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

References

1. Kim, M.Y., Hayat, M.J., Feiveson, A.H., Cucinotta, F.A. Prediction of frequency and exposure level of solar particle events. "Submitted to *Health Phys.*", 2008.
2. Kim, M.Y., Hayat, M.J., Feiveson, A.H., Cucinotta, F.A. Propensity and risk assessment for solar particle events: Consideration of integral fluence at high proton energies. "Submitted to *Adv. Space Res.*", 2008.
3. Cucinotta, F.A., Wilson, J.W., Badavi, F. F. Extension to the BRYNTRN code to monoenergetic light ion beams. Washington DC, NASA Report No. TP-3472, 1994.
4. Lunar Architecture Trade Study II, Lunar Architecture Team, NASA HQ, Aug. 7, 2007.
5. Nounu, H.N., Kim, M.Y., Gernhardt, M.L.,Cucinotta, F.A., A study of the shielding effects of lunar topography and rover design on humans in future lunar exploration missions using nasa-developed radiation analysis software, NASA Human Research Program Investigators' Workshop, Feb. 4-6, 2008.
6. Billings, M.P., Yucker, W.R. The computerized anatomical man (CAM) model. Washington DC, NASA CR-134043, 1973.
7. Hu, S., Kim, M.Y., McClellan, G.E., Cucinotta, F.A., Modeling the acute health effects of astronauts from exposure to large solar particle events, *Health Physics* (in print).
8. Cucinotta, F.A., Kim, M.Y., Willingham, V., George, K.A., Physical and biological organ dosimetry analysis for International Space Station astronauts, *Radiation Res.*, 170, 127-138, 2008.
9. Cucinotta, F.A., Kim, M.Y., Ren, L., Evaluating shielding effectiveness for reducing space radiation cancer risks, *Radiation Meas.*, 41, 1173-1185, 2006.
10. NRC/NAS Committee to Assess Health Risks from Exposure to Low Levels of Ionizing Radiation, *Health Risks from Exposure to Low Levels of Ionizing Radiation: BEIR VII*. National Academies Press. [ISBN: 0-309-09156-X], 2006.

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

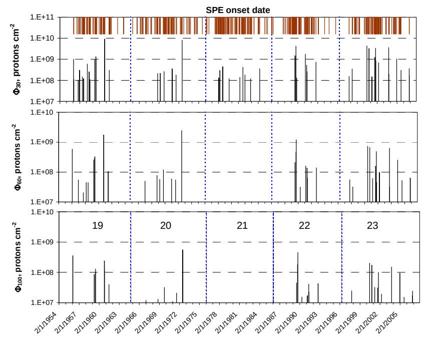
Severity level	Signs and symptoms
5	Vomiting/retching several times including the dry heaves
4	Vomiting/retching once or twice; nauseated and vomiting may recur
3	Nauseated, sweating, frequent retching and swallowing to avoid vomiting
2	Upset stomach clammy and sweaty; mild nausea
1	Normal; no noticeable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

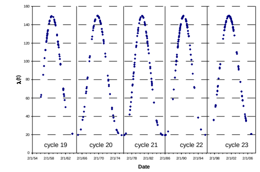
Organ Dose and Acute Radiation Response from Exposure to Historical SPEs and SPEs with Double Intensity during EVA* and inside Spacecraft

	SPE	D_{skin}, Gy	G_{BFO}, Gy-Eq	$G_{stomach}$, Gy-Eq	Upper GI Distress	Fatigability & Weakness
EVA*	Aug 1972	32.15	1.38	0.42	2.8	2.0
	Nov 1960	19.15	0.67	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
	2× Aug72	64.30	2.77	0.83	4.5	2.9
	2× Nov60	38.30	1.35	0.89	2.7	2.0
	2× Sept89	15.36	0.76	0.37	1.0	1.0
	2× Oct89	51.98	1.91	0.87	3.1	2.2
Spacecraft	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
	2× Aug72	5.38	0.93	0.34	3.7	2.5
	2× Nov60	1.46	0.89	0.64	2.4	1.9
	2× Sept89	1.07	0.39	0.22	1.0	1.0
	2× 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

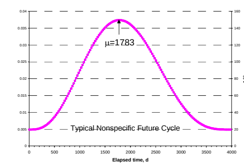




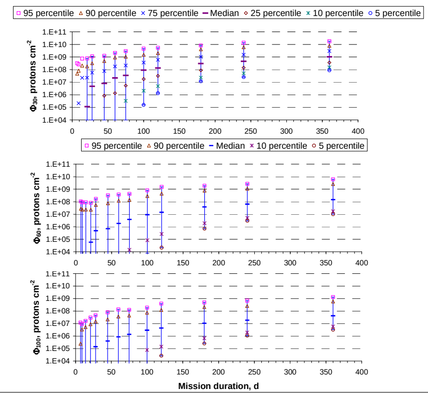
Propensity of SPEs:
Hazard Function of
Offset β Distribution Density Function

$$\lambda(t) = \frac{\lambda_0}{4000} + \frac{K}{4000}\frac{\Gamma(p+q)}{\Gamma(p)\Gamma(q)}\left(\frac{t}{4000}\right)^{p-1}\left(1-\frac{t}{4000}\right)^{q-1}$$

$$(0 \le t \le 4000)$$

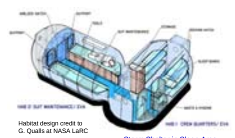


Simulated Distribution of SPE Fluence at 30, 60, and 100 MeV for Mission Period



Probabilistic Assessment of Radiation Risk on Lunar Missions

Conceptual Lunar Habitat and Small Pressurized Rover (SPR)



Habitat design credit to G. Qualls at NASA LaRC

Storm Shelter in Sleep Area
10 g/cm^2 of water shields (total 623 kg) to outer upper wall & side upper wall

Effective dose at Solar Maximum

Effective dose, mSv		Storm shelter		Living area	
		CAM	CAF	CAM	CAF
90-d	GCR only	34.9	35.2	37.9	38.3
	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	GCR only	69.9	70.4	75.9	76.7
	GCR+SPE at Median	72.1	72.6	84.7	84.91
	GCR+SPE at upper 95%CI	157.1	155.5	423.6	402.0
365-d	GCR only	141.7	142.8	153.9	155.5
	GCR+SPE at Median	149.4	150.3	184.6	184.2
	GCR+SPE at upper 95%CI	279.1	276.7	701.5	667.9

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

		90-d mission				180-d mission				365-d mission			
		Male		Female		Male		Female		Male		Female	
Effective dose at median, mSv		35.4		35.7		72.1		72.6		149.4		150.3	
Effective dose at upper 95% CI		107.6		106.1		157.1		155.5		279.1		276.7	
%REID Carcino-genesis	Age, yr	NASA Model	BEIR-VII	NASA Model	BEIR-VII	NASA Model	BEIR-VII	NASA Model	BEIR-VII	NASA Model	BEIR-VII	NASA Model	BEIR-VII
Median	35	0.14	0.14	0.17	0.19	0.28	0.27	0.35	0.38	0.57	0.56	0.71	0.78
	40	0.12	0.13	0.15	0.19	0.25	0.27	0.31	0.38	0.52	0.55	0.63	0.77
	45	0.11	0.13	0.13	0.18	0.22	0.26	0.26	0.37	0.45	0.53	0.54	0.75
	50	0.09	0.12	0.11	0.17	0.19	0.25	0.22	0.36	0.38	0.51	0.46	0.72
	55	0.08	0.12	0.09	0.16	0.16	0.24	0.19	0.33	0.33	0.48	0.38	0.68
Upper 95% CI	35	1.1	1.1	1.3	1.5	1.7	1.7	2.1	2.3	3.2	3.1	3.9	4.2
	40	1.0	1.1	1.2	1.5	1.6	1.7	1.9	2.3	2.8	3.0	3.4	4.2
	45	0.9	1.0	1.0	1.4	1.3	1.6	1.6	2.2	2.5	2.9	2.9	4.1
	50	0.7	1.0	0.9	1.4	1.2	1.5	1.4	2.2	2.1	2.8	2.5	3.9
	55	0.6	0.9	0.7	1.3	1.0	1.5	1.2	2.0	1.8	2.6	2.1	3.7

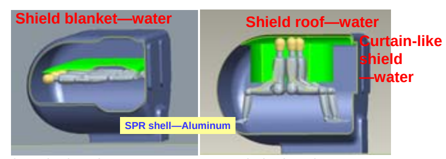
Effective dose at Solar Minimum

Effective dose, mSv		Storm shelter		Living area	
		CAM	CAF	CAM	CAF
90-d	GCR only	76	76	83.3	83.3
180-d	GCR only	152	152	166.7	166.7
365-d	GCR only	304	305	338	338

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

		90-d mission				180-d mission				365-d mission			
		Male		Female		Male		Female		Male		Female	
Effective dose, mSv		76		76		152		152		304		305	
%REID Carcino-genesis	Age, yr	NASA Model	BEIR-VII	NASA Model	BEIR-VII	NASA Model	BEIR-VII	NASA Model	BEIR-VII	NASA Model	BEIR-VII	NASA Model	BEIR-VII
Median	35	0.29	0.28	0.29	0.4	0.58	0.57	0.72	0.79	1.16	1.13	1.44	1.58
	40	0.26	0.28	0.26	0.39	0.52	0.56	0.64	0.78	1.04	1.11	1.27	1.56
	45	0.23	0.27	0.23	0.38	0.45	0.54	0.54	0.76	0.90	1.08	1.08	1.52
	50	0.19	0.26	0.19	0.37	0.39	0.52	0.46	0.73	0.78	1.04	0.92	1.46
	55	0.17	0.25	0.17	0.35	0.33	0.49	0.39	0.69	0.66	0.98	0.77	1.37
Upper 95% CI	35	1.1	1.1	1.1	1.6	2.3	2.3	2.8	3.1	4.6	4.5	5.7	6.2
	40	1.0	1.1	1.0	1.5	2.1	2.2	2.5	3.1	4.1	4.4	5	6.2
	45	0.9	1.1	0.9	1.5	1.8	2.1	2.1	3.0	3.6	4.3	4.3	6.0
	50	0.8	1.0	0.8	1.5	1.5	2.1	1.8	2.9	3.1	4.1	3.6	5.8
	55	0.7	1.0	0.7	1.4	1.3	1.9	1.5	2.7	2.6	3.9	3.0	5.4

Parametric Study of SPR for Shielding



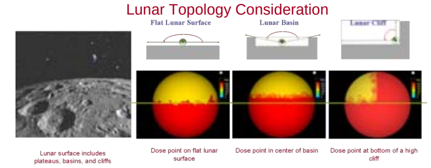
Horizontal Orientation
- Augmented water shield of blanket-like cover.

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

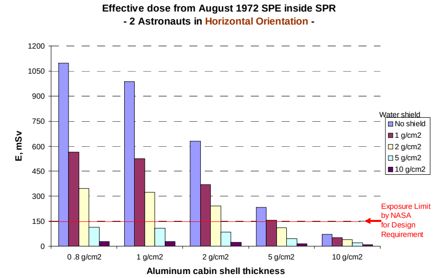
Weight of SPR Cabin Shell Part

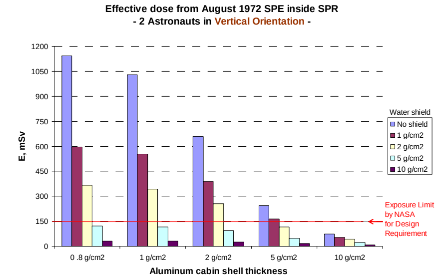
Orientation	Part name	0.8 g/cm^2	1 g/cm^2	2 g/cm^2	5 g/cm^2	10 g/cm^2
	Aluminum Cabin	198.5 Kg	247.8 Kg	494.4 Kg	1224.3 Kg	2407 Kg
Vertical	Water Shield (Roof + Cylinder)		76.7 Kg (43.9+32.8)	151.8 Kg (86.7+65.1)	367 Kg (207.6+159.4)	692.4 Kg (384.5+307.9)
Horizontal	Water Shield Blanket		43.9 Kg	86.7 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.





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.