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NUCLEAR and EMERGING TECHNOLOGIES for SPACE

May 6-10, 2024
Santa Fe, NM

POWERING THE FINAL FRONTIER

NASA's Interest in Radiation Tolerance and Requirements of Candidate Technologies for Fission Surface Power and Further Relevance to Dynamic Radioisotope Power Systems

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Fission Surface Power Project

Phase 1 Requirements [1]	
Power	40 kWe at 10 years continuous power output.
Launch and Landing Loads	See attachment B of [1].
Radiation Protection	5 rem/yr above lunar background at 1 km.

Phase 1 Goals [1]	
Volume	4 m diameter cylinder, 6 m in length in the stowed launch configuration.
Mass	6000 kg.
Power Cycles	Multiple commanded and autonomous on/off power cycling.
User Load	0% to 100% power at the user interface.
Fault Detection and Tolerance	Minimize, detect, and respond to single-point failures. Maintain capability to continue providing no less than 5 kWe under faulted conditions.
System Transportability	Capable of operating from the deck of a lunar lander or be removed from the lander and placed on a separately provided mobile system and transported to another lunar site for operation.

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Fission Surface Power Project

- Phase 1: three design concepts
  - Lockheed Martin, BWXT, Creare
  - Westinghouse, L3Harris
  - Intuitive Machines, X-Energy, Maxar, Boeing
- FSP team is processing Phase 1 and preparing for Phase 2
- Project is actively studying radiation tolerance applications for FSP

Scope of Radiation Tolerance Work

- Gain knowledge to provide oversight for Phase 2
- Model, plan, and execute irradiation tests to enable technology maturation (pending annual budgets)
- Define radiation tolerance requirements

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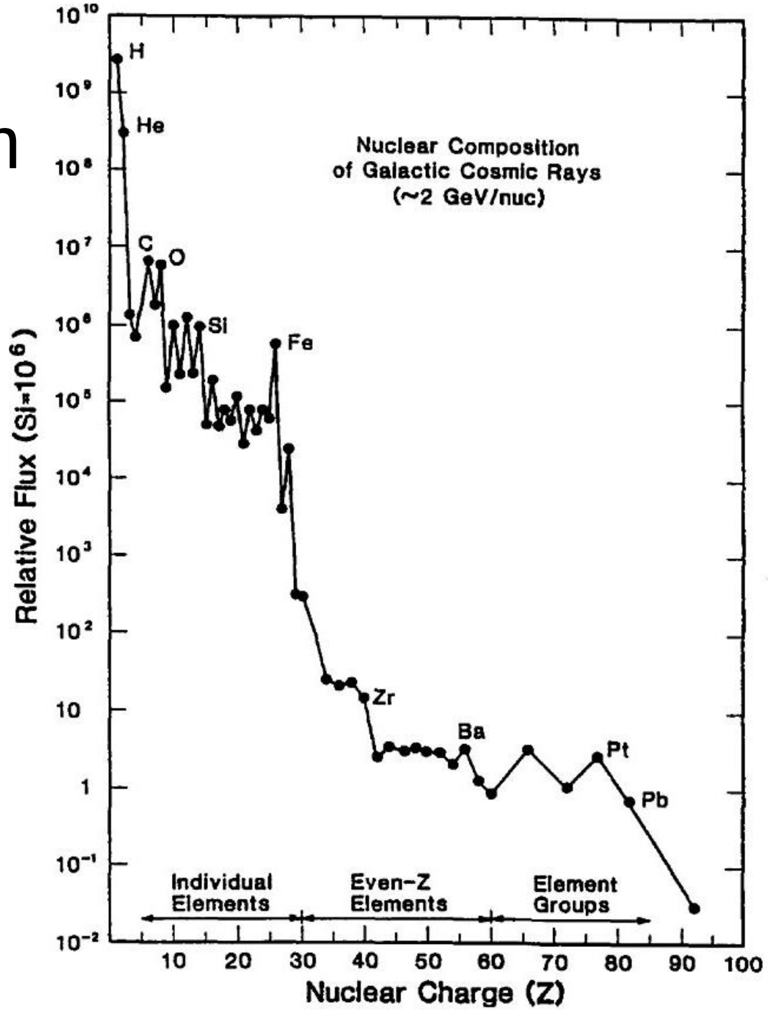
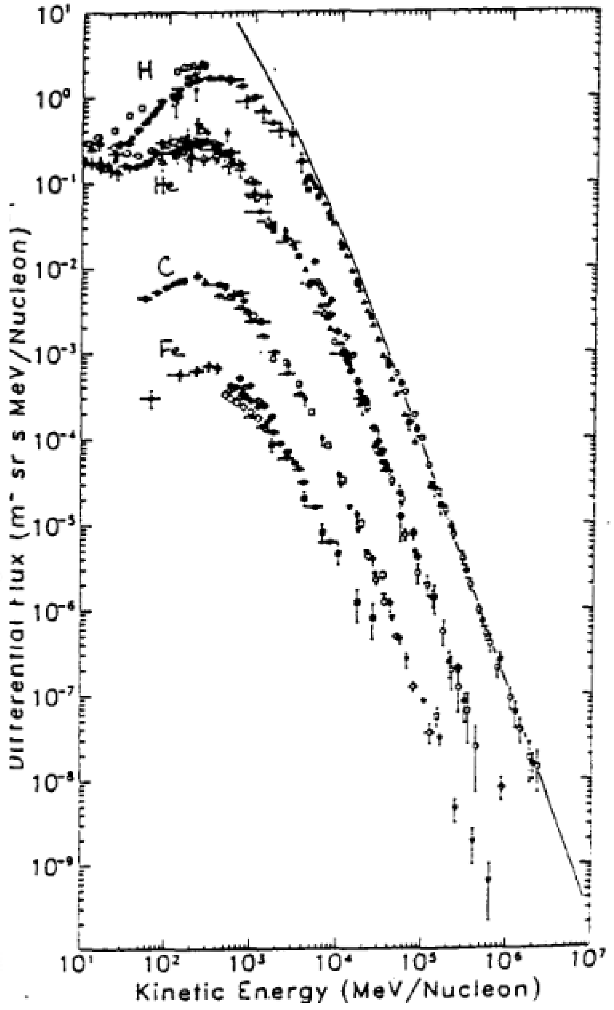
Radiation Environment

- Natural and induced environment (ex-core)
  - GCR: protons, heavy ions [2]
  - Solar: photons, protons, electrons [3], [4]
  - FSP: photons, neutrons
  - Add.: activation, bremsstrahlung, albedo, secondaries
- Will require various facilities
  - Gamma irradiation facilities
  - Ion beams
  - Reactors

Galactic Cosmic Rays

- Origins outside of solar system
- Stripped of electrons





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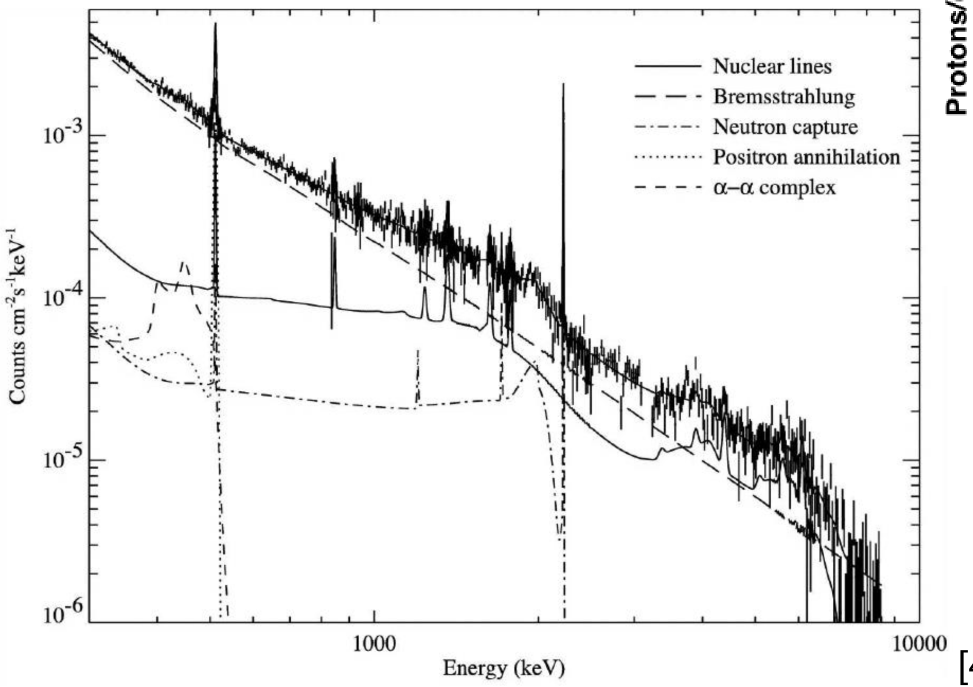
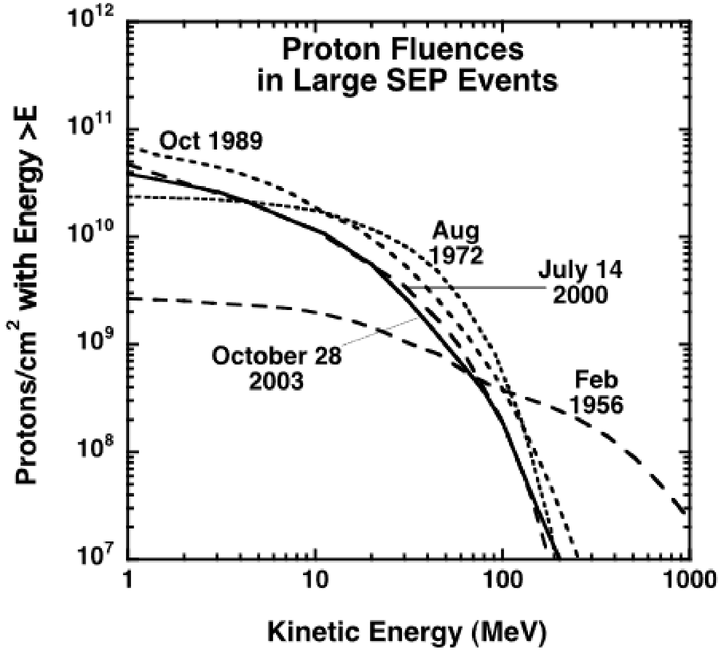
Solar Energetic Particles

- Coronal mass ejections
  - Mostly protons, electrons
- Solar flares
  - EM radiation
    - Radio to gamma
      - (Gamma shown)



[4]



[3]

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Induced Radiation

- FSP
  - At power conversion system: 10 Mrad, 5E14 n/cm^2 after 10 years [6]
  - In-core: will be higher radiation levels
  - At power electronics and controllers: will be lower radiation levels
- DRPS (Pu-238 shown)
  - At GPHS: 1 Mrad, 2E14 n/cm^2 after 20 years [7]
    - Spontaneous fission and alpha,n

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Testing (and Modeling) Candidate (Sub)Systems

- Polymers[5]
- Electronics[8]
- Magnetics[6]
  - SmCo: 2E18 n/cm^2, 2.8E5 krad [9], [10], [11]
- Structural?
- Other
  - Coatings, working fluids, etc.

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Polymers

- Proton, electron, gamma irradiation
  - Cross-linking: increase tensile strength
  - Chain-scission: broken polymer chains
- Temperature, radiation, time
- Outgassing
- Examples:
  - Epoxies
  - Dry lubricants
  - O-rings

[5]

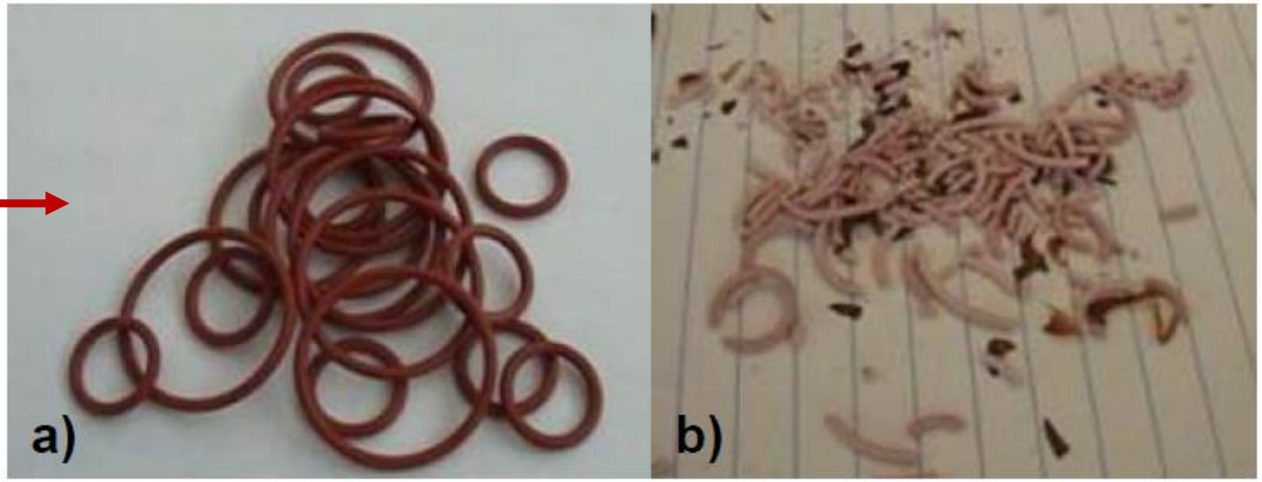

Figure 6. Effect of outgases on o-ring degradation, a) no degradation after exposures to 200 °C with or without gamma radiation, but individually, i.e., o-ring alone and b) after 200 °C exposure with other ASC organics together for 117 days.

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Electronics (1 of 2)

	Total ionizing dose (TID)	Single event effects (SEE)	Displacement damage dose (DDD)	Prompt dose
Radiation	GCR: protons, heavy ions Solar: protons, electrons, photons Rx/GPHS: photons, neutrons	GCR: protons, heavy ions Solar: protons Rx/GPHS: **neutrons**	GCR: protons, heavy ions Solar: protons Rx/GPHS: neutrons	Solar: photons Rx/GPHS: photons
Effect	Accumulated dose over time charges dielectrics	A single high energy strike causing a transient, upset, latch-up, damage, or other effect	Damage to lattice from many strikes	Large sudden photocurrents in bulk of die
Impact	ELDRS (bipolar devices), lasting parametric shift/drift	SEL, SET, SEU, SEFI, SEGR	PKA, vacancies, interstitials	Dose rate upset, dose rate latch-up
Test method	Gamma facility, reactor, accelerator	Accelerator, reactor	Accelerator, reactor	Gamma facility
Mitigation (other than rad hard IC)	Shielding	Redundancy, detection, and reset	Shielding	Redundancy, detection, and reset

~[12]

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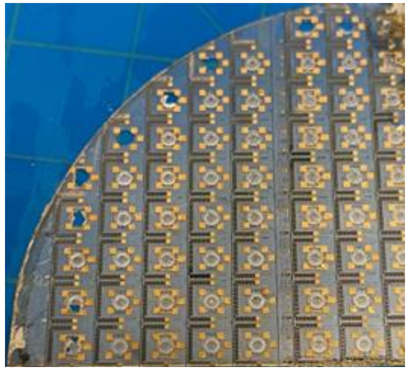
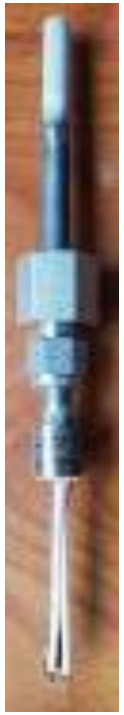
Electronics (2 of 2)

- Power management and distribution
- Power conversion system controllers
- Sensing instrumentation
- Electrically driven mechanical devices
  - Control drum motors, valves, etc.





Batch fabricated P/T sensors

Lightning talk this morning: Emerging High Temperature Sensors and Electronics for Future Lunar-Martian Reactors

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Test Facilities

Reactors	Gamma Ray Irr. Fac.	Ion Facilities

This slide captures some (not all) *potential* collaborations; it does not imply any preference.

Some facilities can fit in multiple boxes – only shown once to portray breadth of options.

Collaboration

- NASA GRC is studying radiation tolerance for FSP
- Seeking to engage the community
  - Experts of radiation effects on subsystems and relevant technology
  - Irradiation and post-irradiation testing
  - Radiation tolerance of components across technology readiness levels
  - Insight on practical and useful requirements
    - Top-down (goals) and bottom-up (vulnerabilities)
- Feel free to reach out

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