



# Probabilistic Risk Model for Organ Doses and Acute Health Effects of Astronauts on Lunar Missions



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## Introduction

- Exposure to large solar particle events (SPEs) is a major concern during EVAs on the lunar surface and in Earth-to-Lunar transit.
- 15% of crew times may be on EVA with minimal radiation shielding.
- Therefore, an accurate assessment of SPE occurrence probability is required for the mission planning by NASA.
- We apply probabilistic risk assessment (PRA) for radiation protection of crews and optimization of lunar mission planning.

## PRA Methods for Lunar Missions

- Randomness of SPE occurrence: Using SPEs' onset dates for the past 5 solar cycles<sup>(1)</sup>.
- Propensity of SPE occurrence defined as a function of mission period and time within a solar cycle.
- Randomness of each event size of SPE,  $\Phi_E$ : Using historical database of measurements of protons with energies >30, >60, and >100 MeV<sup>(2)</sup>.
- Simulation of total  $\Phi_E$  distribution in a mission period.
- Transport properties of the shielding materials and the astronaut's body tissues:
  - NASA BRYNTRN code system<sup>(3)</sup>
- Shielding distribution by vehicle geometry on lunar missions:
  - Initial representative shield configurations: Spacesuit (0.3 g/cm<sup>2</sup> Aluminum); Equipment room of a Spacecraft (5.0 g/cm<sup>2</sup> Aluminum)
  - Conceptual lunar habitat: Storm shelter and Living quarter<sup>(4)</sup>
  - Small pressurized rover: Parametric study with astronauts' orientation<sup>(5)</sup>
- Body shielding distribution at the sensitive organs of astronaut:
  - Computerized Anatomical Man (CAM) model<sup>(6)</sup>
- Risk quantities:
  - Symptoms of acute radiation response using RIPD code<sup>(7)</sup>
  - Organ dose and effective dose assessments<sup>(8)</sup>
  - Cancer risk assessments using NCRP/SRP<sup>(9)</sup> and BEIR-VII<sup>(10)</sup> models

## References

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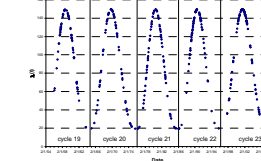
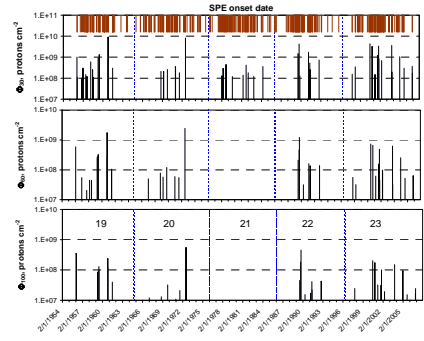
## Human Response Quantification for Symptoms of Acute Radiation Response (ARR)

Severity level	Signs and symptoms
5	Vomiting/retching several times including the dry heaves
4	Vomiting/retching once or twice; nauseated and vomiting may recur
3	Nauseated, sweating, frequent retching and swallowing to avoid vomiting
2	Upset stomach clammy and sweaty; mild nausea
1	Normal; no noticeable effect

## Organ Dose and Acute Radiation Response from Exposure to Historical SPEs and SPEs with Double Intensity during EVA\* and inside Spacecraft

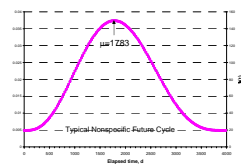
	SPE	EVA*		Spacecraft		Upper GI	Fatigability	Distress & Weakness	
		D <sub>min</sub> Gy	G <sub>50D</sub> Gy-Eq	G <sub>20moch</sub> Gy-Eq	G <sub>20moch</sub> Gy-Eq				
EVA*	Aug 1972	32.15	1.38	0.42	2.8	2.0			
	Nov 1960	19.15	0.87	0.44	1.0	1.0			
	Sept 1989	7.68	0.38	0.19	1.0	1.0			
	Oct 1989	25.99	0.96	0.43	1.6	1.6			
	2x Aug72	64.30	2.77	0.83	4.5	2.9			
	2x Nov60	38.30	1.35	0.89	2.7	2.0			
Spacecraft	2x Sept89	15.36	0.76	0.37	1.0	1.0			
	2x Oct89	51.98	1.91	0.87	3.1	2.2			
	Aug 1972	2.69	0.46	0.17	2.0	1.7			
	Nov 1960	0.73	0.45	0.32	1.0	1.0			
	Sept 1989	0.53	0.19	0.11	1.0	1.0			
	Oct 1989	1.45	0.45	0.25	1.0	1.0			
Spacecraft	2x Aug72	5.38	0.93	0.34	3.7	2.5			
	2x Nov60	1.46	0.89	0.64	2.4	1.9			
	2x Sept89	1.07	0.39	0.22	1.0	1.0			
	2x Oct89	2.90	0.91	0.50	2.4	1.9			
	* 3 hours EVA at the peak								

## SPE Database for the Past 5 Solar Cycles and Model-Based Prediction of SPEs

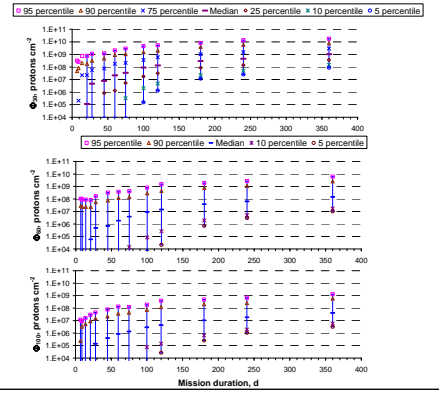


Propensity of SPEs: Hazard Function of Offset (t) Distribution Density Function

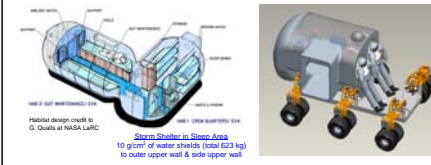
$$\lambda(t) = \frac{\lambda}{4000} \frac{\Gamma(p+q)}{\Gamma(p)\Gamma(q)} \left(\frac{t}{4000}\right)^{p-1} \left(1 - \frac{t}{4000}\right)^{q-1} \quad (0 \leq t \leq 4000)$$



## Simulated Distribution of SPE Fluence at 30, 60, and 100 MeV for Mission Period

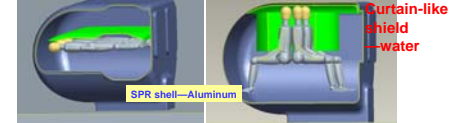


## Conceptual Lunar Habitat and Small Pressurized Rover (SPR)



## Probabilistic Assessment of Radiation Risk on Lunar Missions

### Parametric Study of SPR for Shielding

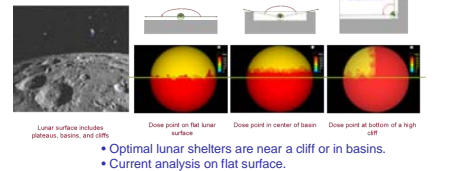


- Horizontal Orientation**
  - Augmented water shield of blanket-like cover.
- Vertical Orientation**
  - Augmented water shield of roof and cylindrical curtain.
  - Cylindrical shield: Stored in a compartment on the side; deployed like a curtain.

### Weight of SPR Cabin Shell Part

Orientation	Part name	0.8 g/cm <sup>2</sup>	1 g/cm <sup>2</sup>	2 g/cm <sup>2</sup>	5 g/cm <sup>2</sup>	10 g/cm <sup>2</sup>
Vertical	Aluminum Cabin	198.5 Kg	247.8 Kg	494.4 Kg	1224.3 Kg	2407 Kg
	Water Shield (Roof + Cylindrical)	76.7 Kg (43.9+32.8)	151.8 Kg (86.7+65.1)	303.7 Kg (207.6+156.4)	692.4 Kg (384.5+307.9)	
Horizontal	Water Shield Blanket	43.9 Kg	86.7 Kg	207.6 Kg	384.5 Kg	

### Lunar Topology Consideration



- Optimal lunar shelters are near a cliff or in basins.
- Current analysis on flat surface.

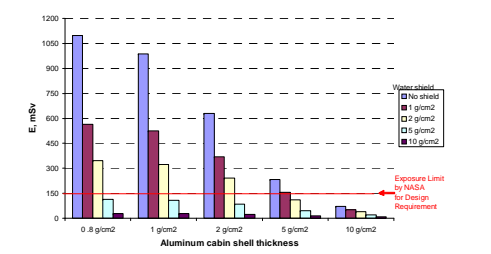
Effective dose at Solar Maximum

Effective dose, mSv	Storm shelter		Living area	
	CAM	CAF	CAM	CAF
90-d	34.91	35.21	37.91	38.31
GCR only				
GCR+SPE at Median	35.4	35.7	39.7	40
GCR+SPE at upper 95%CI	107.6	106.1	327.7	309.4
180-d	69.84	70.4	75.9	76.7
GCR only	72.1	72.6	84.7	84.91
GCR+SPE at Median	157.1	155.5	423.6	402.0
GCR+SPE at upper 95%CI	141.7	142.8	153.9	155.5
365-d	141.7	142.8	153.9	155.5
GCR only	141.7	142.8	153.9	155.5
GCR+SPE at Median	279.11	276.71	701.51	667.9
GCR+SPE at upper 95%CI				

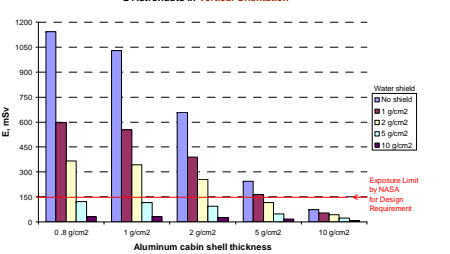
### Cancer Fatality of %REID (Risk of Exposure Induced Death) at Solar Maximum (Storm Shelter)

Effective dose at median, mSv	90-d mission		180-d mission		365-d mission	
	Male	Female	Male	Female	Male	Female
35.4	35.7	72.1	72.6	149.4	150.3	
107.6	106.1	197.1	155.5	276.1	276.7	
Age	NASA	BEIR	NASA	BEIR	NASA	BEIR
Model	VEI	Model	VEI	Model	VEI	Model
35	0.14	0.14	0.37	0.39	0.35	0.38
40	0.12	0.13	0.15	0.19	0.25	0.27
45	0.11	0.13	0.18	0.22	0.26	0.27
50	0.09	0.12	0.13	0.19	0.25	0.22
55	0.08	0.12	0.09	0.16	0.22	0.18
60	0.07	0.10	0.10	0.14	0.17	0.15
65	0.06	0.09	0.07	0.11	0.14	0.12
70	0.05	0.08	0.06	0.09	0.12	0.10
75	0.04	0.07	0.05	0.08	0.11	0.09
80	0.03	0.06	0.04	0.07	0.10	0.08
85	0.02	0.05	0.03	0.06	0.09	0.07
90	0.01	0.04	0.02	0.05	0.08	0.06
95	0.01	0.03	0.02	0.04	0.07	0.05

### Effective dose from August 1972 SPE inside SPR - 2 Astronauts in Horizontal Orientation -



### Effective dose from August 1972 SPE inside SPR - 2 Astronauts in Vertical Orientation -



## Conclusions

- For managing space radiation risk in the new era of space exploration:
  - Propensity for SPE occurrence and particle fluence of SPEs in a mission period estimated.
  - Acute radiation response:
    - Large historical SPEs inside a typical spacecraft or during EVA: Performance to be impaired from the moderate early effects induced to crew members without effective shielding and medical countermeasure tactics.
    - SPEs with doubled intensity of August 1972 SPE: Significantly increased ARR, and high incidence of mortality (3%) without medical treatment.
  - Future mission planning based on the probabilistic analysis of the risk and shielding with the current conceptual lunar habitat:
    - At solar minimum (Y2028-2030), lunar missions to 90 days allowed; - At solar maximum, longer lunar missions up to 210 days allowed;
    - Crew selection provided; - Mitigation strategy easily utilized.
  - Radiation analysis of small pressurized rover (SPR) for optimization of shield mass and dose reduction:
    - Lunar topology consideration: Optimal lunar shelters to be found near cliff or in basin; - Great dose reduction per multi-functional shield mass achieved by augmented water shield to roof and curtain; - Rover design requirement by NASA: Short-term exposure limit of 150 mSv for whole-body effective dose achieved with the current SPR model.