobynde, M. I., & Guo, J. (2021). Radiation environment at the surface and subsurface of the Moon: Model development and validation. Journal of Geophysical Research: Planets, 126, e2021JE006930. https://doi.org/10.1029/2021JE006930

ICRP145 Human Phantoms

Anatomically accurate computational human phantoms
- Male: 73 kg, 176cm tall
- Female: 60 kg, 163 cm tall
- 186 organs/tissues constructed by over 8 million tetrahedrons

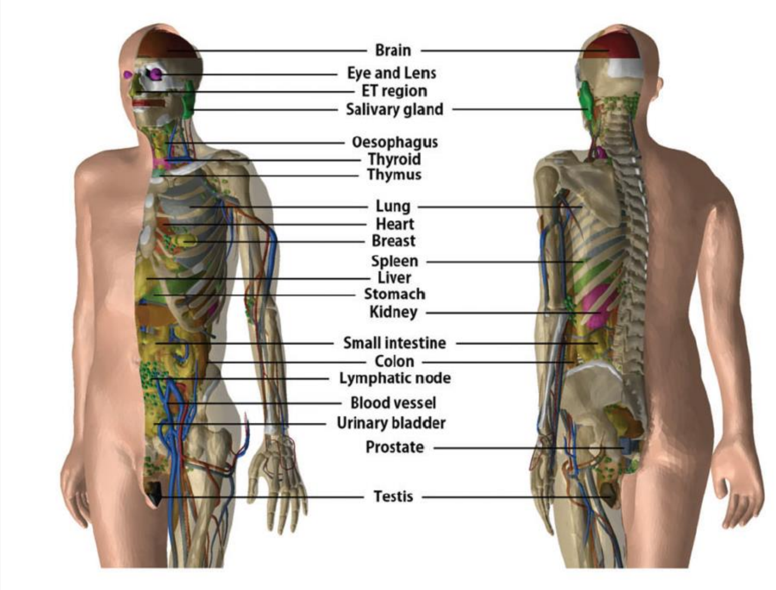
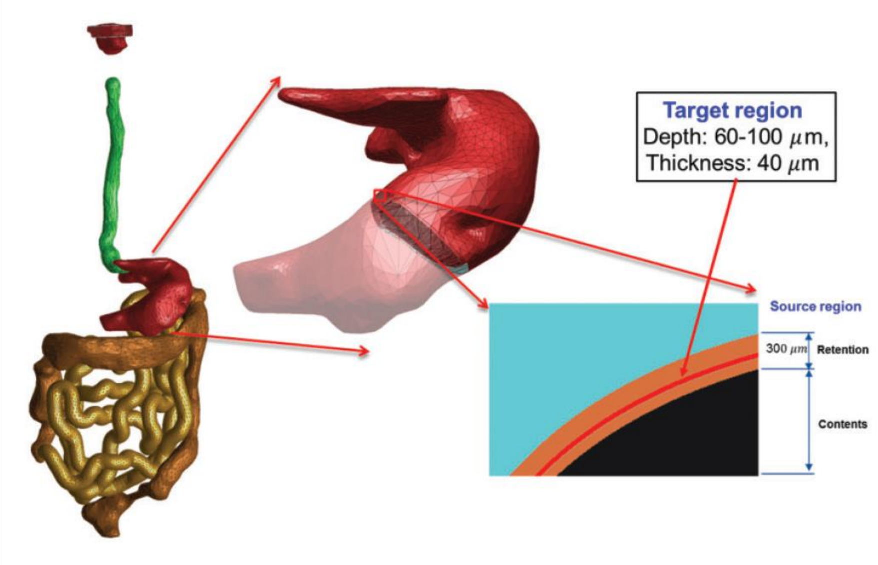
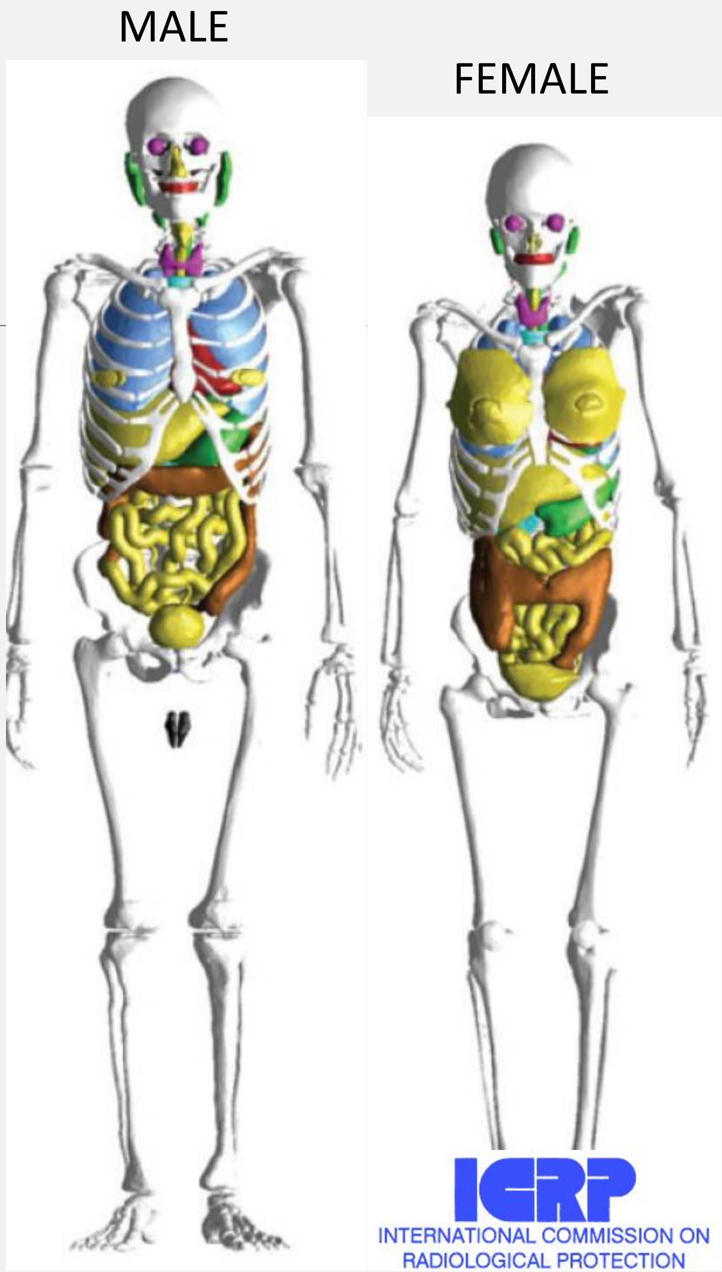


Fig. 6.1. Mesh-type ICRP adult male reference phantom.





Images from Kim, C.H. *et al.* 2020. ICRP publication 145: adult mesh-type reference computational phantoms. Annals of the ICRP, 49(3).

Table 1. Example career Effective dose limits for 1-year missions for a 3% REID and estimates of average life-loss if death occurs.

	E(mSv) for a 3% REID (Ave. Life-loss per Death, y)	
Age at Exposure, y	**Males**	**Females**
30	620 (15.7)	470 (15.7)
35	720 (15.4)	550 (15.3)
40	800 (15.0)	620 (14.7)
45	950 (14.2)	750 (14.0)
50	1150 (12.5)	920 (13.2)
55	1470 (11.5)	1120 (12.2)

Table 2. Dose limits for Short-term or Career Non-Cancer Effects (in mGy-Eq. or mGy).

Organ	**30-day Limit**	**1 Year Limit**	**Career Limit**
Lens*	1000 mGy-Eq	2000 mGy-Eq	4000 mGy-Eq
Skin	1500	3000	6000
BFO	250	500	Not applicable
Heart**	250	500	1000
CNS***	500	1000	1500
CNS*** ($Z \geq 10$)	-	100 mGy	250 mGy

Cucinotta, F. (2010) Radiation Risk acceptability and limitations. https://three.jsc.nasa.gov/articles/AstronautRadLimitsFC.pdf.

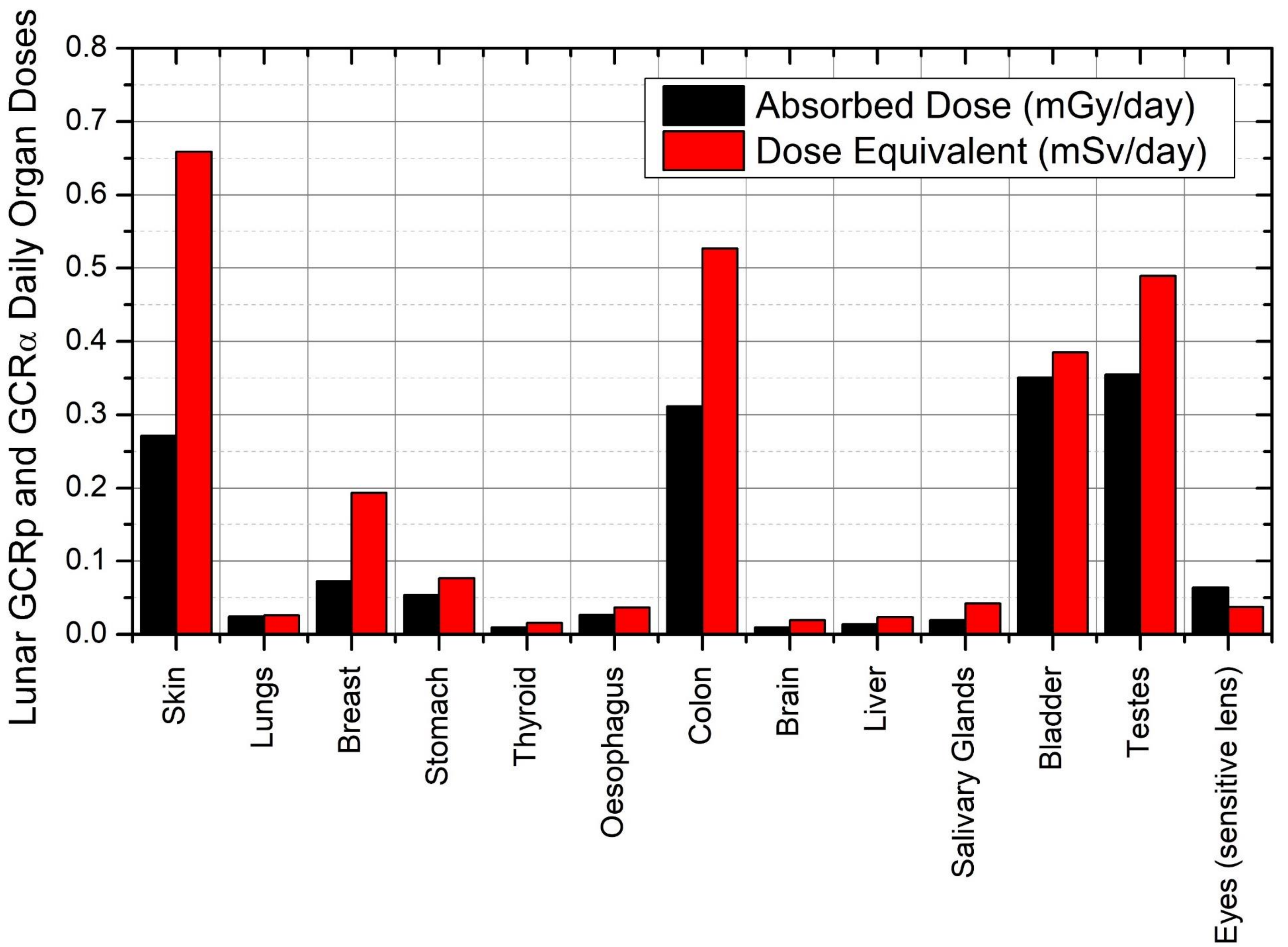
Calculating Daily Organ Exposures on the Moon

- Absorbed dose, **D** (mGy), to organs/tissues calculated as average energy deposited in each tissue divided by their respective weight.
- Average radiation quality factor, **Q**, calculated from microdosimetric spectra yd(y) vs y obtained within each organ/tissue.
- Dose equivalent, **H** (mSv), calculated as:
  - H (mSv) = D (mGy) * Q

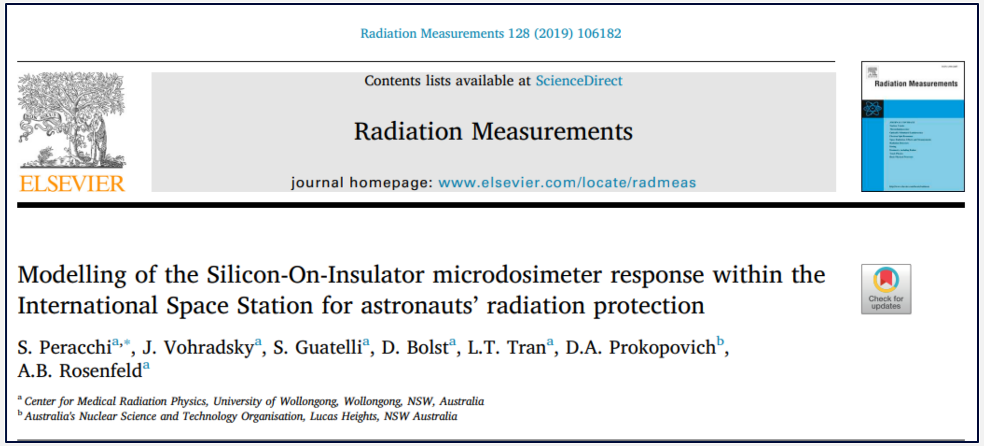
Mission	Total Duration	Lunar Surface Duration	Average Radiation Dose*
Apollo 11	08 days, 03 hrs, 13 mins	21 hrs, 38 mins	0.18 rad
Apollo 12	10 days, 4 hrs, 31 mins	31 hrs, 31 mins	0.58 rad
Apollo 14	09 days, 01 min	33 hrs 31 mins	1.14 rad
Apollo 15	10 days, 01 hr, 11 mins	66 hrs, 54 mins	0.30 rad
Apollo 16	11 days, 01 hr 51 mins	71 hrs, 2 mins	0.51 rad
Apollo 17	12 days, 13 hrs, 51 mins	74 hrs, 59 mins	0.55 rad

Solar flare during Apollo 14

Image/table from Lloyd, C. W., Townsend, S., Reevers, K. K., *Space Radiation* [PowerPoint presentation], Nasa Human Research Program. **URL:** https://www.nasa.gov/sites/default/files/atoms/files/space_radiation_ebook.pdf


Lunar GCRp and GCRα Daily Organ Doses
Absorbed Dose (mGy/day)
Dose Equivalent (mSv/day)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Skin
Lungs
Breast
Stomach
Thyroid
Oesophagus
Colon
Brain
Liver
Salivary Glands
Bladder
Testes
Eyes (sensitive lens)

Characterising Si Microdosimeters in a Lunar Radiation Field



Radiation Measurements 128 (2019) 106182

Contents lists available at ScienceDirect

Radiation Measurements

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Modelling of the Silicon-On-Insulator microdosimeter response within the International Space Station for astronauts' radiation protection

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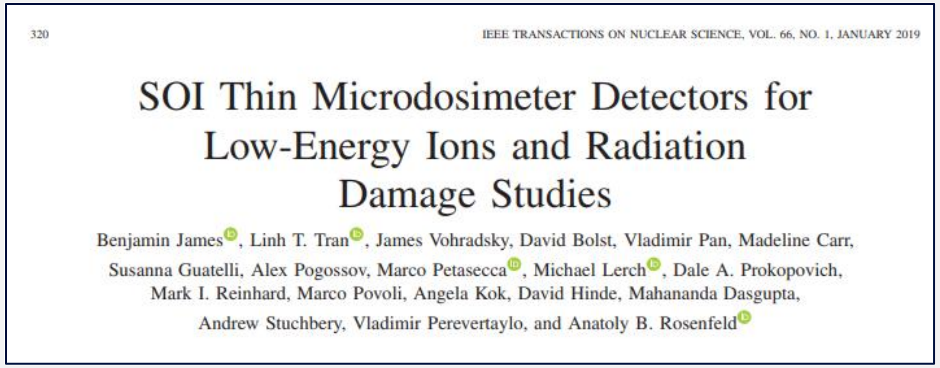
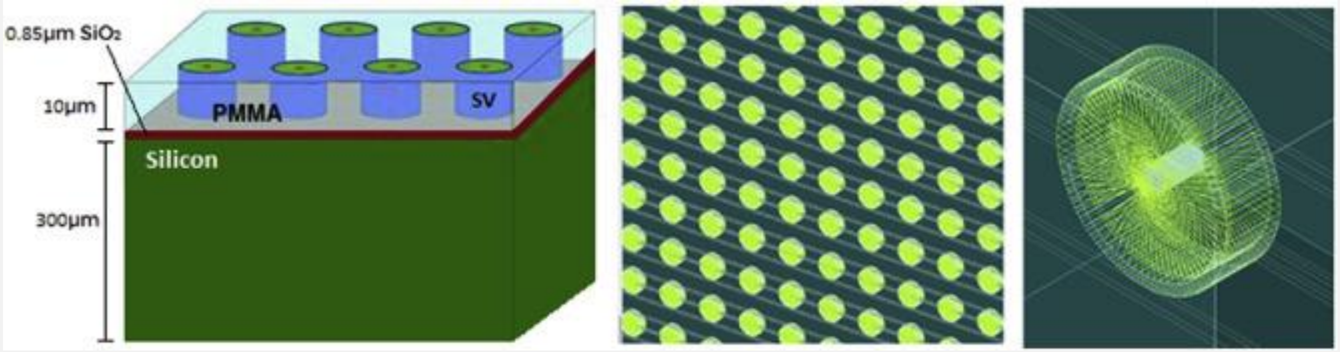
[b] Australia's Nuclear Science and Technology Organisation, Lucas Heights, NSW Australia

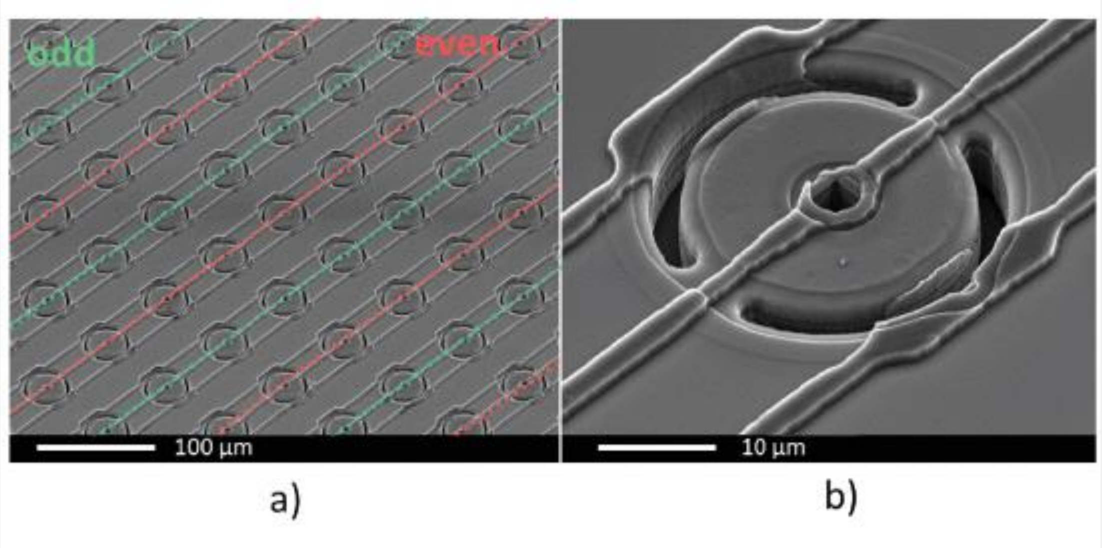


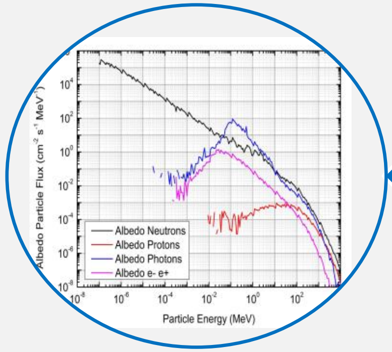
320 IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 66, NO. 1, JANUARY 2019

SOI Thin Microdosimeter Detectors for Low-Energy Ions and Radiation Damage Studies

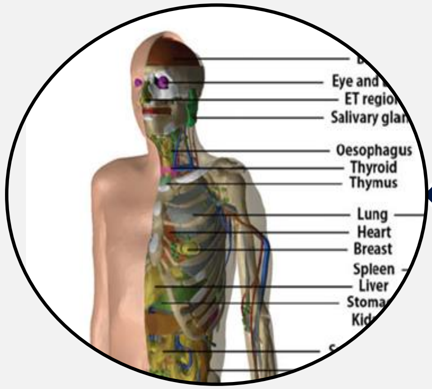
Benjamin James, Linh T. Tran, James Vohradsky, David Bolst, Vladimir Pan, Madeline Carr, Susanna Guatelli, Alex Pogossov, Marco Petasecca, Michael Lerch, Dale A. Prokopovich, Mark I. Reinhard, Marco Povoli, Angela Kok, David Hinde, Mahananda Dasgupta, Andrew Stuchbery, Vladimir Perevertaylo, and Anatoly B. Rosenfeld



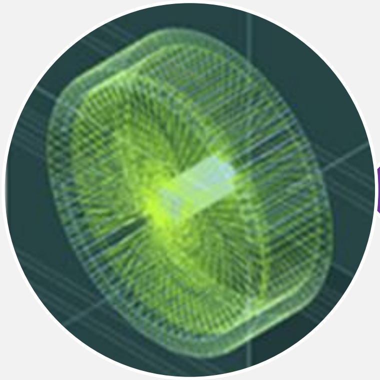




Successful simulations of secondary radiation environment on the Lunar Surface



Preliminary organ dose rates calculated for humans on lunar surface

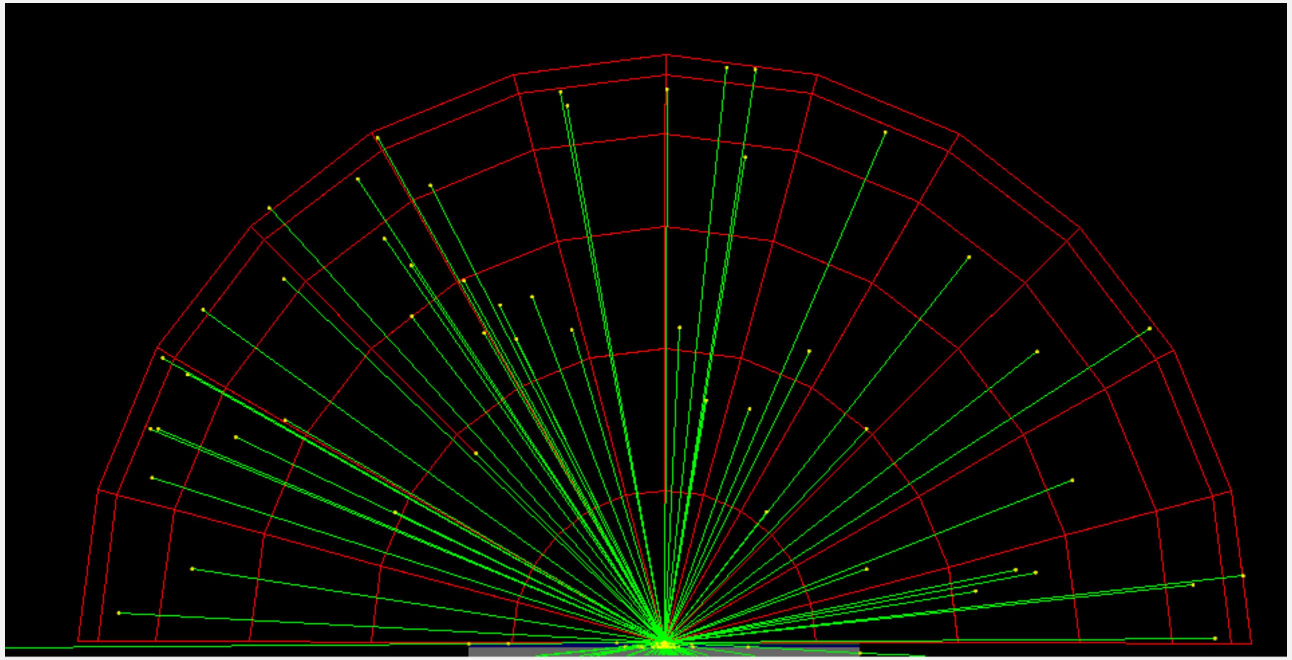


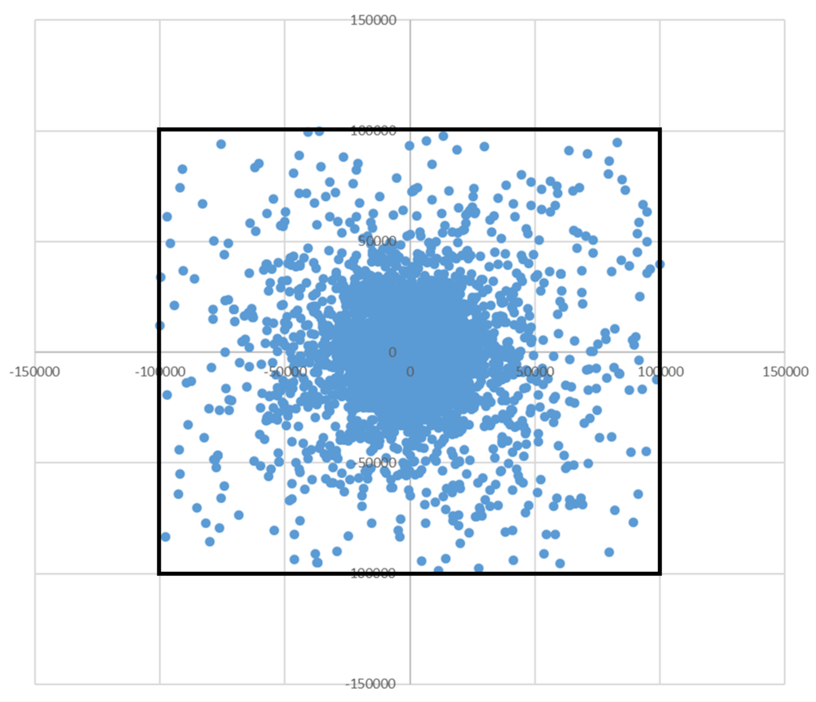
Future work will characterise Silicon Microdosimeters in Lunar Radiation Environment

UNIVERSITY OF WOLLONGONG AUSTRALIA

CENTRE FOR MEDICAL RADIATION PHYSICS

Simulation Geometry





RADIUS (mm)	% of Total Secondaries
4000	90.75
5000	93.33
10000	97.13
50000	99.67
100000	99.97

The mushroom microdosimeter structure used in this paper is called a trenched 3-D and it consists of 3-D cylindrical SVs with a core columnar n^+ region and each SV is surrounded with p^+ trench to form a p-n-junction. The mushroom microdosimeter has a thickness of 9.1 μm and diameter of 30 μm fabricated on high resistivity p-type silicon ($> 10\ \mathrm{k\Omega \cdot cm}$). Each SV is surrounded with a trench of air with p^+ doping on the outer wall, designed to physically eliminate the possibility of charge generated outside the SV from being collected. In order to electrically connect SVs in an array, two half-moon trenches were made by leaving some silicon present for the metal contacts between the inner n^+ electrodes. Outer Al busses were connected to p^+ outer electrodes of 3-D SVs [9]. Fig. 2 shows SEM images of arrays of (a) mushroom SVs and (b) a single SV.

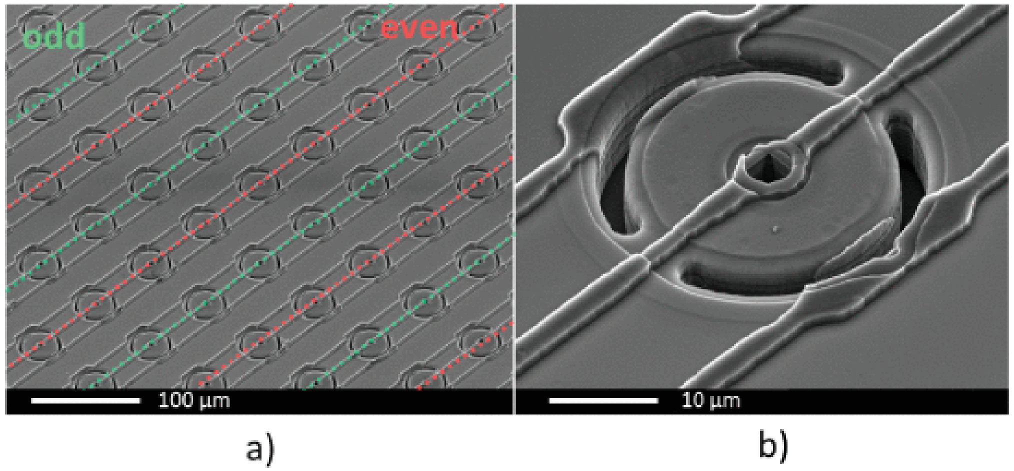
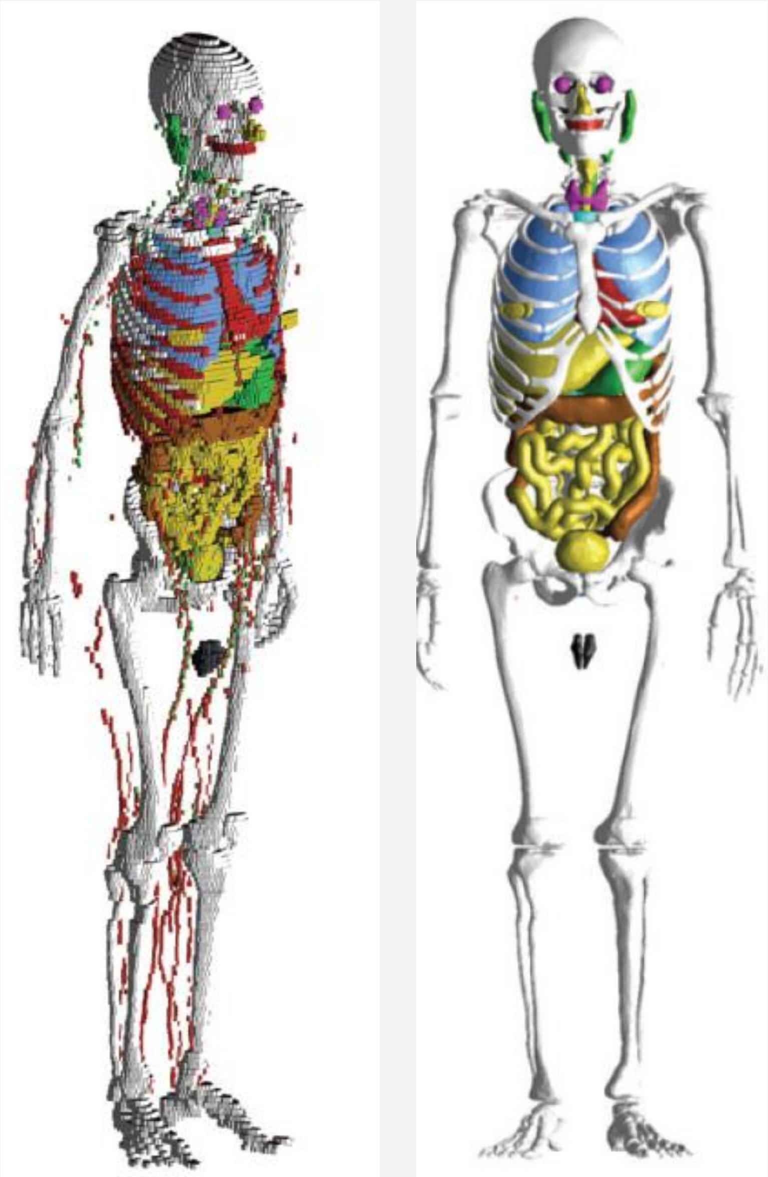


Fig. 2.
SEM images of 3-D mushroom microdosimeter SVs. (a) Array of SVs. (b) Single SV [8].

B. James et al., "SOI Thin Microdosimeter Detectors for Low-Energy Ions and Radiation Damage Studies," in IEEE Transactions on Nuclear Science, vol. 66, no. 1, pp. 320-326, Jan. 2019, doi: 10.1109/TNS.2018.2885996.



Images from Kim, C.H. *et al.* 2020. ICRP publication 145: adult mesh-type reference computational phantoms. Annals of the ICRP, 49(3).

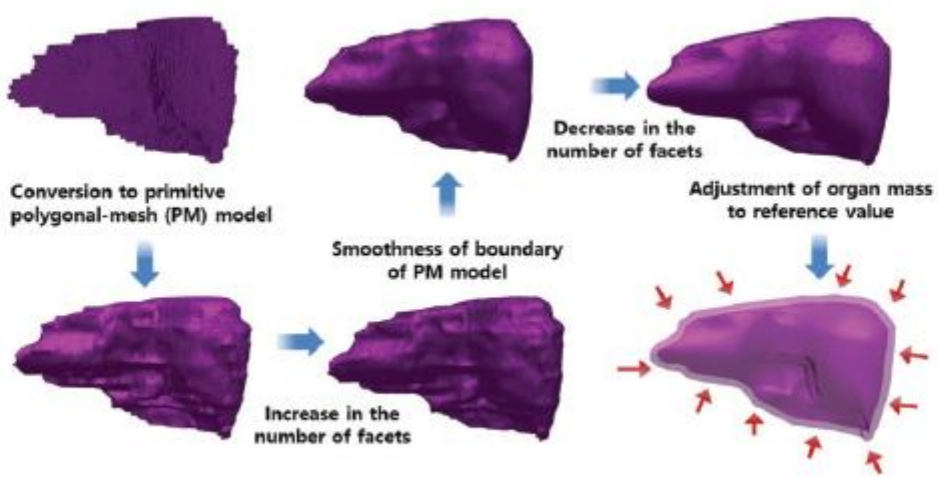


Fig. 3.1. Conversion procedure applied for most organs and tissues.

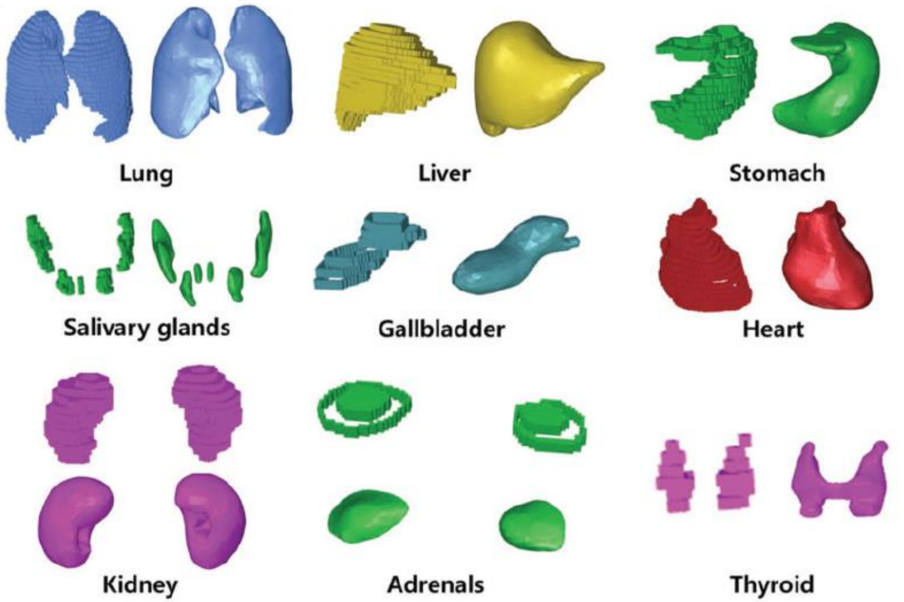


Fig. 6.3. Comparison of organs and tissues of the mesh-type male phantom with those of the *Publication 110* (ICRP, 2009) male phantom.

Benchmarking of Results (Reitz *et al.*, 2012)

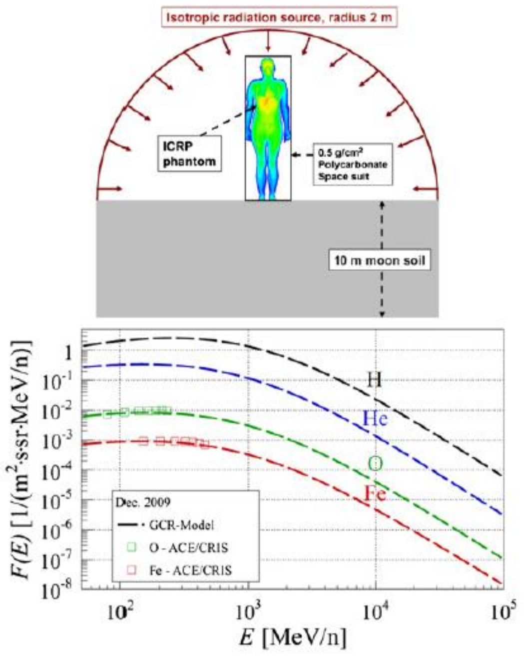


Fig. 2. Top—Simulation scenario for the estimation of the radiation exposure on the surface of Moon. Bottom—Galactic cosmic ray energy spectra (Matthiae et al., under review) for selected nuclei during solar minimum. The oxygen and iron spectra are compared to ACE/CRIS data during the very deep solar minimum in the end of 2009. (For interpretation of the reference to color in this figure, the reader is referred to the web version of this article.)

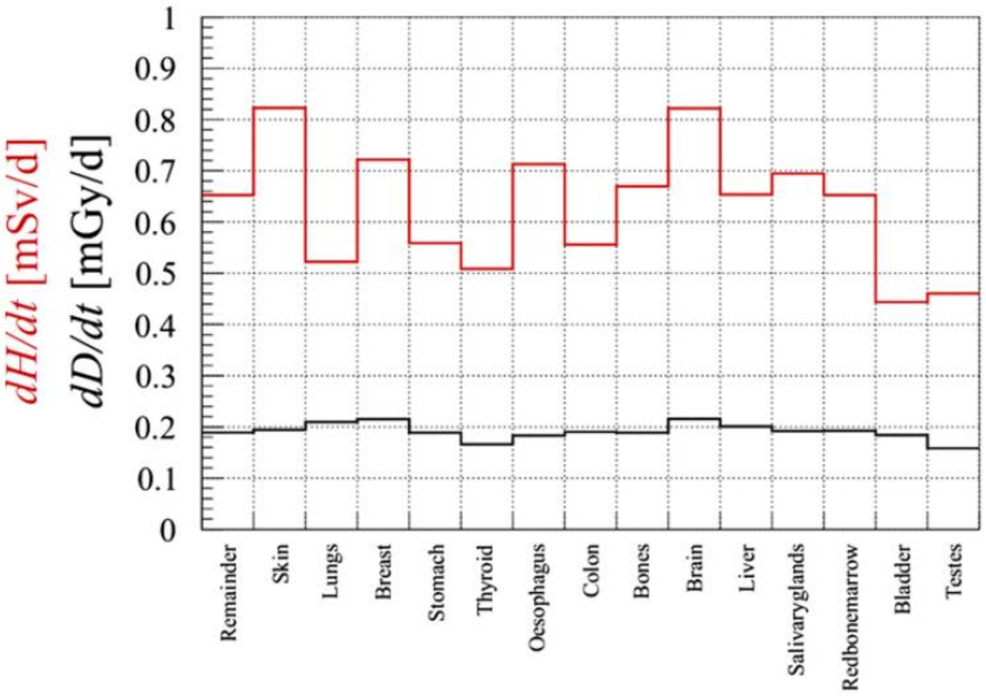


Fig. 3. Organ absorbed dose rates dD/dt (lower line) and dose equivalent rates dH/dt (upper line) from galactic cosmic rays for solar minimum conditions on the lunar surface.

Figures from Reitz, G., Berger, T. and Matthiae, D., 2012. Radiation exposure in the moon environment. *Planetary and Space Science*, 74**(1)**, pp.78-83.