Radiation and Nuclear Technology in Planetary Cave Environments

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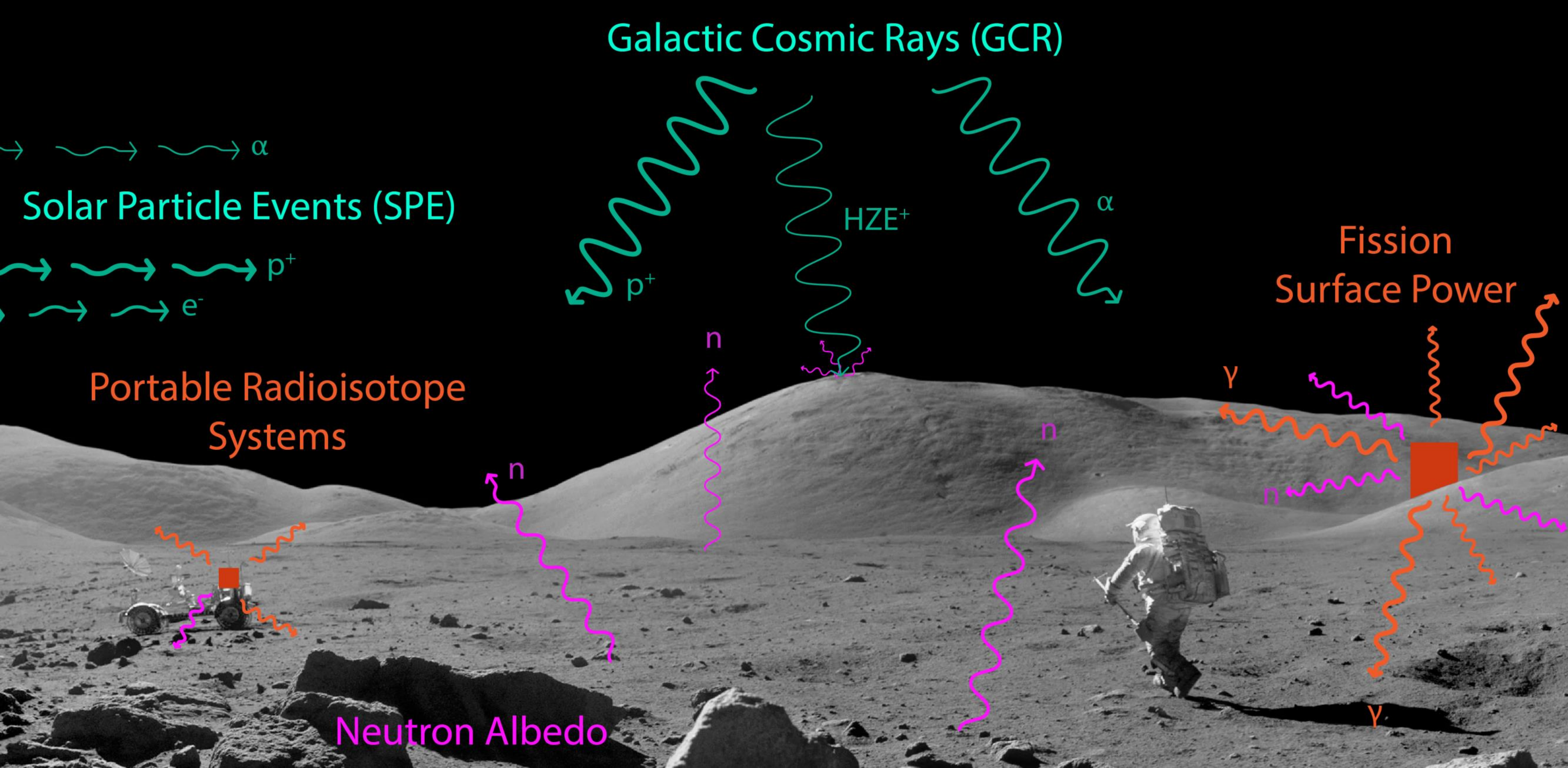
Introduction

- Motivation:
  - We are a group of nuclear/radiation engineers and geologists at NASA
  - We live in cave central USA – Tennessee-Alabama-Georgia (TAG)
  - Interesting work and interesting hobbies are bound to intersect!
- Three areas of study:
  1) Cosmic Ray Sheltering in Planetary Caves
  2) Fission Power for Surface or Subsurface Operations
  3) Portable Radioisotope Power Systems for Cave Exploration
- Modelling and simulation tools for combining realistic source environments with realistic geometries

Sources of Ionizing Radiation on the Lunar Surface



NASA Radiation Dose Limits

NASA STD 3001 recently updated, includes:

Lifetime/Career Dose < 600 mSv

Nuclear Technology < 20 mSv per mission year

(Other detail especially regarding Solar events)

Protective Principle:

As Low As Reasonably Achievable (ALARA)

Sidenote on Mitigation Methods:

Reduce **Time** of Exposure / Increase **Distance** from Source / Increase **Shielding**

NASA-STD-3001, VOLUME 1, REVISION B

4.8.2 Career Space Permissible Exposure Limit for Space Flight Radiation

[V1 4030] An individual astronaut's total career effective radiation dose due to space flight radiation exposure **shall** be less than 600 mSv. This limit is universal for all ages and sexes.

4.8.4 Crew Radiation Limits for Nuclear Technologies

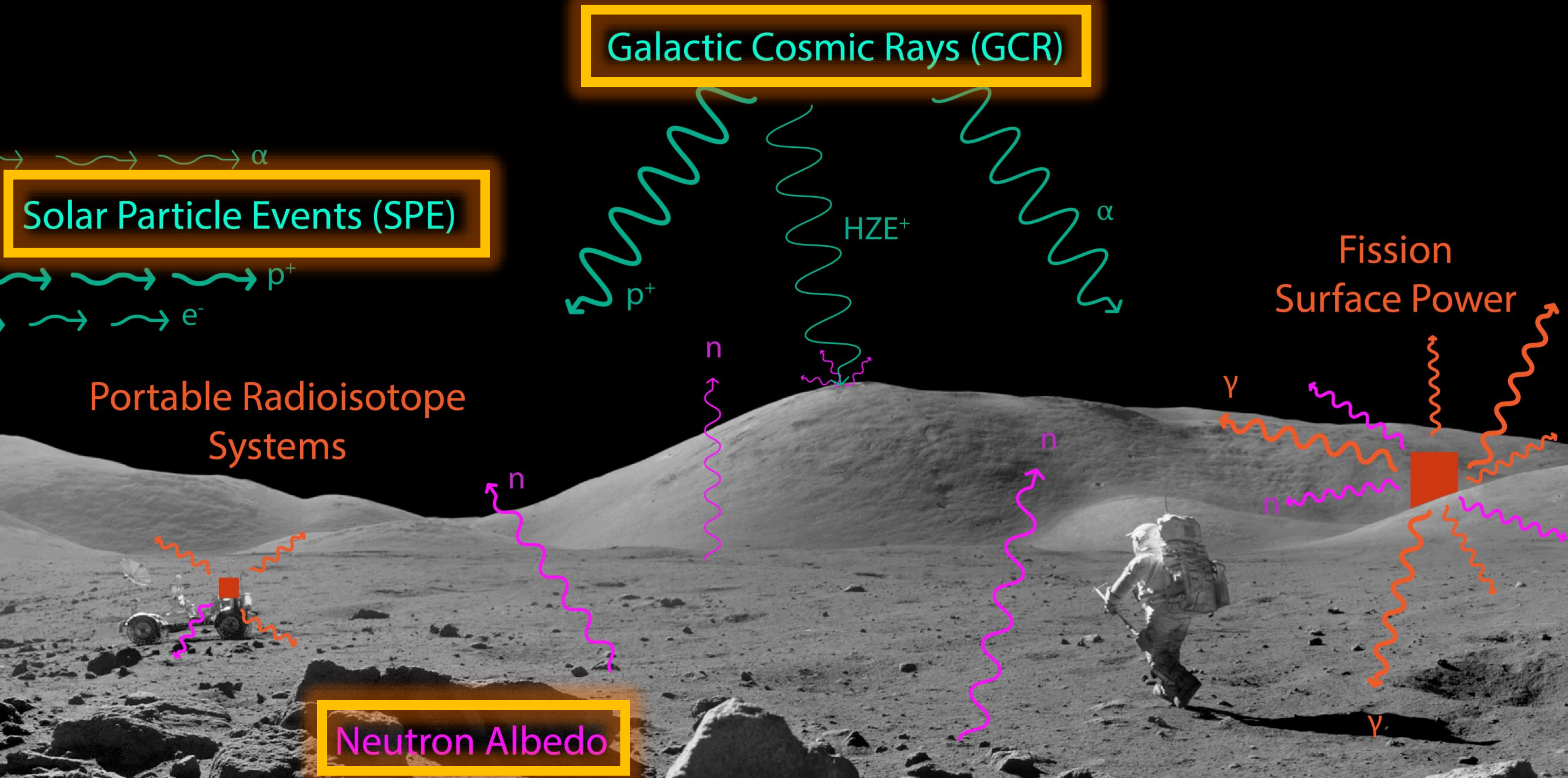
[V1 4032] Radiological exposure from nuclear technologies emitting ionizing radiation to crewmembers (e.g., radioisotope power systems, fission reactors, etc.) **shall** be less than an effective dose of 20 mSv per mission year (prorated/extrapolated to mission durations) and utilizing the ALARA principle.

[Rationale: This limit is based on not adding more than 10% radiation exposure beyond the space environment radiation of the mission. Based on an analysis for a surface-based mission (see Figure 2, Effective Dose [mSv per Earth Mission Day] Variation with Solar Cycle), the radiation environment exposure is approximately 0.5 mSv per day; and 10% of this value sets the standard to 0.05 mSv per day and ~20 mSv/mission year. This standard is applied to both surface and free-space missions regardless of mission solar cycle. Twenty (20) mSv was also based on the occupational workers' limit guideline from the ICRP, The 2007 Recommendations of the International Commission on Radiological Protection, ICRP 103, 2007).

For a typical surface power application, the allowable astronaut dose can be converted to an effective reactor dose for shield sizing. The effective reactor dose would be calculated by estimating the time an astronaut spends in a shielded habitat versus the time spent during unshielded EVAs over a typical mission timeline. Exact mission assumptions should be considered when performing the calculation; parameters should include estimates of time in a habitat, habitat shielding, and EVA frequency. Example parameters to be considered: time fraction (67%) in the habitat, habitat shielding (20 g/cm^2), terrain shielding, distance from source, line of sight to source, and time fraction (33%) of performing EVAs.

Space radiation and radioactive source tradeoff for a waiver of standard consideration: For missions that are leveraging nuclear sources for a propulsion system, the tradeoff of reduced mission duration due to faster transit which reduces the crew exposure to space flight radiation exposure should be considered compared to the increased exposure due to the nuclear source. For example, if the nuclear propulsion system saved 90 days of exposure during the transit to Mars which equates to 1.5 mSv/day × 90 days = 135 mSv "saved" space flight radiation exposure and the source generates 150 mSv, then the net exposure is +15 mSv. Other considerations for reduced mission time on engineering risks (systems reliability, logistics, etc.) and other human risks such as bone loss, renal stone development, and medical care should also be considered in the waiver process.]

SPE and Cosmic Ray Sheltering



Cosmic Ray Sheltering

- Lava tubes and pits act as natural radiation shields
  - Reduction of solar and cosmic radiation burden
  - May preserve crew health and hardware reliability
  - But, some radiation effects/trends are not intuitive

- There are many non-radiation related challenges for sheltering in planetary caves
  - Logistics of relocating habitation hardware and personnel
  - Risks of landing near relevant terrain

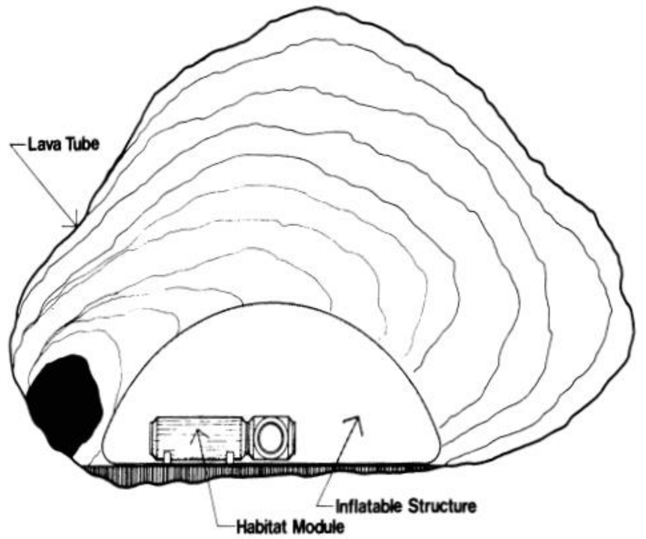
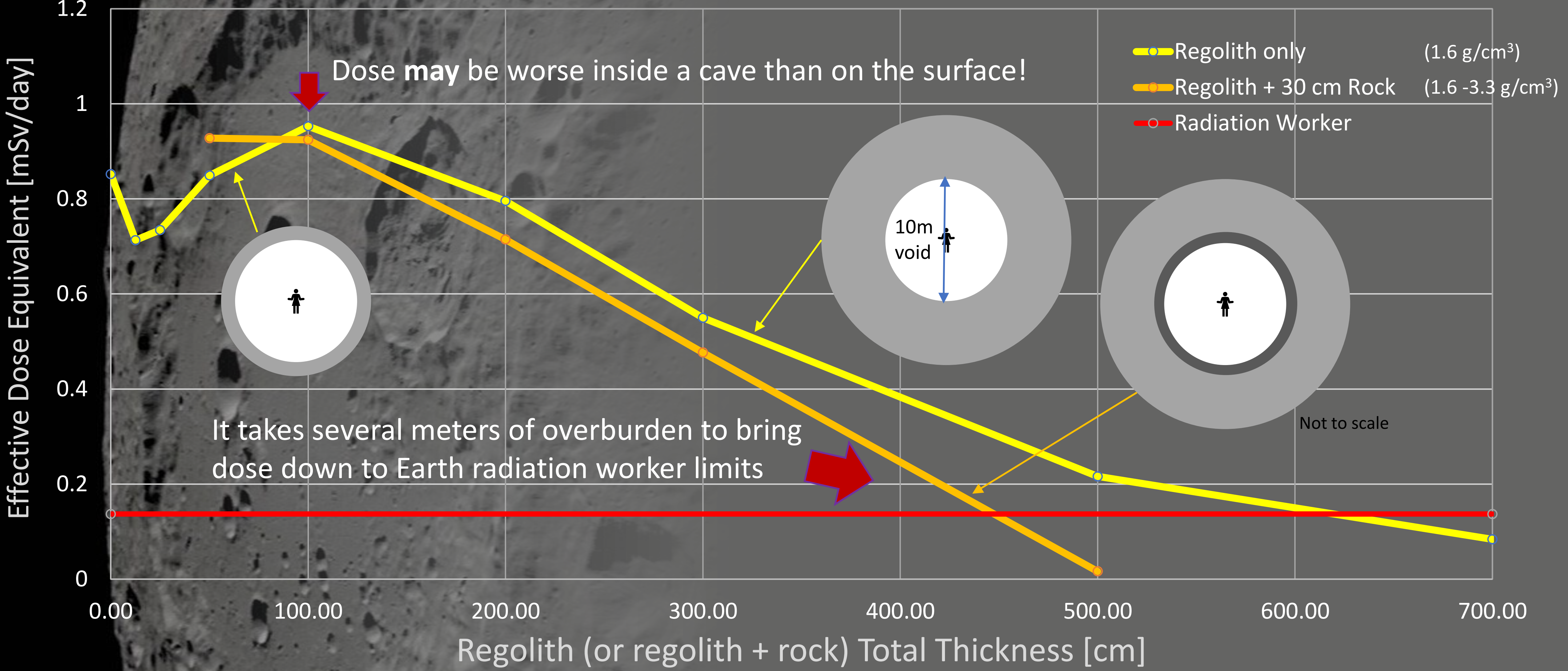


Fig. 1. Unpressurized lava tube cross-section with inflatable structure and habitat module[22)]

DeAngelis, Wilson, Clowdsley et al (2002)

Whole Body Effective Dose Rates from OLTARIS - mSv/day



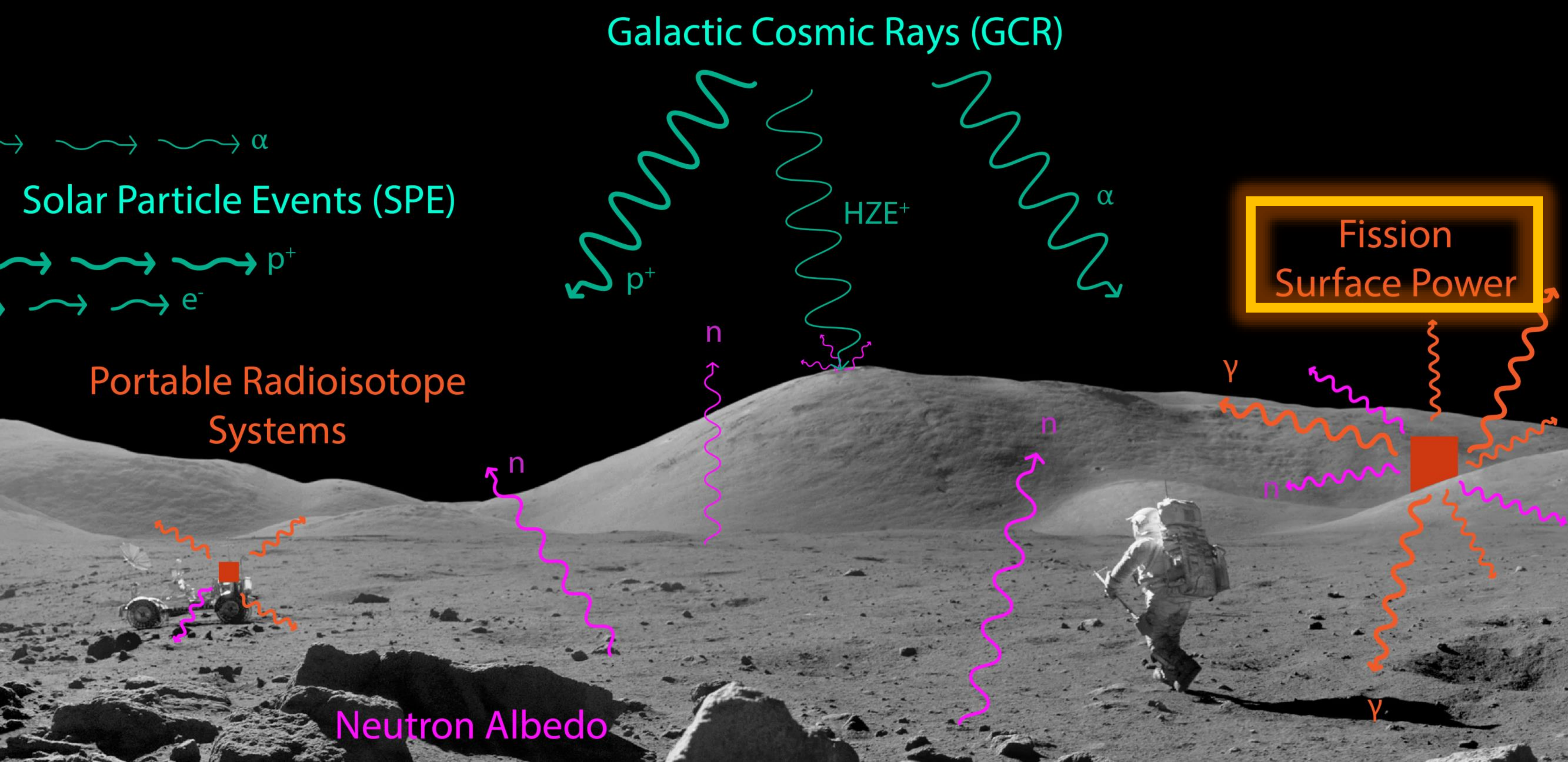
➢ **Dose depends strongly on regolith overburden characteristics: Thickness, Density, and Composition**

Calculations performed using:

- TARIS v5.0, 3D transport
- Environment: GCR, Lunar Surface, 1977 Solar Min (worst case)
- Geometry: spherical with FAX phantom

https://oltaris.nasa.gov/

Fission Surface Power Considerations



Fission Power for Surface or Subsurface Operations

Benefits:

- Round-the-clock power for long-term habitation modules or bases
- Applicable environments:
  - Lunar surface: Permanently shadowed regions, non-polar regions
  - Mars: Dust storms affecting solar power availability

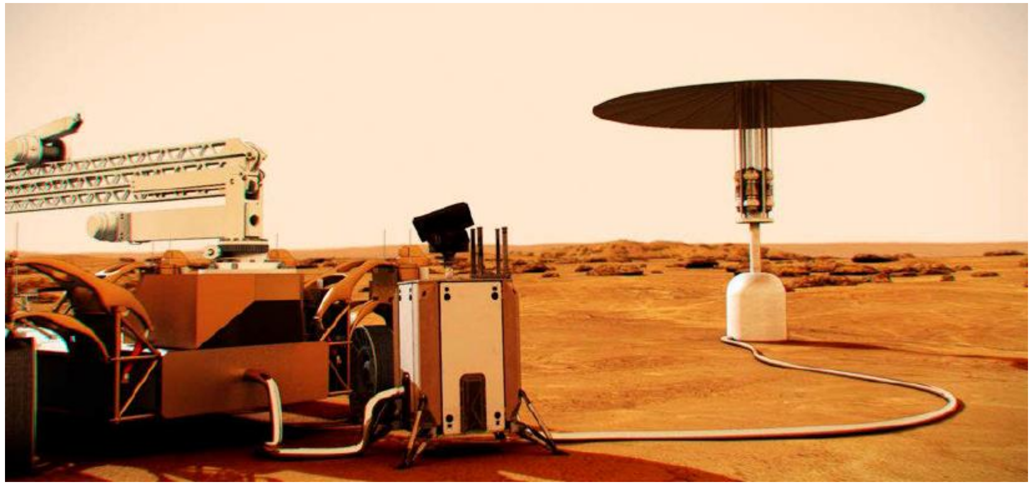


Image Credit: NASA

Image Credit: NASA

Fission Power for Surface or Subsurface Operations

Challenges:

- Large radiation source during operation mandates special placement considerations:
    - Additional shielding mass landed with power system OR
    - Large distances between habitat and power source OR
    - In-situ regolith restructuring/digging OR
    - Using natural features such as cave/pits, craters, etc
- Residual radiation after shutdown:
    - Post Shutdown Decay Products
    - Secondary Activation After Removal

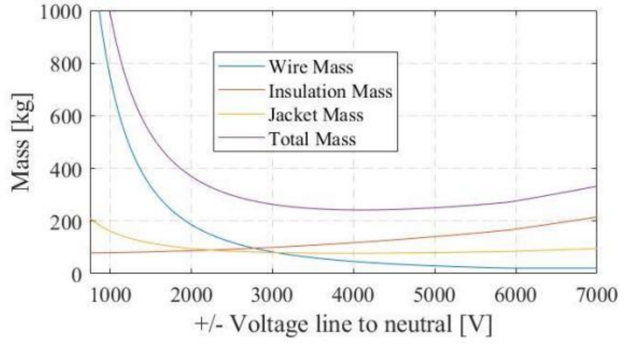
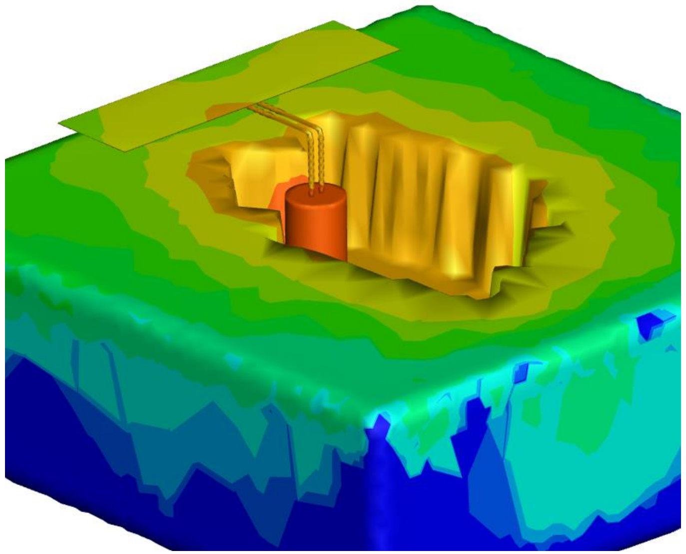
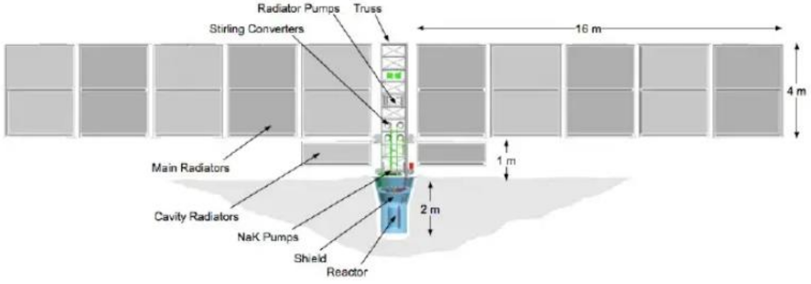


Figure 3: Total mass with breakdown for a 40 kW, 3 km, 95% efficient aluminum conductor DC cable.

Barth and Pike, 2022 – NASA Glenn
https://ntrs.nasa.gov/citations/20220002315



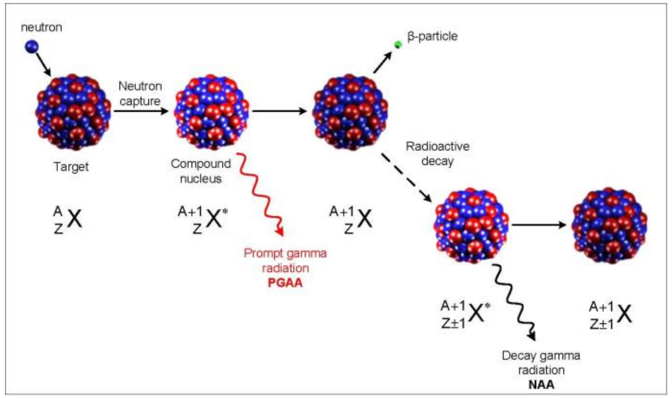


Houts and Mason, 2011 – NASA MSFC and GRC

Fission Power for Surface or Subsurface Operations

Scientific opportunity!?

- Reactors are useful for neutron-activation and spectral analysis
  - Composition Identification, Some forms of geochronology
- Radiation attenuation and secondary production measurements
- Inference of density and composition variation near reactors



CHANG'E-5 Lunar Sample Return

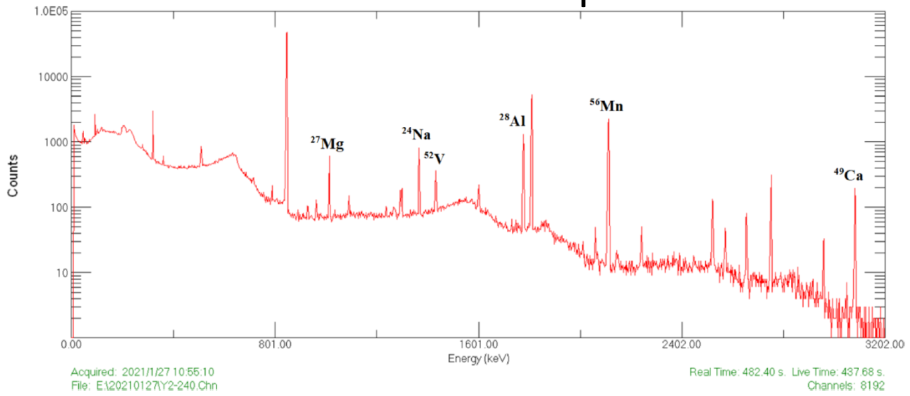
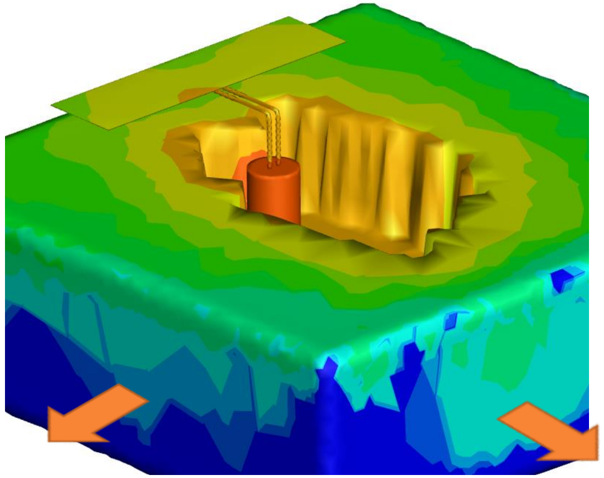
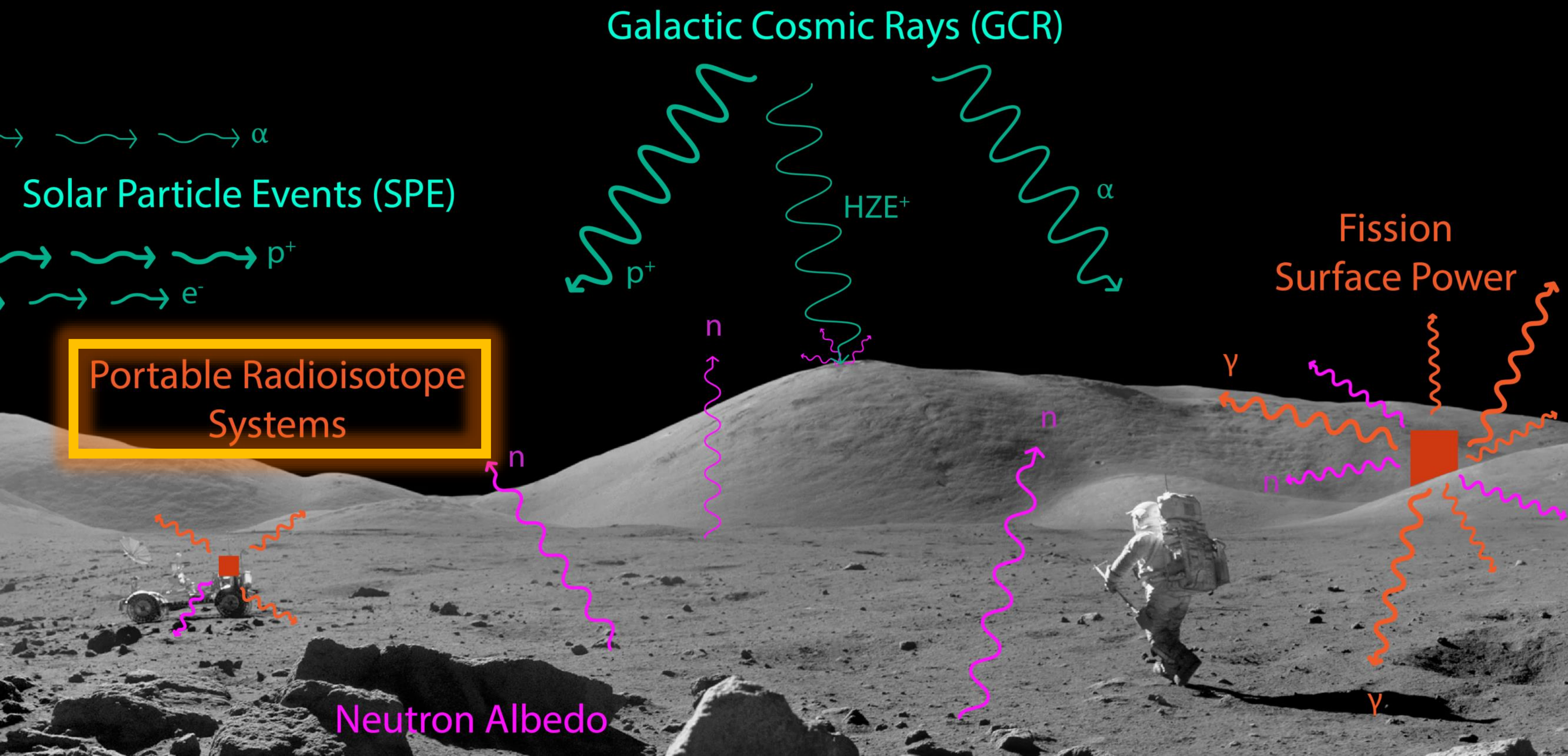


Figure 1. Spectrum of gamma rays for the short-time irradiated sample CE5C0800YJFM003. The spectrum was obtained using an HPGe detector combined with a digitized multichannel analyzer (MCA). The sample CE5C0800YJFM003 was irradiated for 300 s in the MNSR at the CIAE and counted for 437.68 s (live time) at a decay time of 17.25 min.

Instrumental Neutron Activation Analysis of Chang'E-5 Lunar Regolith Samples
Yonggang Yao, Caijin Xiao, Pingsheng Wang, Chunlai Li, and Qin Zhou
Journal of the American Chemical Society **2022** *144* (12), 5478-5484
DOI: 10.1021/jacs.1c13604



Portable Radioisotope Systems Considerations



Radioisotope Power Systems

- RPS were deployed on Apollo:
  - SNAP-27 on Apollo 12-17
  - Powered ALSEP Experiment Packages 1969-1977

- Flight proven on Voyager, Galileo, New Horizons, Curiosity, Perseverance…

- Look ahead to new alternatives with reduced cost and regulatory burden

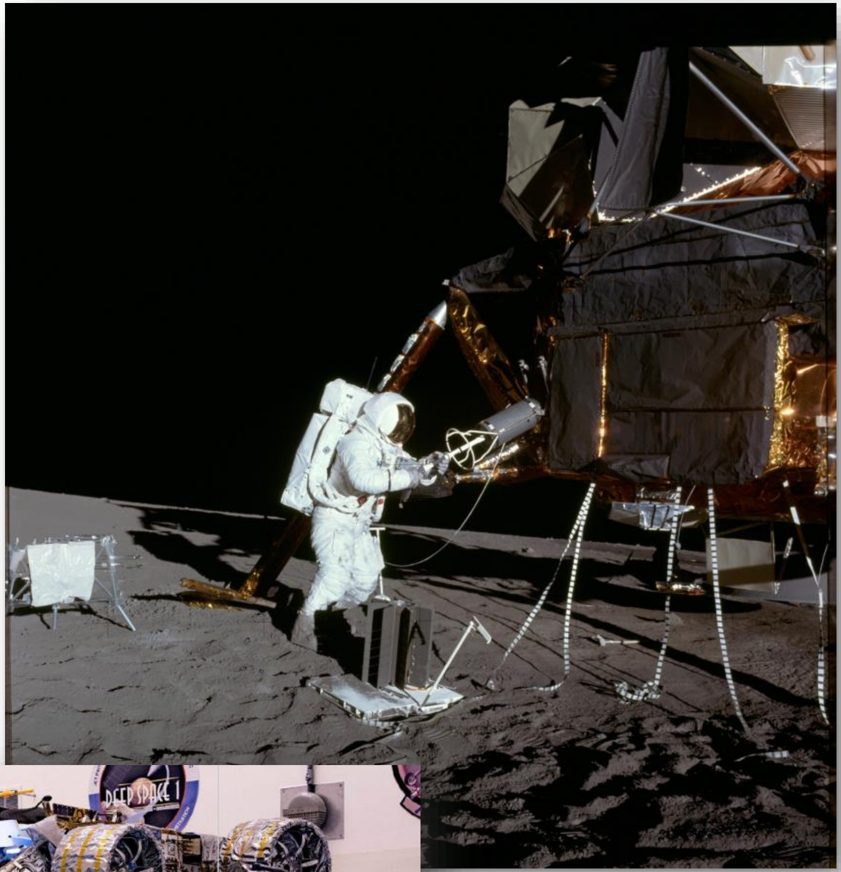


Image Credit: NASA

Image Credit: NASA

Portable Power Systems for Cave Exploration

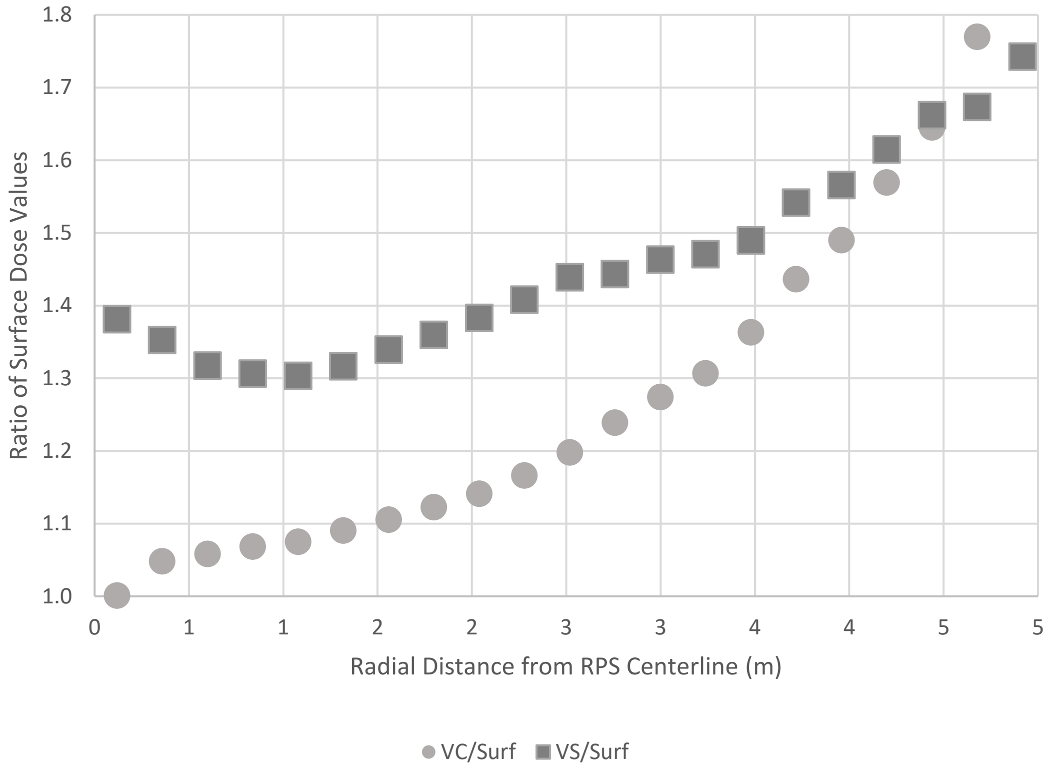
Benefits:

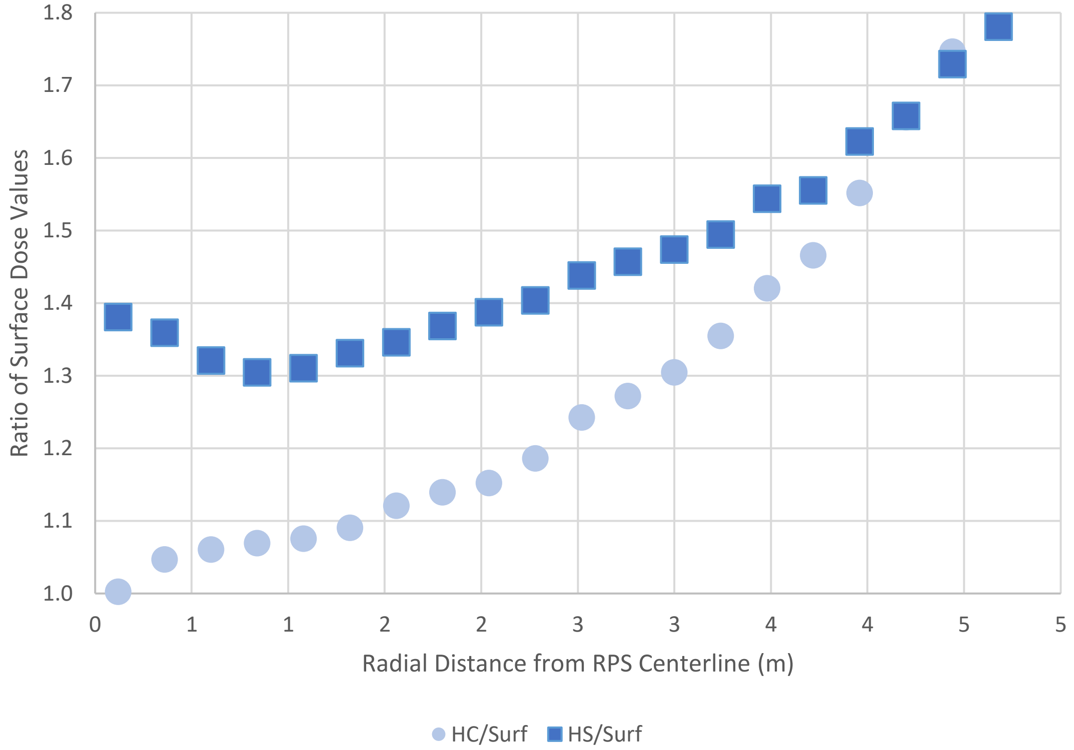
- No reliance on solar exposure
- Extended mission durations
- Enhanced mobility

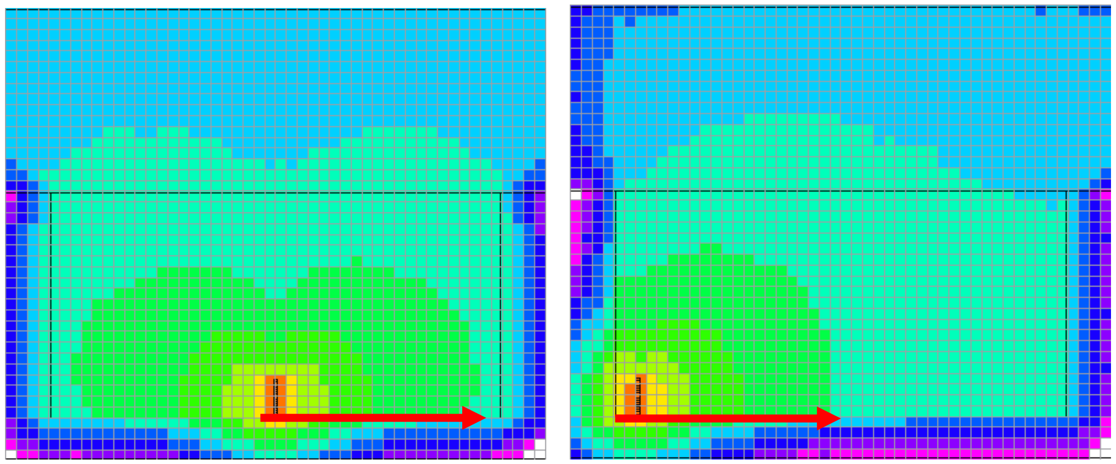
Potential Challenges:

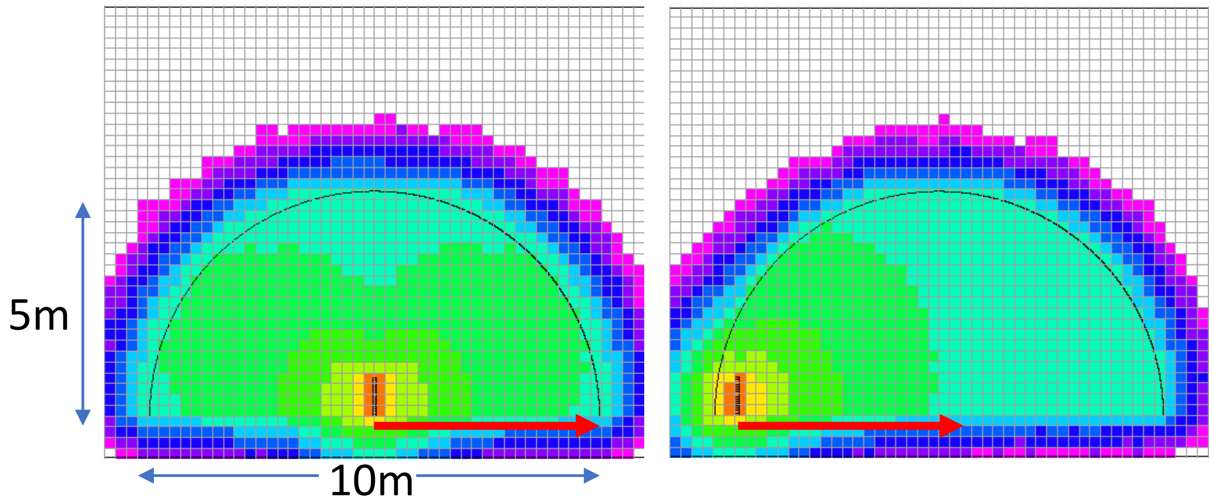
- Implications for personnel or sensitive equipment proximity
- Confined volumes are not the typical use-case
  - Additional ionizing radiation scatter from cave walls
  - Heat rejection to regolith differs from heat rejection to deep space

RPS Radial Dose Trends in Enclosed Spaces









Integrated Transport Modelling

Point Cloud Scan (e.g. SLAM/LiDaR)

⇩

Surface Mesh

⇩

Volume Mesh

⇩

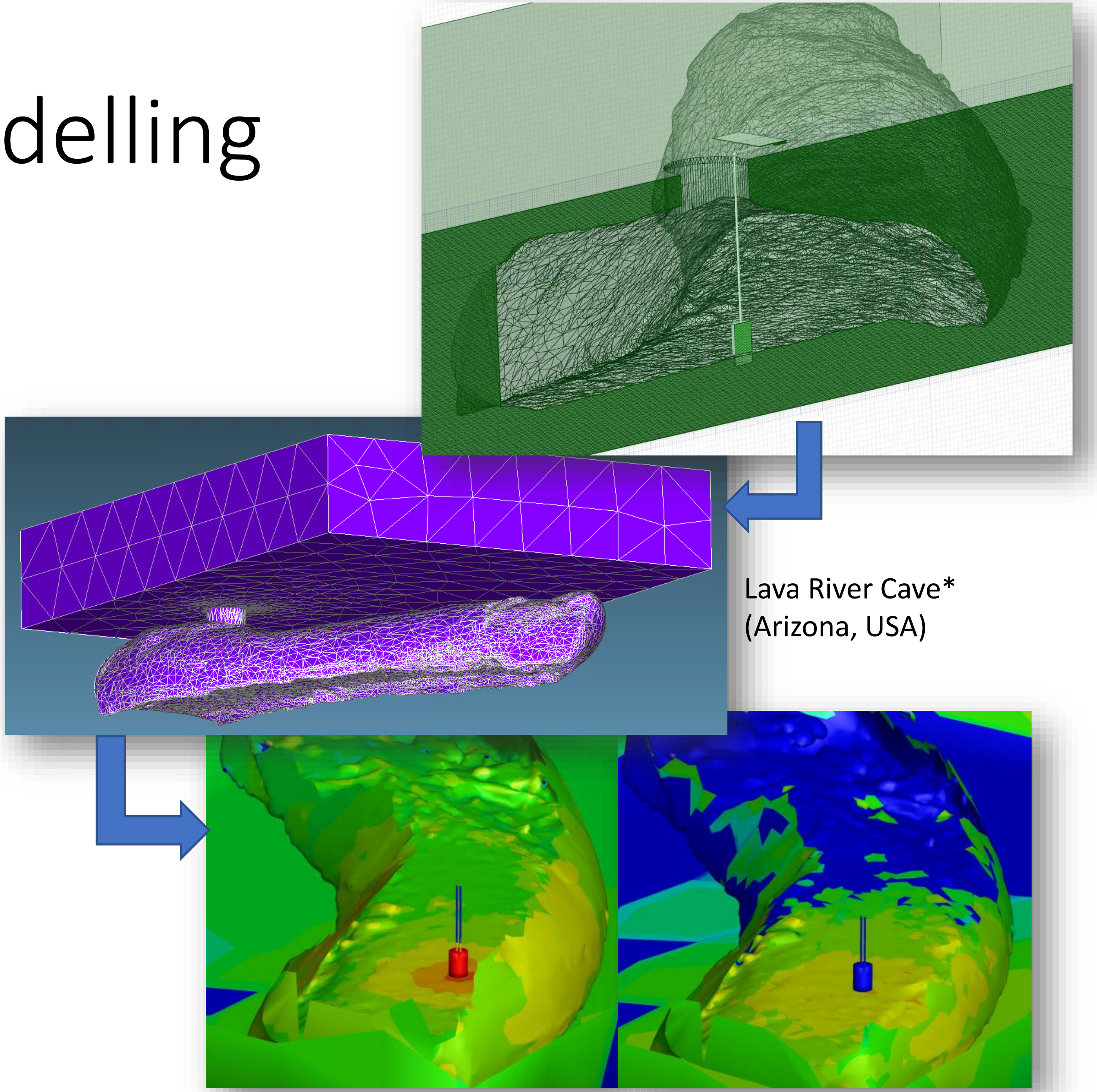
Define sources, materials
and dose values of interest

⇩

Transport Radiation

⇩

Visualization



Lava River Cave*
(Arizona, USA)

Reactor Source Skylight/Cosmic Source**
(not to the same color-scale between them)

*Real Cave Geometry - King W. E., Zanetti M. R., Hayward E. G., Miller K. A., 4th Int. Plan. Caves - 2023
**Artificial skylight, arbitrary reactor, and cosmic source applied for demonstration

Summary

- Many advantages of caves/pits for mitigating radiation effects from natural and technological sources
- Accurate material characteristics and geometry are required for radiation modelling
  - Input and feedback from planetary geological community are essential
- Fission surface power systems are in development
  - Would including a Neutron Activation mechanism be helpful to the planetary geology community? (e.g. geochronology?)
- Thank you to the organizers of the 4th International Planetary Caves Conference!
- Interested in collaboration? We are!

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