NETS 2025

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Coalescence of Designed and Natural Space Radiological Environments

Tyler R. Steiner, PhD
NASA Glenn Research Center

Jarvis A. Caffrey, PhD
NASA Marshall Space Flight Center

Jonathan D. Barth
NASA Goddard Space Flight Center

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Scope

- <u>Examples</u> of:
  - Radioisotope power systems (Pu-238)
  - Fission surface power
  - Nuclear electric propulsion
  - Nuclear thermal propulsion
  - Natural environments:
    - Lunar surface
    - Martian surface
    - Earth orbit
    - Jovian orbit

Images: NASA.gov

Motivation

- Context for mission scope
  - Completed designs
- Unexpected overlaps
- Expected differences
- Nuance

Image: iStock

Radioisotope power systems | Pu-238 neutrons

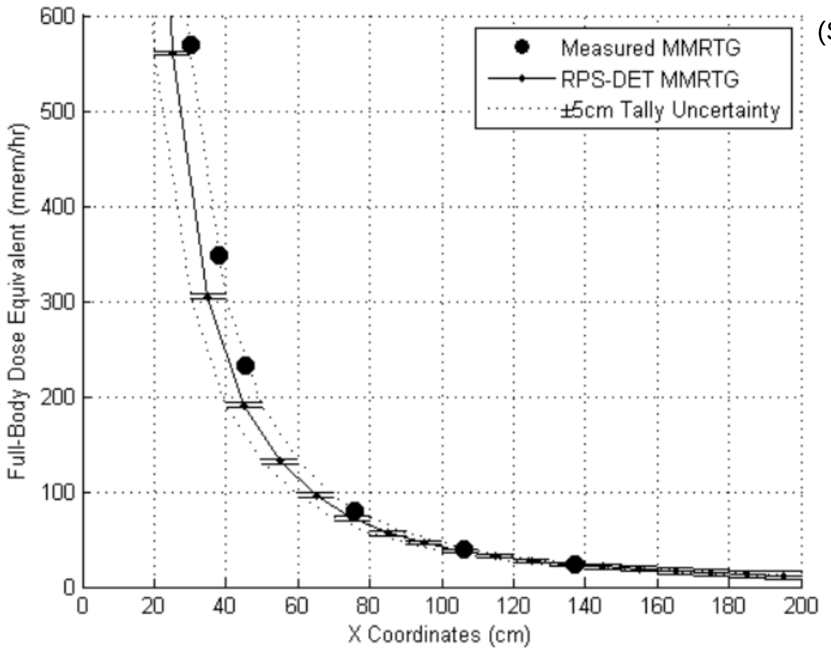
- PuO_2 (Pu-238) radioisotope thermoelectric generators (RTG) have been flown on several space missions
- Pu-238 neutron production (Taherzadeh [2]):
  - Spontaneous fission
  - Induced fission
  - (α,n) interactions with low-Z isotopes
  - Photoneutron
- PuO_2 containing 81% Pu-238 neutron activity: 11,300 n/s/g (Matlack [3])

Radioisotope power systems | Pu-238 gammas

- Pu-238 gamma yield (Matlack [3]):
  - Unshielded: 4.4 krad/hr/g at 1 cm
  - 0.08 cm thick Ta shield: 44 mrad/hr/g at 1 cm
    - 1E5 reduction
  - Daughters induce a minor increase gamma intensity over time (Matlack [3])
    - After 5 years:
      1cm unshielded dose increases by 7 rad/hr/g
      1cm shielded (0.08 cm Ta) dose increases by 0.073 rad/hr/g

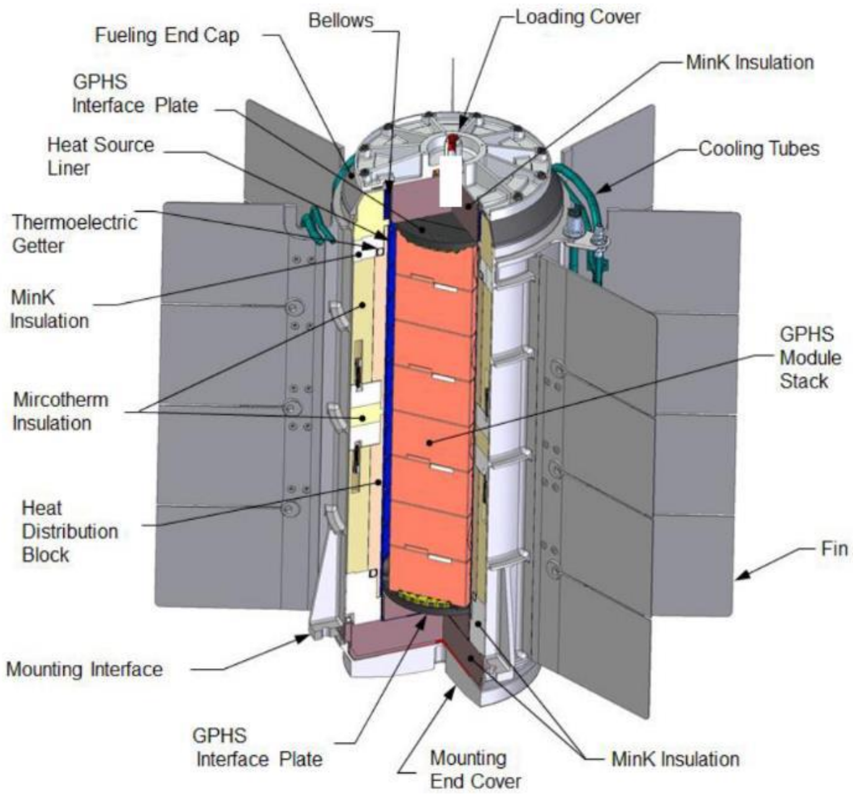
Radioisotope power systems | Pu-238 system

- RPS-DET MMRTG 8x 3-year-old GPHS dose



(Smith [4])

"shielding"



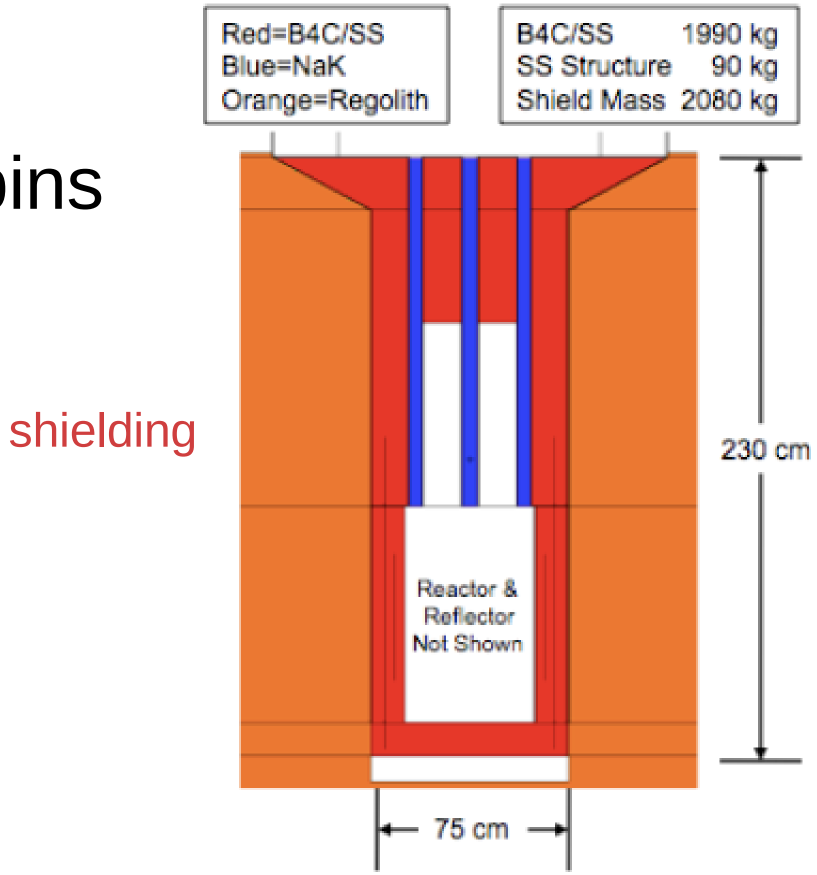
(Clayton [5])

- MMRTG BOM: 2000 W_{th} , 110 W_e

Fission surface power (2010)

- 186 kW_{th} , 40 kW_e
- Highly enriched uranium (HEU) UO_2 fuel pins
- Buried: 2 m lunar regolith
- 8 yr planned operation

(Mason [8])

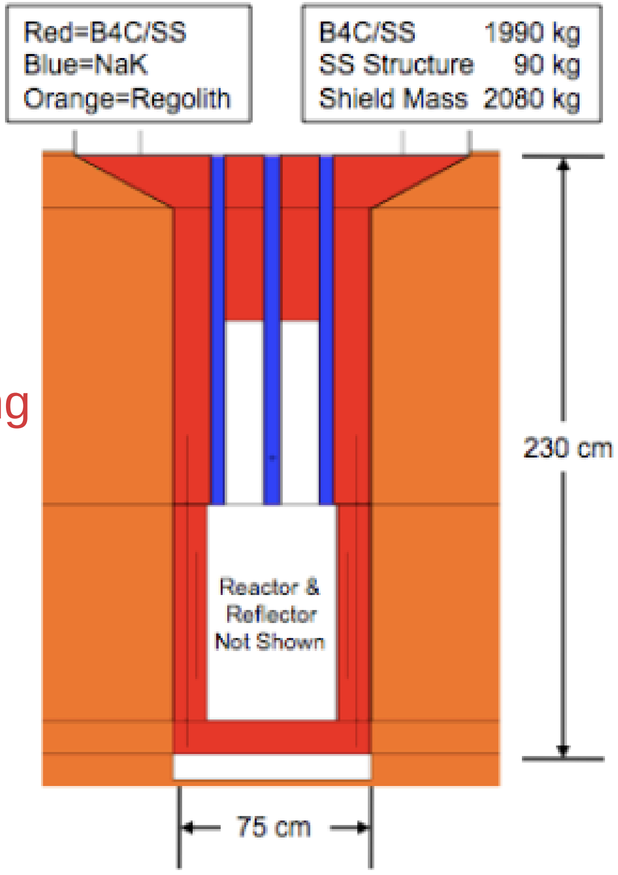


(Mason [8])

Fission surface power (2010)

- Outside of shield (Mason [8]):
  - 2.5E14 n/cm^2
    - 1E6 n/cm^2/s for 8 yr
  - 5 Mrad(Si)
    - 20 mrad(Si)/s for 8 yr
- In 2011 (Bowman [9]):
  - Power conversion system radiation limit specification:
    - 5E14 n/cm^2
    - 10 Mrad(Si)

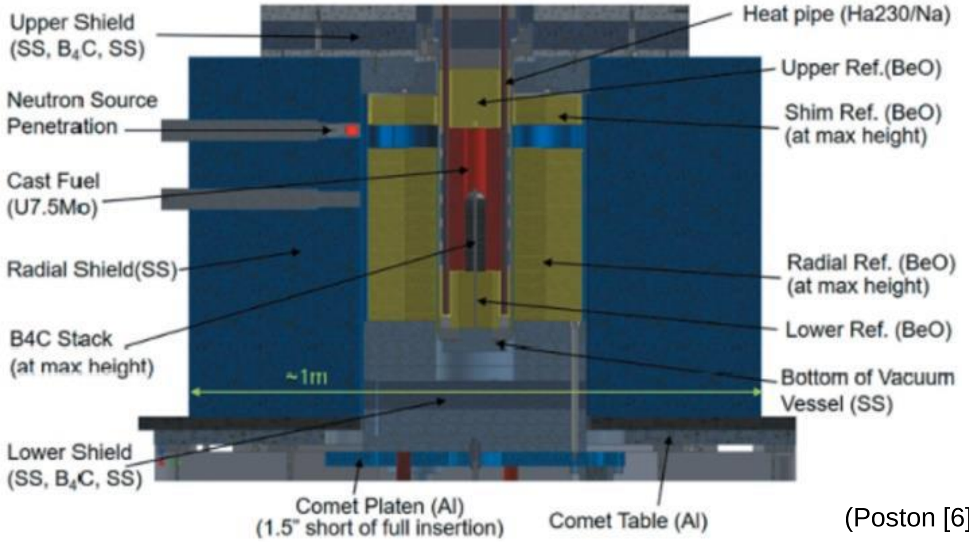
shielding



KRUSTY

- 5 kW_{th} , 1 kW_e
- HEU UMo fuel
- 28 hours of operation
- At 1 m (Poston [6,7]):
  - 8E13 n/cm^2
    - 1E9 n/cm^2/s
  - 5 krad(Si)
    - 200 rad(Si)/hr

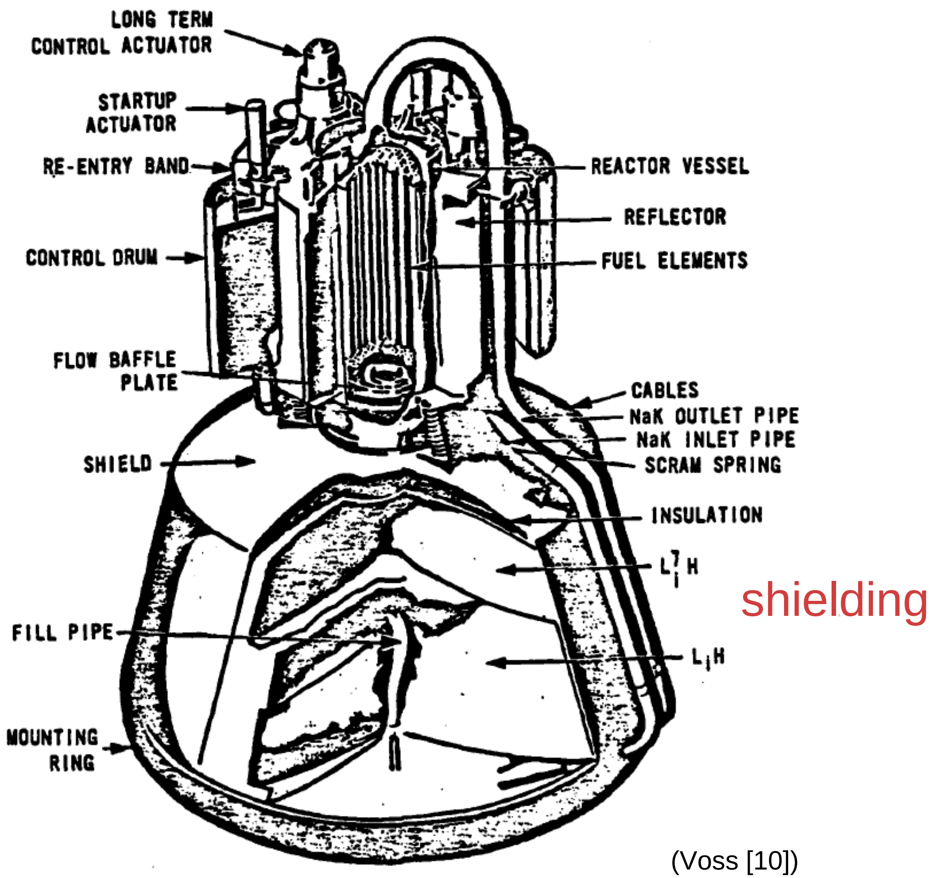
shielding



(Poston [6])

SNAP 10A

- 34 kW_{th} , 0.5 kW_e
- HEU UZrH fuel pins
- 43 days of operation
- At 533 cm (Voss [10]):
  - 1.6E5 $n/cm^2/s$
  - 1.2 rad/s



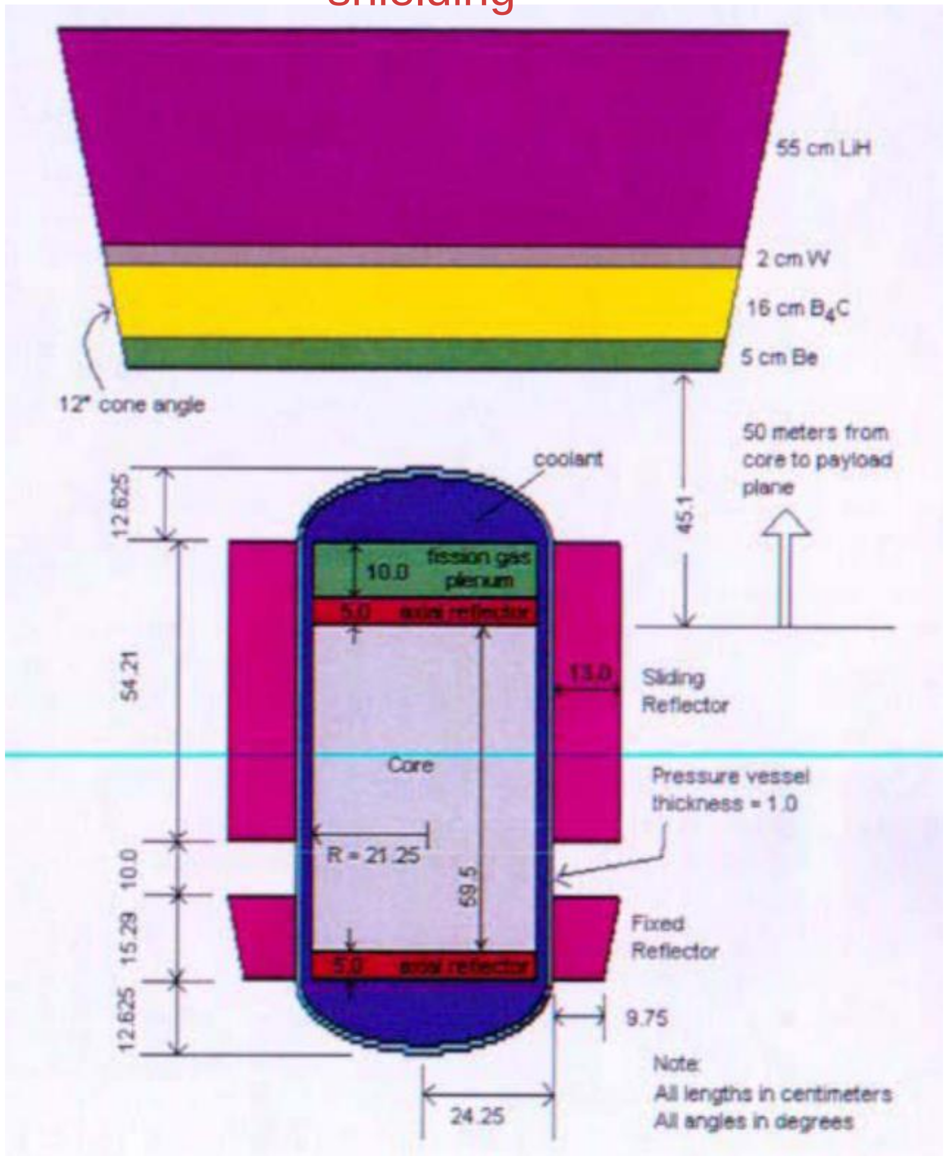
(Voss [10])

Nuclear electric propulsion (JIMO)

- 1000 kW_{th} , 200 kW_e
- HEU UO_2 fuel pins
- 15 yr planned operation
- At 50 m (payload):
  - 5E10 n/cm^2
  - 2.5 krad(Si)

shielding

(Stephens [15])



Nuclear electric propulsion (JIMO)

(Stephens [15])

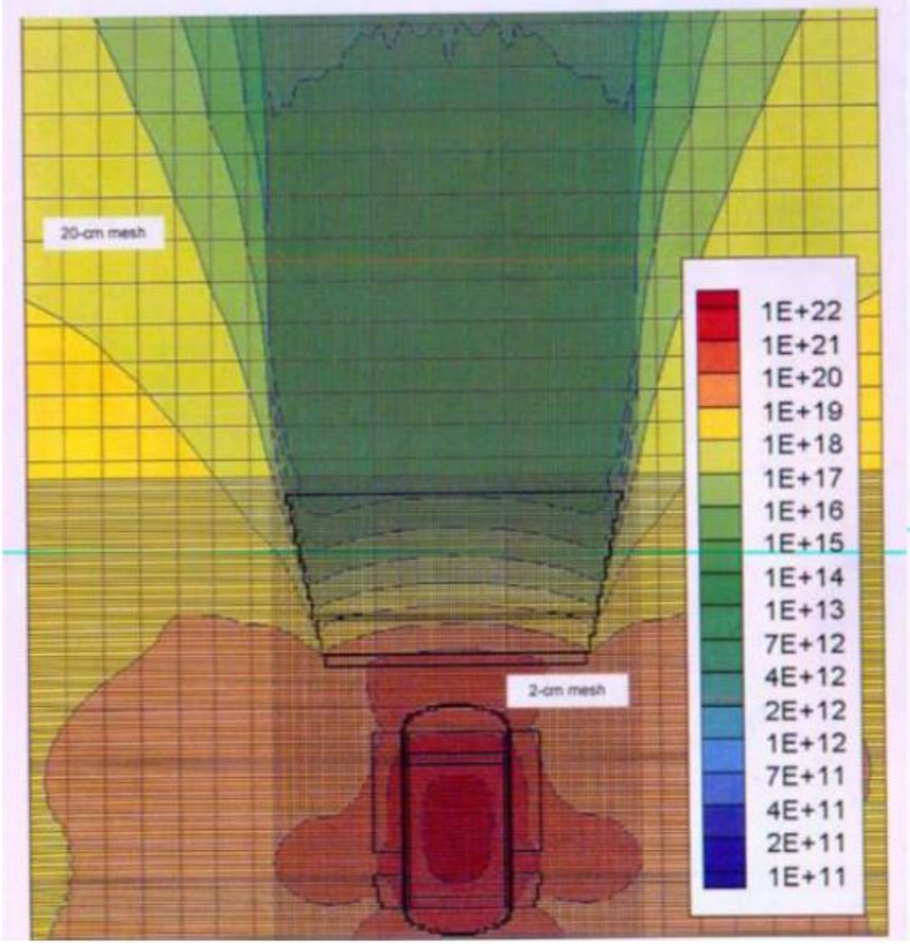
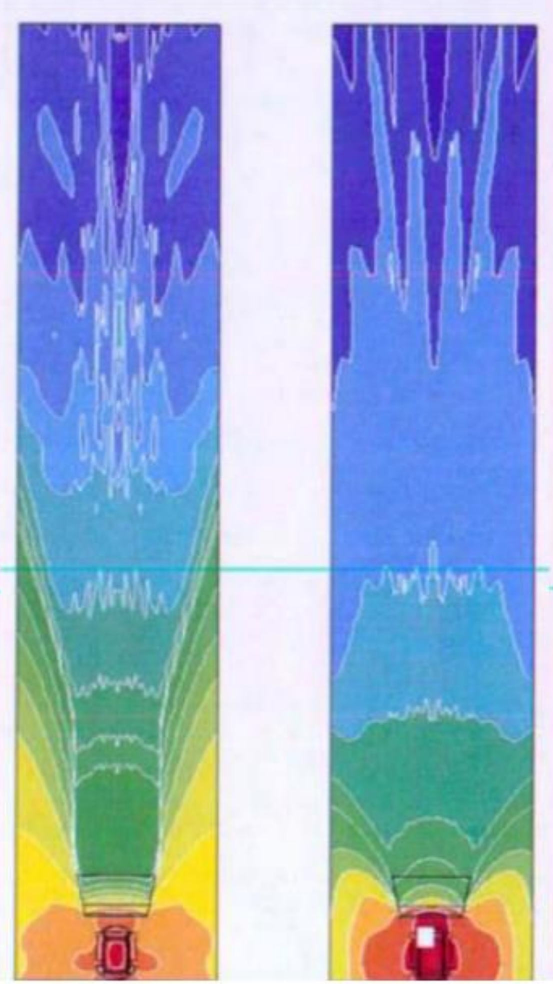


Figure 5: 1-MeV Equivalent Silicon-Damage Neutron Fluence for H Model in PARTISN



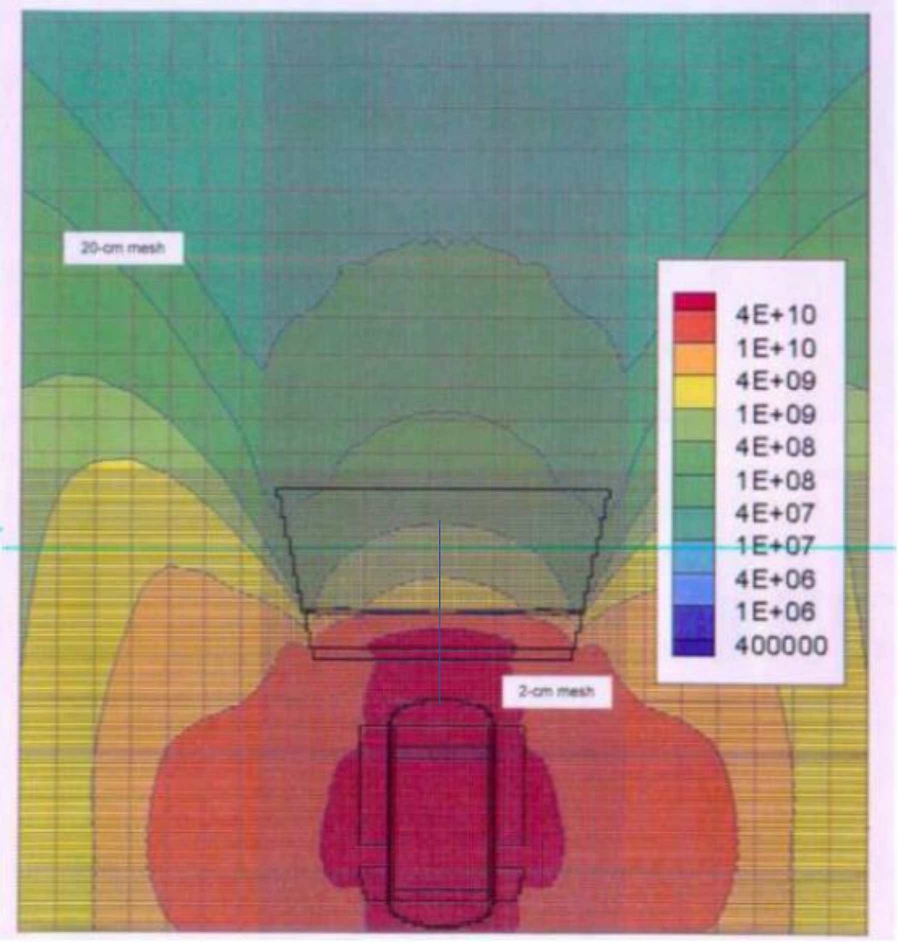


Figure 6: Gamma Dose (rads-Silicon) for H Model in PARTISN

4 m x 5 m

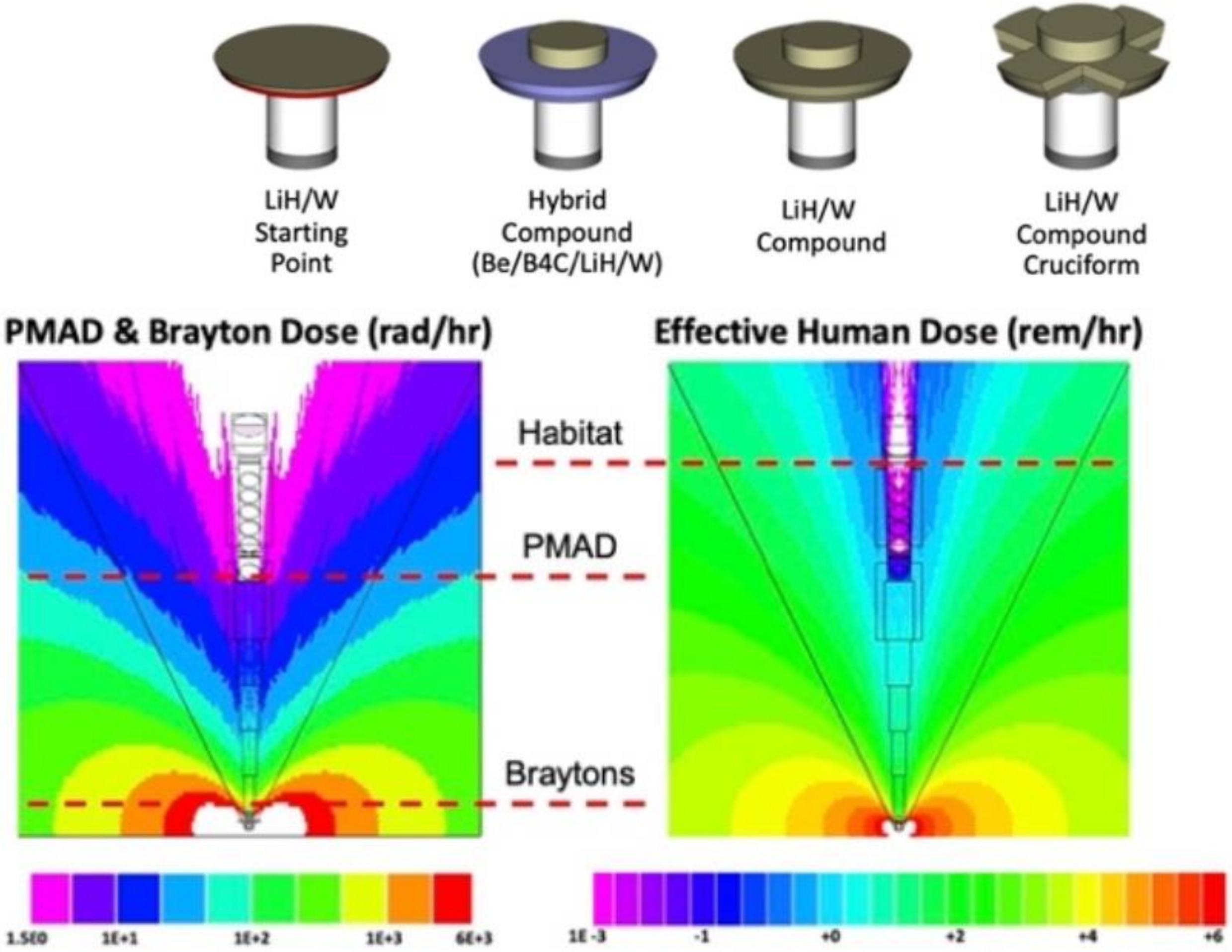
4 m x 18 m

4 m x 5 m

Nuclear electric propulsion (COMPASS)

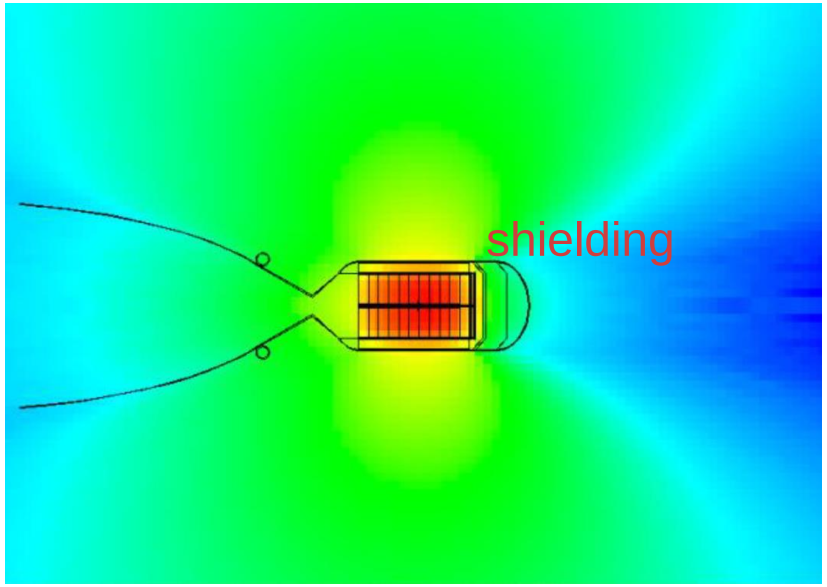
- 10 MW_{th} , 2 MW_e
- High-assay low enriched uranium
- 2 yr planned round-trip mission
- At 50 m (Mason [17]):
  - 1E11 n/cm^2
  - 25 krad

shielding (Mason [17])

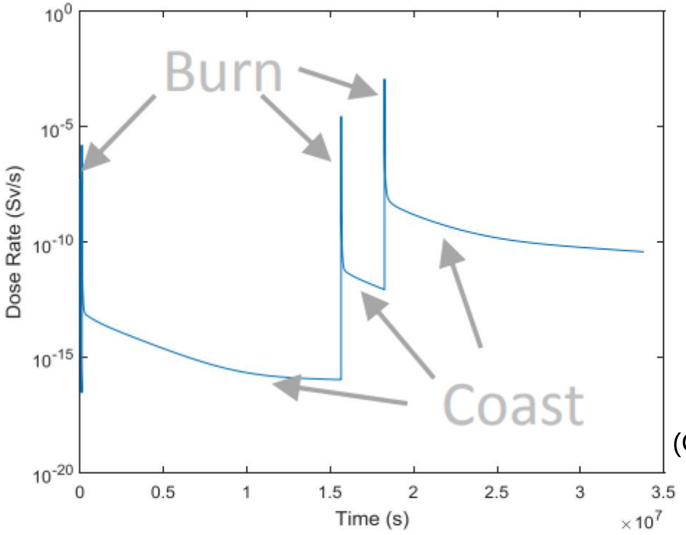


Nuclear thermal propulsion (NERVA)

(Caffrey [18])



- 1.5 GW_{th} , 75 klbf
- Near reactor (actuator test) (Mayer [21]):
  - 2E16 n/cm^2
  - 50 Mrad
- Visual example text for NTP burn transient



(Caffrey [18])

Natural radiation sources

- Galactic cosmic rays (GCR): protons, heavy ions
  - 10 rad(Si)/yr (TID)
    - Through 2.54 mm Al
    - High LET → SEE and **effective** dose dominate GCR-induced hazards
- Solar energetic particles (SEP): [photons], protons, electrons, heavy ions
  - Solar flares
  - CME
- Planetary radiation belts: see above
  - Trapped by planetary magnetic fields

Lunar surface

- Similar to interplanetary radiation environment
  - 2π shield from Moon
- Regolith secondary particles
  - Introducing neutrons
- 2.2 krad(Si)/yr
  - Through 2.54 mm Al

Martian surface

- Thin atmosphere attenuates lower energy components
  - SEP largely attenuated
  - Some GCR
- GCR and secondary particles at surface
  - 2π shield from Mars
- 7.6 rad(Si)/yr
  - Through 2.54 mm Al

Earth orbit

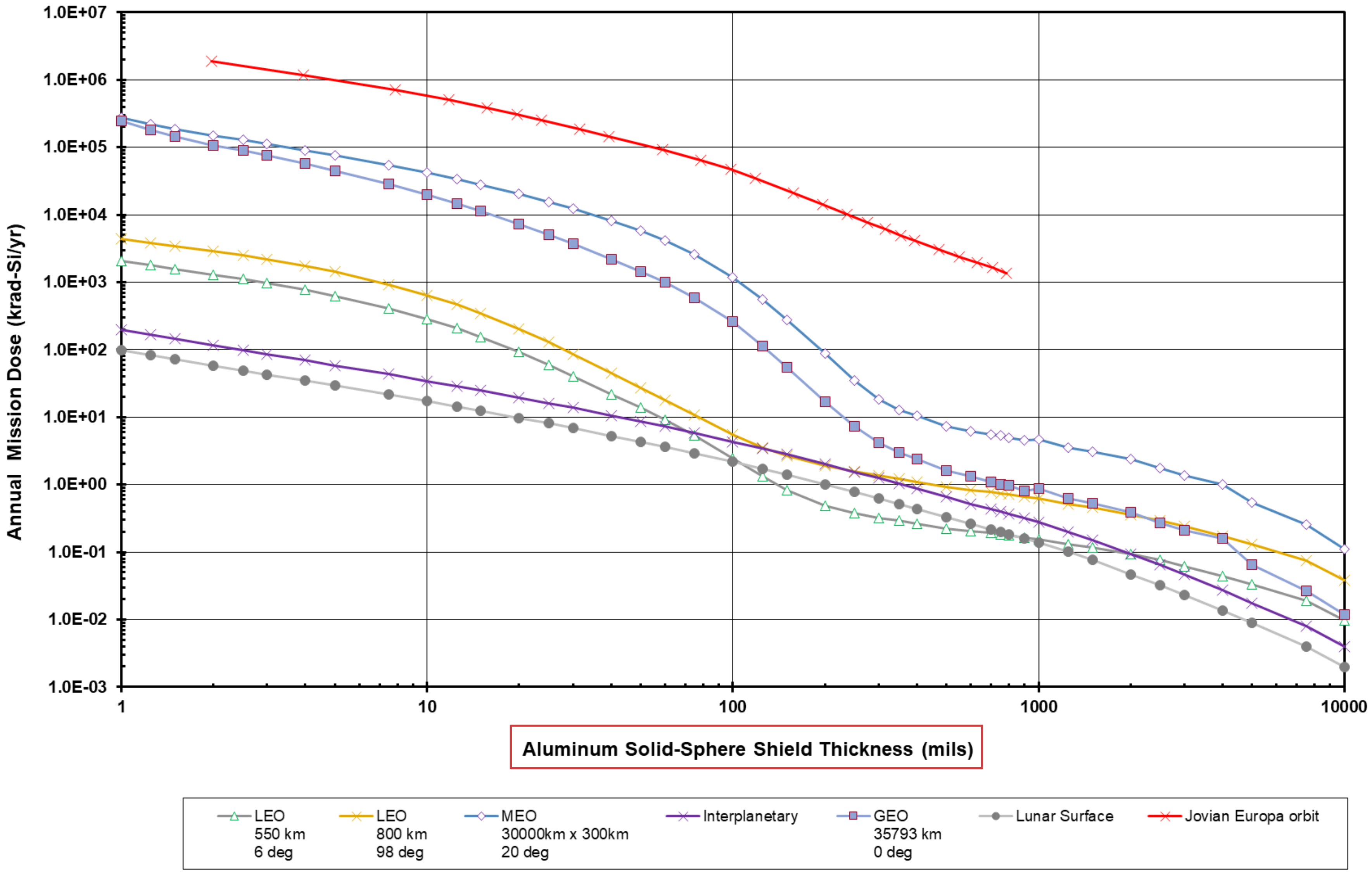
Through 2.54 mm Al

- LEO
  - Generally below inner radiation belt; poles and SAA can increase dose
    - 550 km 6° circular orbit: 2.5 krad(Si)/yr
    - 800 km 98° circular orbit (polar): 5.6 krad(Si)/yr
- MEO
  - Can pass through inner and outer belts several times per day – electrons and protons
    - 30,000 km apogee, 300 km perigee 20° eccentric orbit: 1195 krad(Si)/yr
- GEO
  - Parked in outer radiation belt – substantial amount of electrons
    - 35,793 km 0° circular orbit: 259 krad(Si)/yr

Jovian orbit

- TID dominated by electrons in Jupiter's magnetosphere
- 20 hr Europa flyby: 10 krad(Si)
  - 5 mm Al shield

Natural radiation summary



SPENVIS for calculations

Considerations

- Cannot generalize
- Expected differences
- Unexpected overlaps
- NASA-STD-3001, VOL1, REV C V1 4030: individual's total career effective radiation dose due to spaceflight radiation exposure shall be less than **600mSv** (**60 rem**)
- NASA-STD-3001, VOL1, REV C V1 4032: individual's exposure from nuclear technologies emitting ionizing radiation shall be less than **20mSv** (**2 rem**) **per mission year** (prorated)*

* Credits available (see NASA-STD-3001)

Environment “comparison”

Image: iStock

Context	Power [kW_{th}]	Duration [d]	Shield	Dist. [m]	Neutron fluence [n/cm^2]	TID [krad]	Ref.
MMRTG	2	6205	MMRTG	0.30	~ 2E11	86	4
MMRTG	2	6205	MMRTG	0.50	1.0E11	22	31, 4
FSP (2010)	186	2920	Lunar reg. + B_4C + SS	2.0	2.5E14	5.0E3	8
KRUSTY	5	1.17	SS + B_4C + SS	1.0	8.0E13	5.0	6, 7
SNAP 10A	34	43	LiH	5.33	5.9E11	4.5E3	10
NEP (JIMO)	1.0E3	5475	Be + B_4C + W + LiH	50	5.0E10	2.5	15
NEP (COMPASS)	1.0E4	730	W + LiH	50	1.0E11	25	17
NTP (NERVA)	1.5E6	0.42	BATH (B_4C + Al + Ti + H_2) + Pb	Near	2.0E16	5.0E4	21
GCR	N/A	365	2.54 mm Al	N/A	N/A	1E-2	CREME
Lunar surface	N/A	365	0.025 mm Al (surface)	N/A	N/A	1.0E2	SPENVIS
Lunar surface	N/A	365	2.54 mm Al (surface)	N/A	N/A	2.2	SPENVIS
Martian surface	N/A	365	2.54 mm Al (surface + atmosphere)	N/A	N/A	7.6E-3	SPENVIS
LEO 550 km 6° circular	N/A	365	0.025 mm Al	N/A	N/A	2.0E3	SPENVIS
LEO 550 km 6° circular	N/A	365	2.54 mm Al	N/A	N/A	2.5	SPENVIS
LEO 800 km 98° circular	N/A	365	0.025 mm Al	N/A	N/A	4.5E3	SPENVIS
LEO 800 km 98° circular	N/A	365	2.54 mm Al	N/A	N/A	5.6	SPENVIS
MEO 30,000 km x 300 km 20° eccentric	N/A	365	0.025 mm Al	N/A	N/A	2.0E5	SPENVIS
MEO 30,000 km x 300 km 20° eccentric	N/A	365	2.54 mm Al	N/A	N/A	1.2E3	SPENVIS
GEO 35,793 km 0° circular	N/A	365	0.025 mm Al	N/A	N/A	2.0E5	SPENVIS
GEO 35,793 km 0° circular	N/A	365	2.54 mm Al	N/A	N/A	2.6E2	SPENVIS
Jovian orbit (Europa flyby)	N/A	365	0.25 mm Al	N/A	N/A	8.0E5	SPENVIS
Jovian orbit (Europa flyby)	N/A	365	5 mm Al	N/A	N/A	1.1E4	SPENVIS

tyler.r.steiner@nasa.gov

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