Minimizing Astronauts' Risk from Space Radiation during Future Lunar Missions

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Problem

- Continuous galactic cosmic rays (GCR) pose a serious health risk to humans and contribute to failure rates for electronics during space missions. The risks must be predicted accurately for future lunar missions.

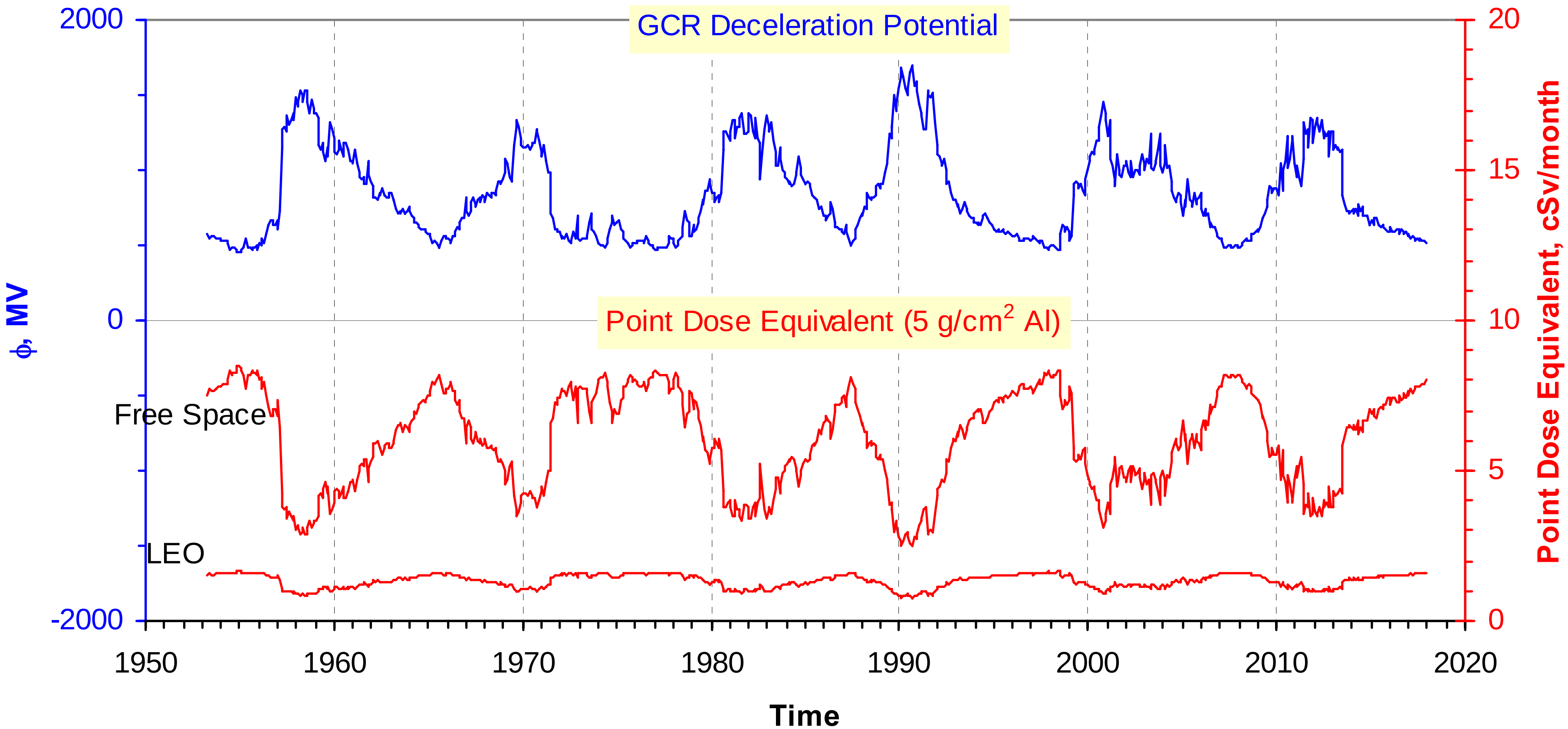
→ We develop a practical approach of expected GCR environment.

- Solar particle events (SPEs) are a concern for space missions outside Earth's geomagnetic field.
- The sporadic occurrence of SPEs and number of large SPEs in a short period are major operational problems for planning space missions and protecting humans during missions.

→ We develop a probability of large SPE during a given mission duration.

An integrated strategy for radiation protection on lunar exploration missions.

GCR Environment
and
Point Dose Equivalent inside Spacecraft



Database of Solar Particle Events

Solar Cycle	# of SPE	# of Day	Period	Fluence, Φ_E
Cycle 23	92	3897	5/1/1996-12/31/2006	$\Phi_{10,30,50,60,100}$ (1)
Cycle 22	77	3742	2/1/1986-4/30/1996	$\Phi_{10,30,50,60,100}$ (1)
Cycle 21	70	3653	2/1/1976-1/31/1986	$\Phi_{10,30}$ (2)
Cycle 20	63	4140	10/1/1964-1/31/1976	$\Phi_{10,30}$ (2) and $\Phi_{10,30,60}$ (3)
Cycle 19	68	3895	2/1/1954-9/30/1964	$\Phi_{10,30,100}$ (2) and $\Phi_{10,30}$ (4)
Impulsive Nitrate Events	71	390 years	1561 - 1950	Φ_{30} (5 and 6)
Energy Spectra(7 and 8) or Weibull Distribution Function(9 and 10)				

(1) GOES SEM data: http://goes.ngdc.noaa.gov/data/

(2) Feynman, Armstrong, Dao-Gibner, and Silverman, J. Spacecraft, **27**, No. 4, pp. 403-410, July-August, 1990.

(3) King, J. H., solar proton fluences for 1977-1983 space missions, J. Spacecraft, **11**, No. 6, pp. 401-408, June 1974.

(4) Shea and Smart, Solar Physics, **127**, pp. 297-320, 1990.

(5) McCracken, K. G., Dreschhoff, G. A. M., Zeller, E. J., Smart, D. F., and Shea, M. A., Solar cosmic ray events for the period 1561-1994, 1. Identification in polar ice, 1561-1950. J. Geophys. Res., **106**, No. A10, 21585-21598, October 1, 2001.

(6) Siverman, S., Silverman catalog of ancient auroral observations, 666BCE to 1951, http://nssdc.gsfc.nasa.gov/space/auroral/auroral.html, 2002.

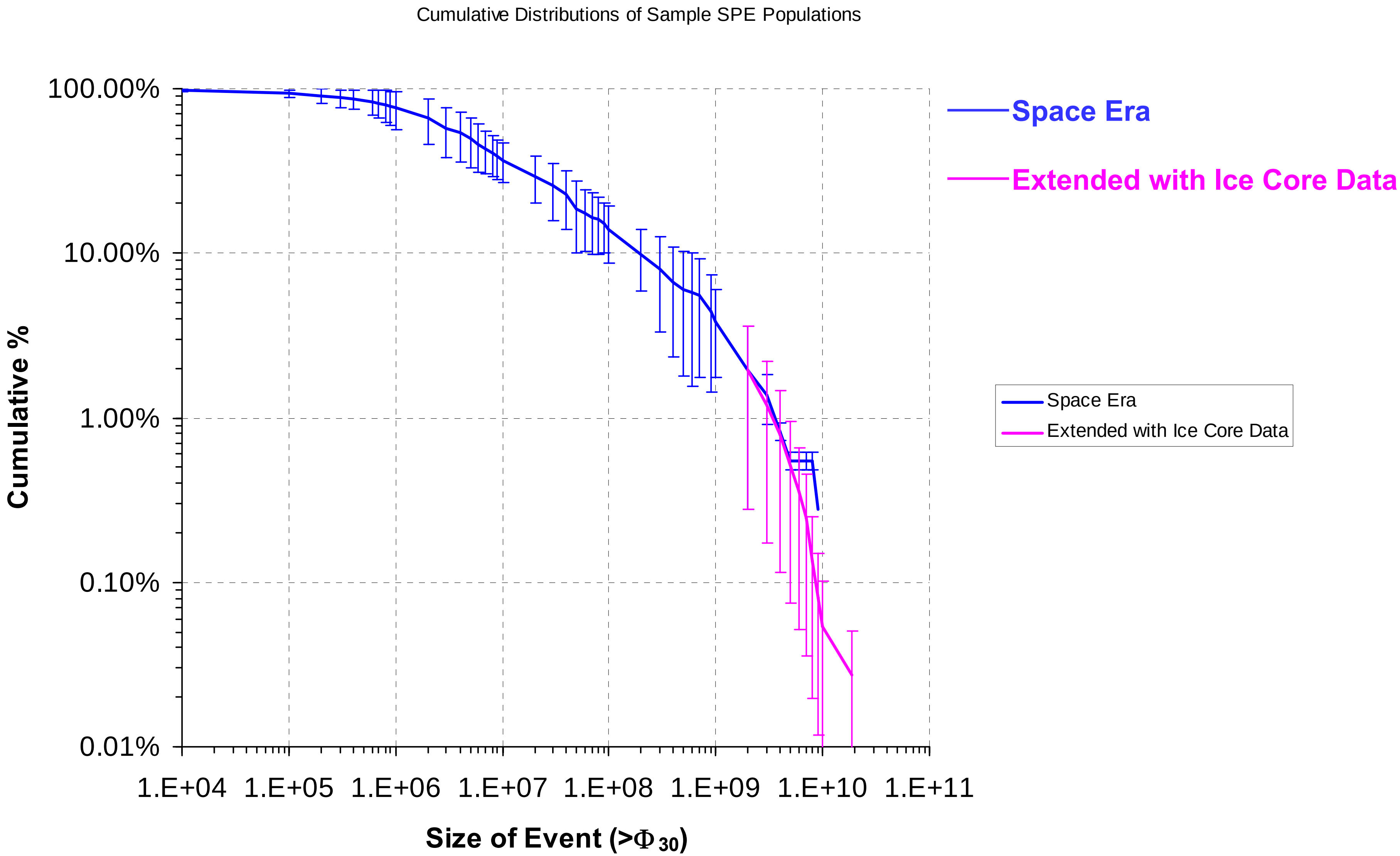
(7) Freier, P. S. and Webber, W. R., “Exponential Rigidity Spectrums for Solar-Flare Cosmic Rays,” *J. Geophys. Res*., Vol. 68, No. 6, 1963, pp. 1605-1629.

(8) Biswas S., Fichtel, C. E., and Guss, D. E., “Study of the Hydrogen, Helium, and Heavy Nuclei in the November 12, 1960 Solar Cosmic-Ray Event,” *Phys. Review*, Vol. 128, No. 6, 1962, pp. 2756-2771.

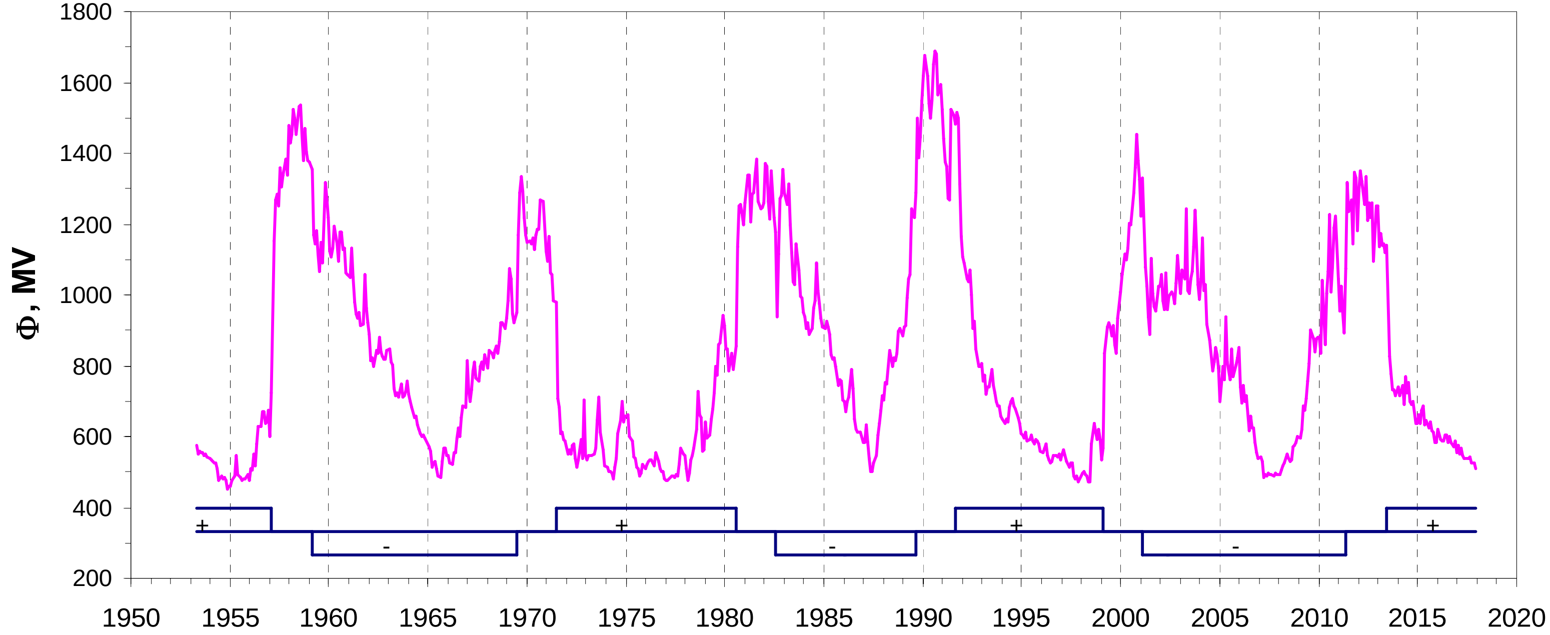
(9) Kim, M. Y., Cucinotta, F. A., and Wilson, J. W., A temporal forecast of radiation environments for future space exploration missions, Radiat. and Environ. Biophys., **46**, No. 2, pp. 95-100, June 2007.

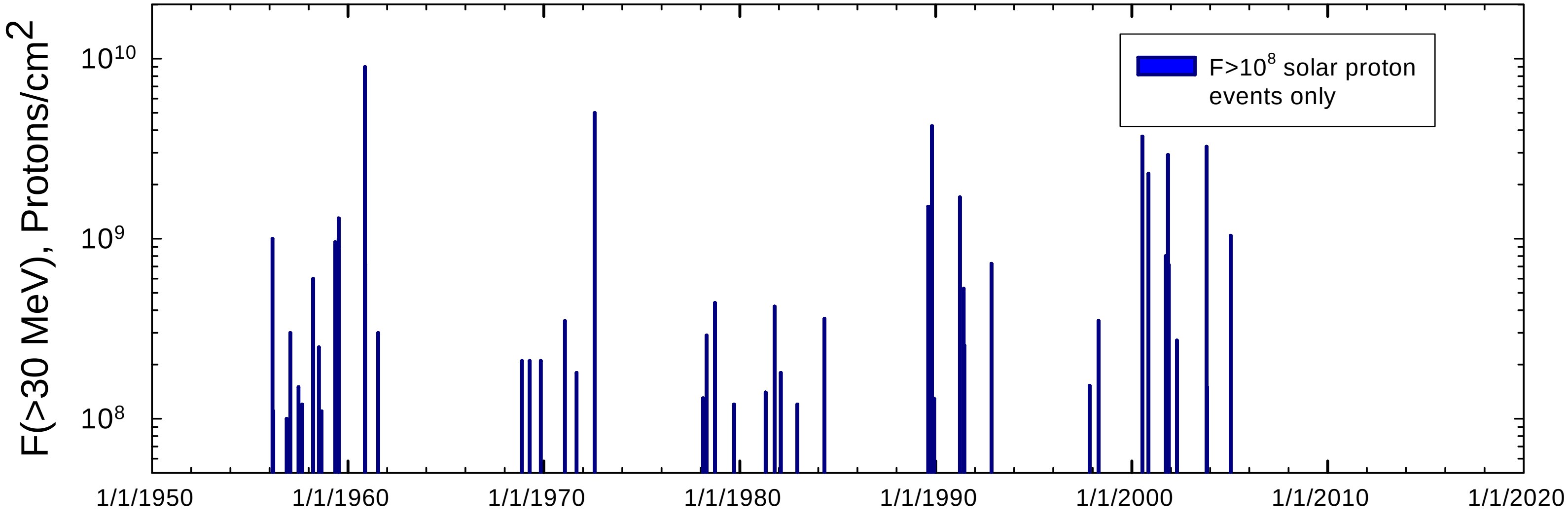
(10) Xapsos *et al*., *IEEE Trans. Nuc. Sci.* **47**(6), 2218-2223, 2000.

Cumulative Distributions of Sample SPE Populations

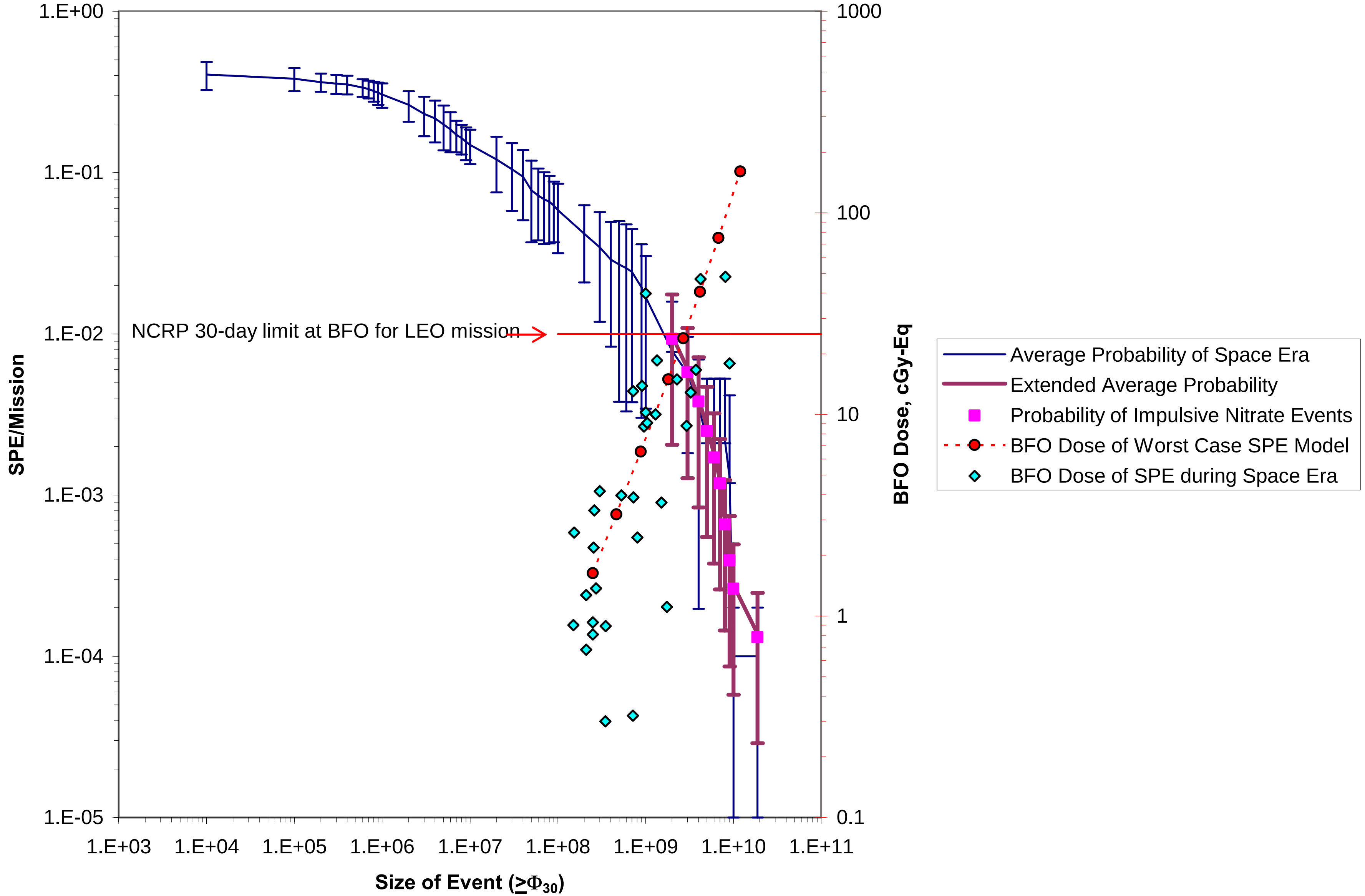


GCR Deceleration Potential

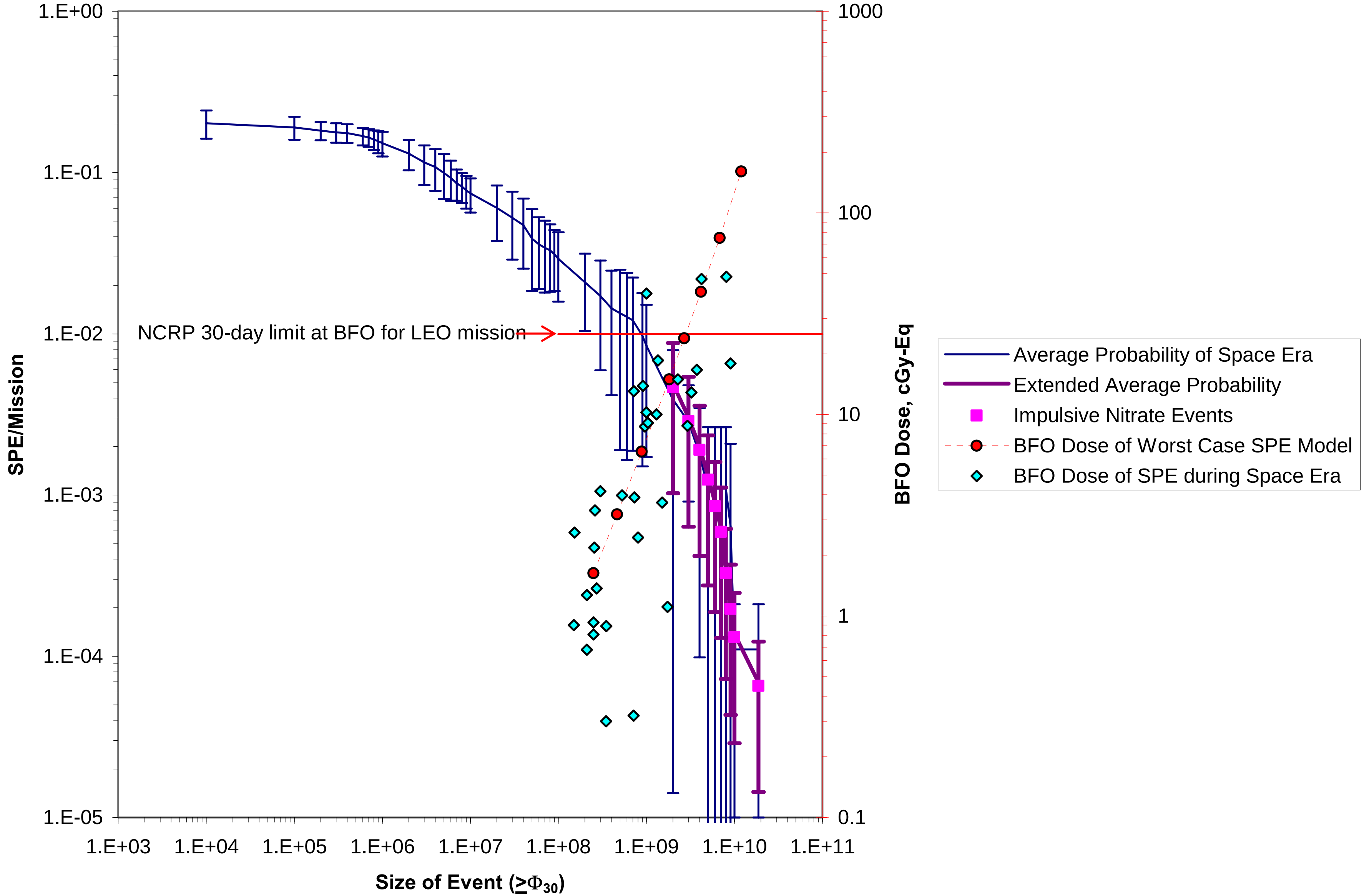




SPE Probability in 2-Week Mission and BFO Exposure Level inside a Typical Equipment Room in Free Space



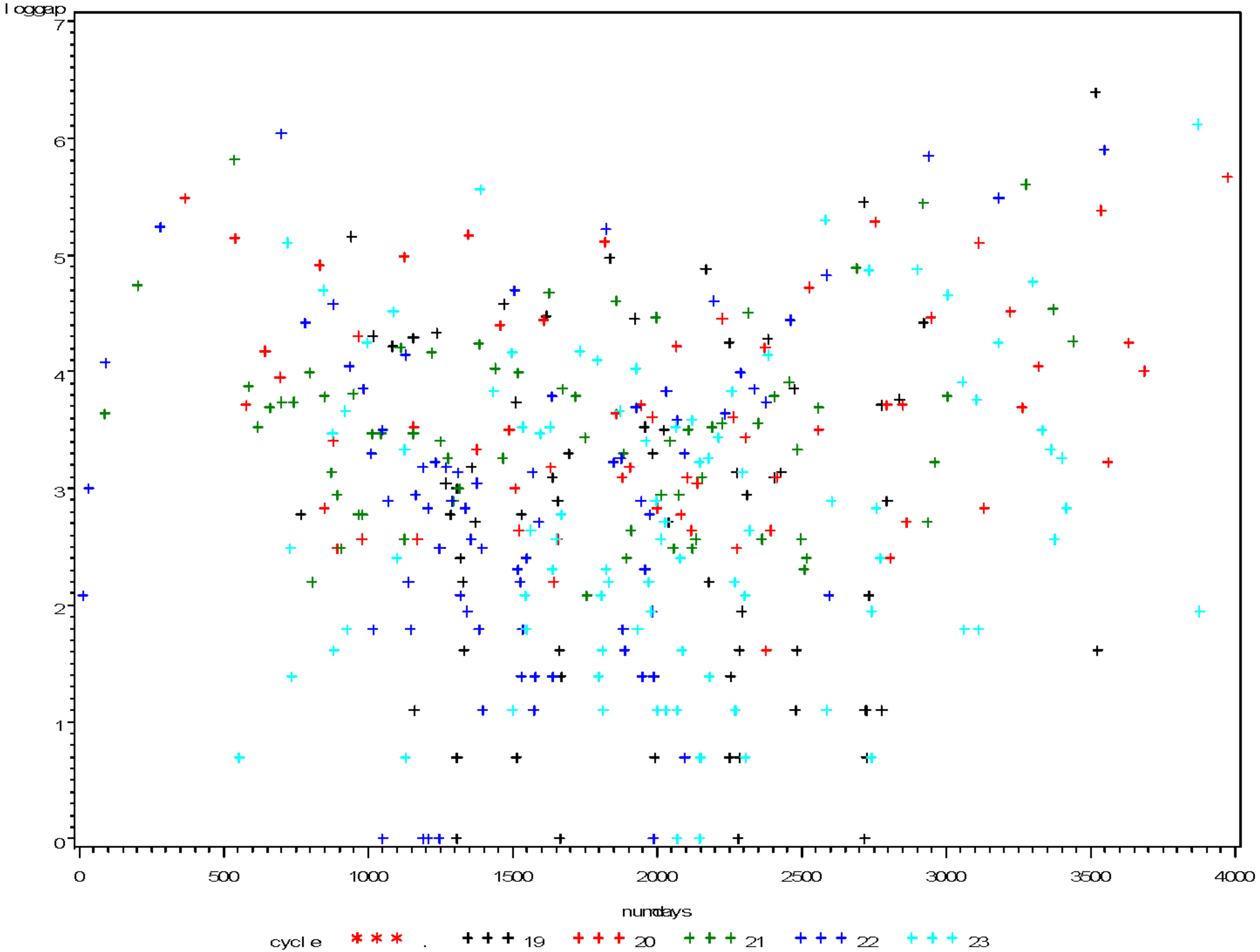
SPE Probability in 1-Week Mission and BFO Exposure Level inside a Typical Equipment Room in Free Space



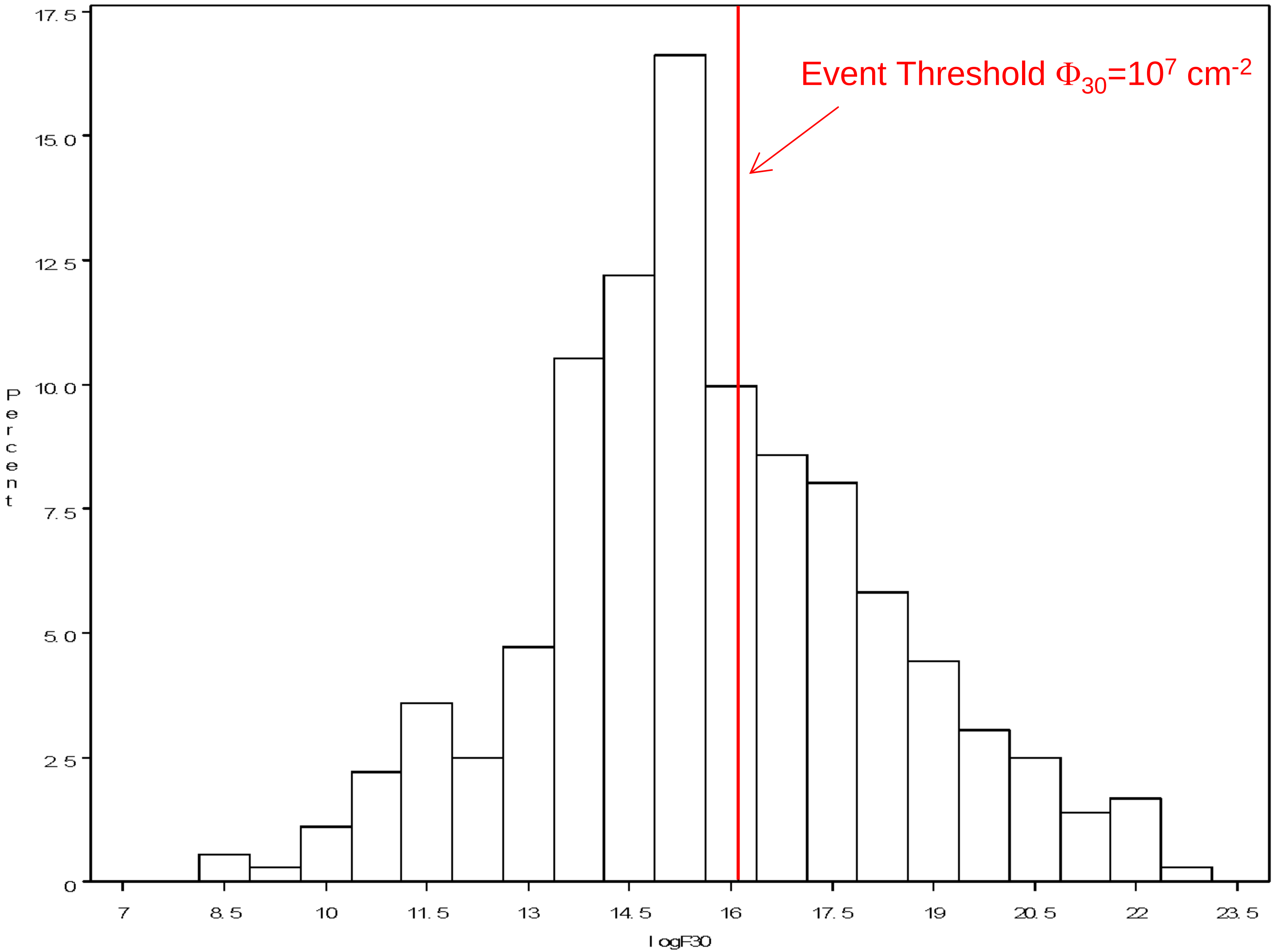
Probability of SPE with $\Phi_{30} > 2 \times 10^9$ cm^{-2} in 1-Week Mission

	Sample	**P($\Phi_{30} \geq 2\times10^9$ cm^{-2})**
Calculation	SPEs in Space Era	0.39 % ± 0.4 %
	SPEs in Space Era + the interval 1561-1950	0.49 % ± 0.39 %
Observation	SPEs in the interval 1561-1950	0.47 %

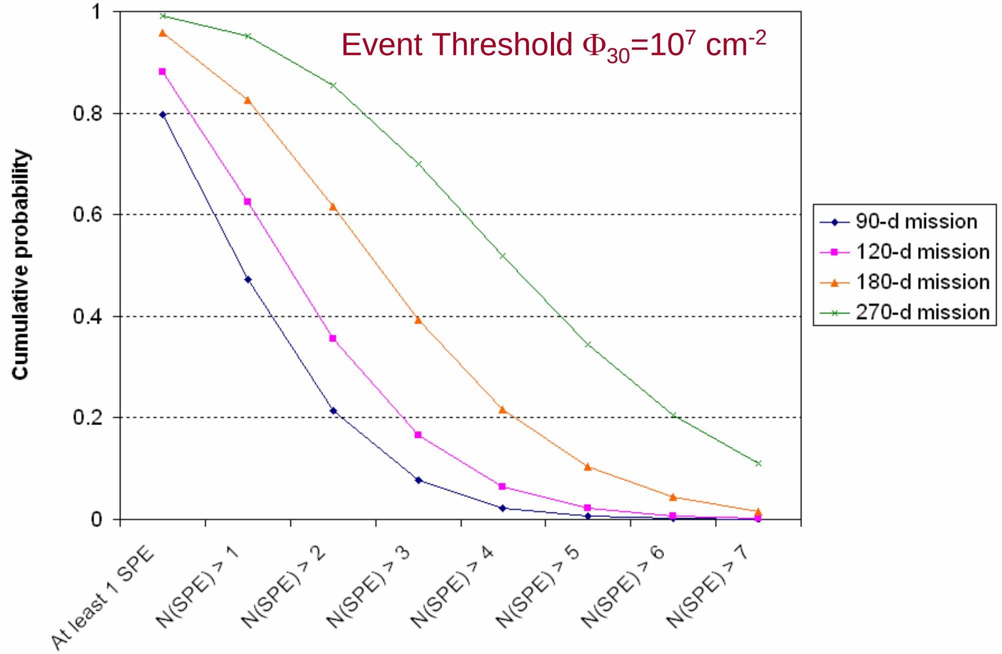
Hazard Model of SPE Gap Times

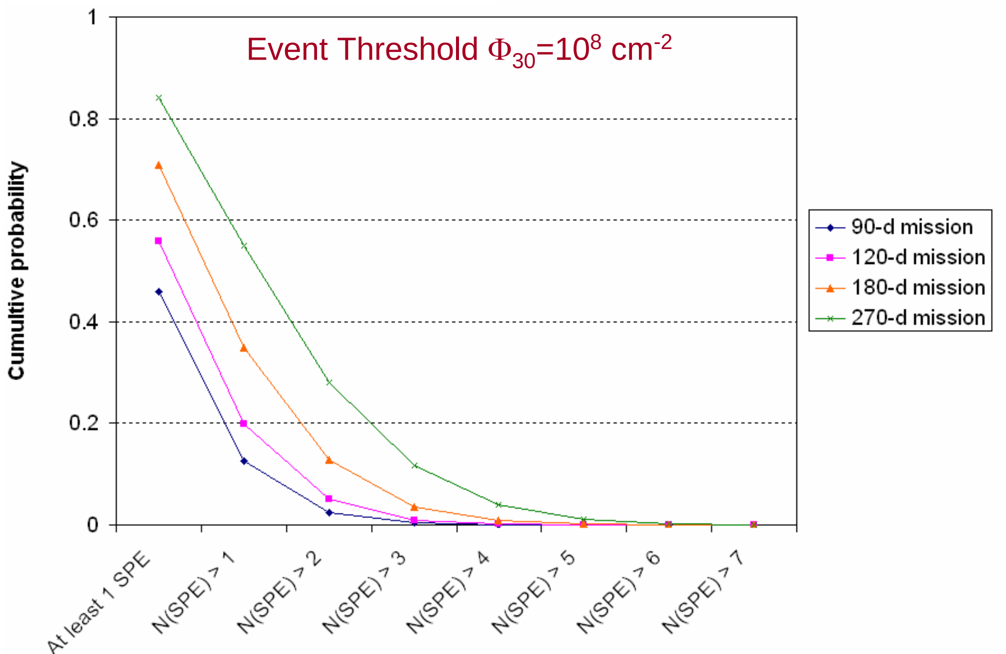


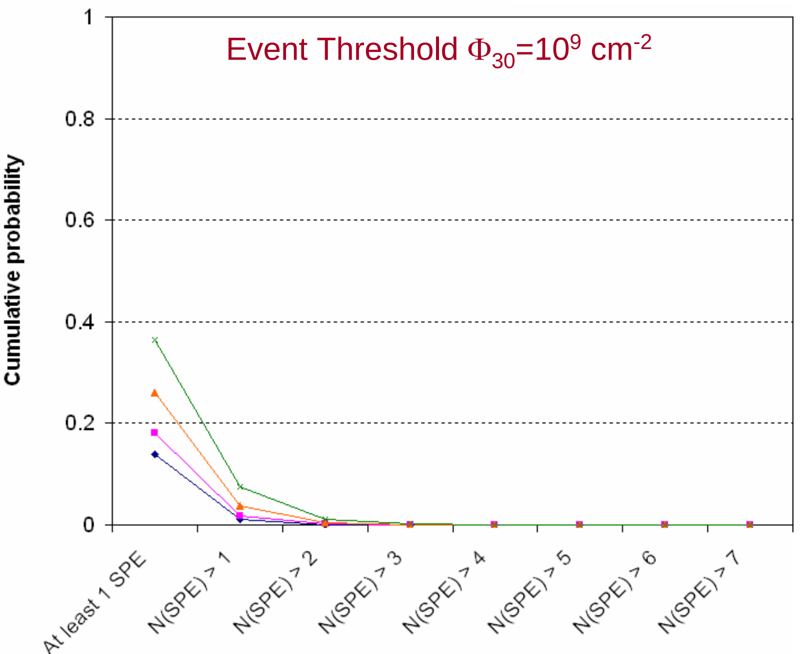
Histogram of Event Size, log(Φ_{30})



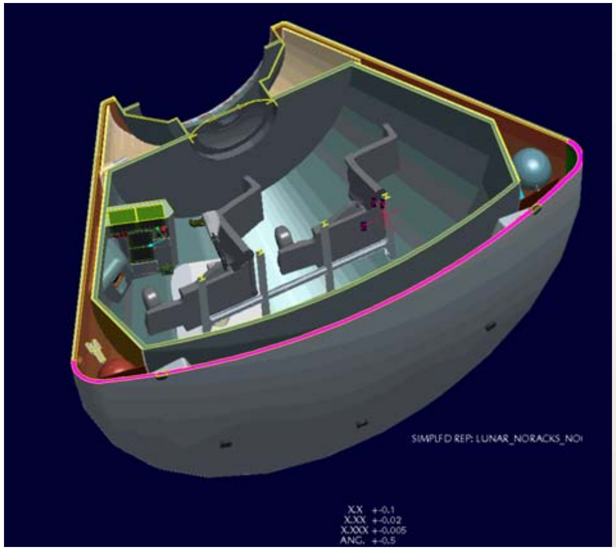
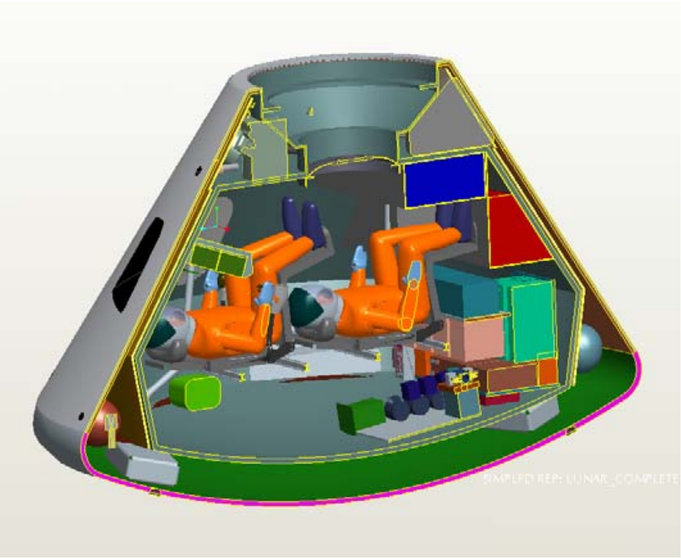
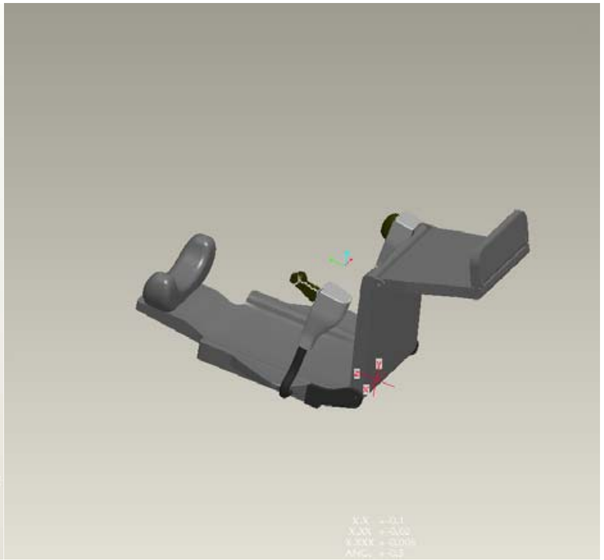
Cumulative Probability during a Given Mission Period



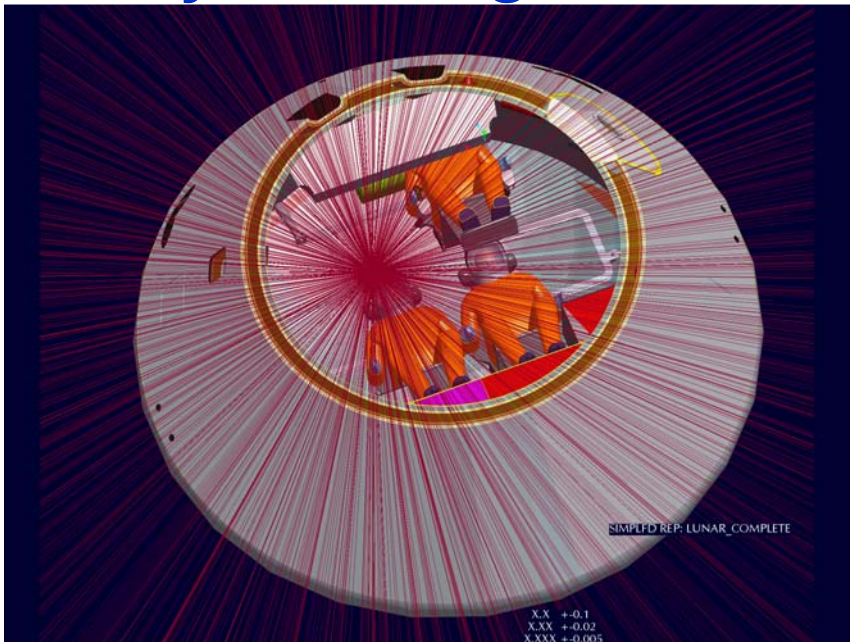


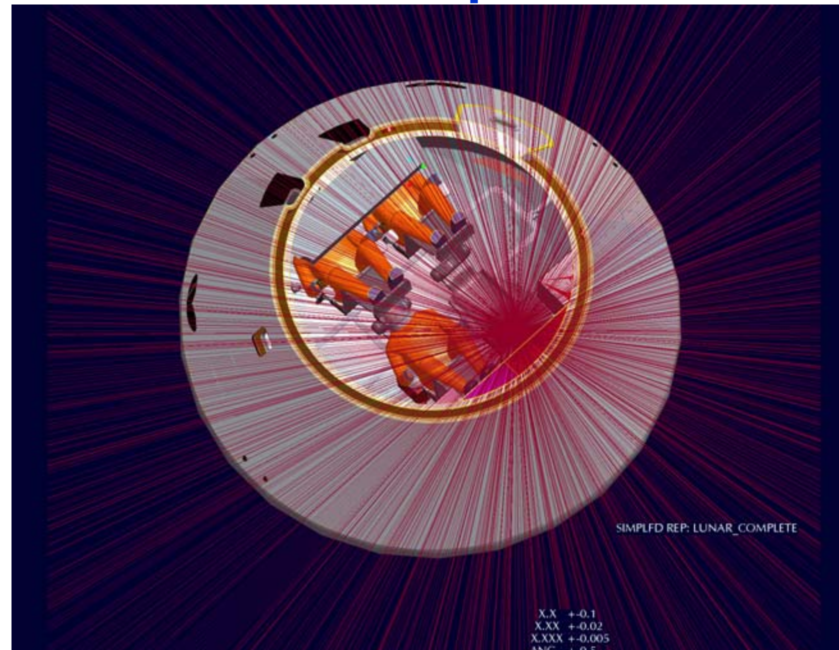


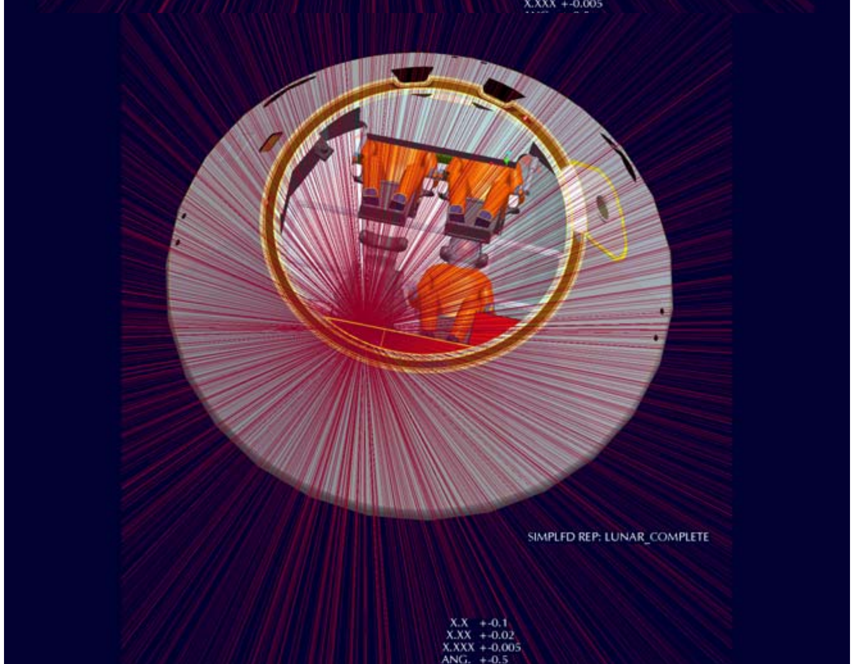
Structural Distribution Model Using ProE™
Various Composition Layers for Exploration-Class Spacecraft

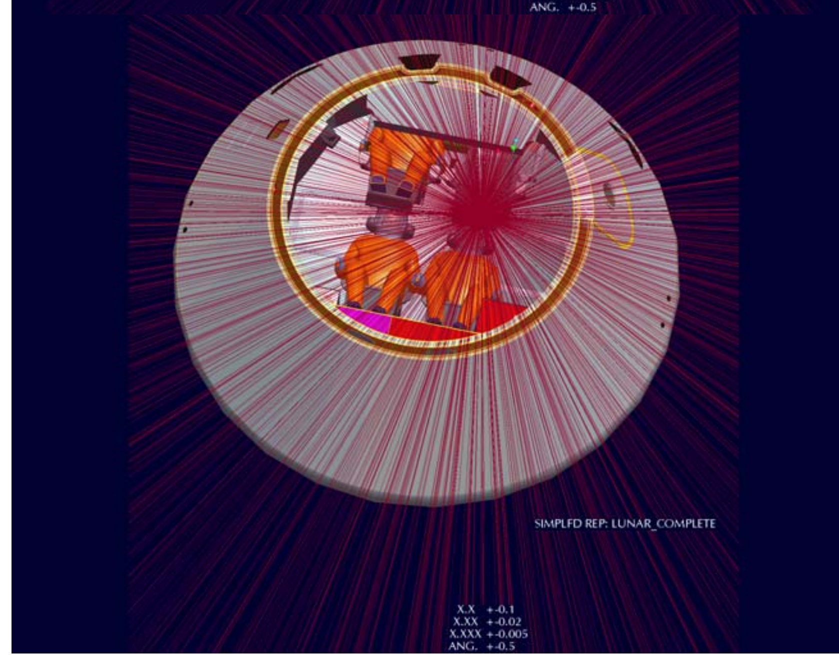




Ray Tracings at 4 DLOCs inside Spacecraft

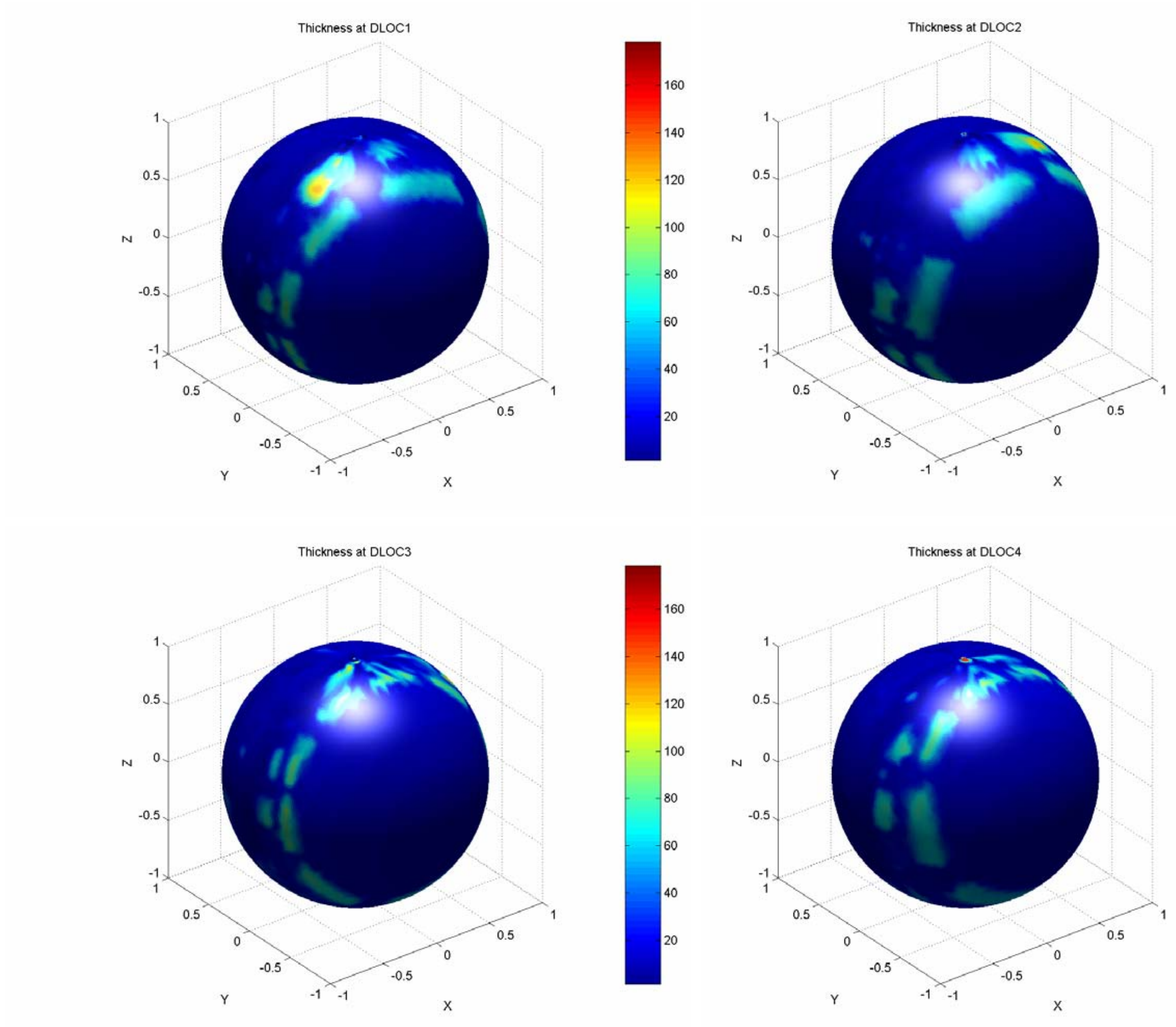








Shielding Distributions at 4 DLOCs of Spacecraft

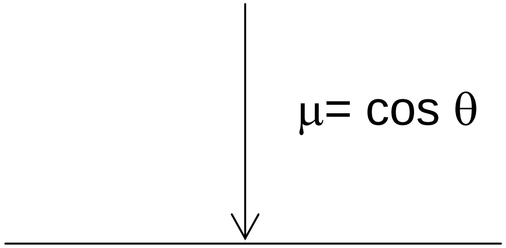


Idealization of the Actual Motion of Astronauts

<u>Random Orientation</u>

- Discrete number of evenly scattered rays over 4π solid angle
- Isotropic angular distribution (for the same volume element):

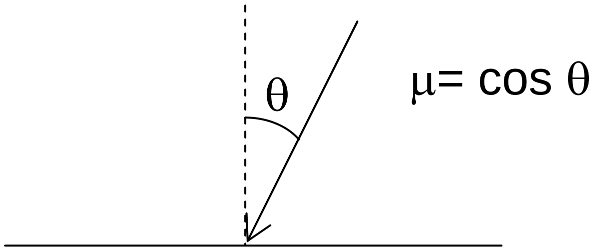
  $p(\mu)$ = constant



<u>Aligned Orientation</u>

- A continuously distributed source rays
- Cosine angular distribution in a small interval on spherical polar coordinates (for each volume element):

  $p(\mu) = \mu$



Idealization of the Actual Motion of Astronauts

Random Orientation

$$H_{organ} = \frac{1}{N}\sum_{i=1}^{N} H_{organ}(X_i)$$

where

N = the given number of rays

X_i = the amount of shielding by material composition layers at the i^{th} ray

Aligned Orientation

$$H_{organ} = \int \int_{\theta=\frac{-\pi}{2}}^{\frac{\pi}{2}} \cos\theta \, d\theta \, d\phi \, H\big(X(\theta,\phi) + Y(\theta,\phi)\big)$$

where

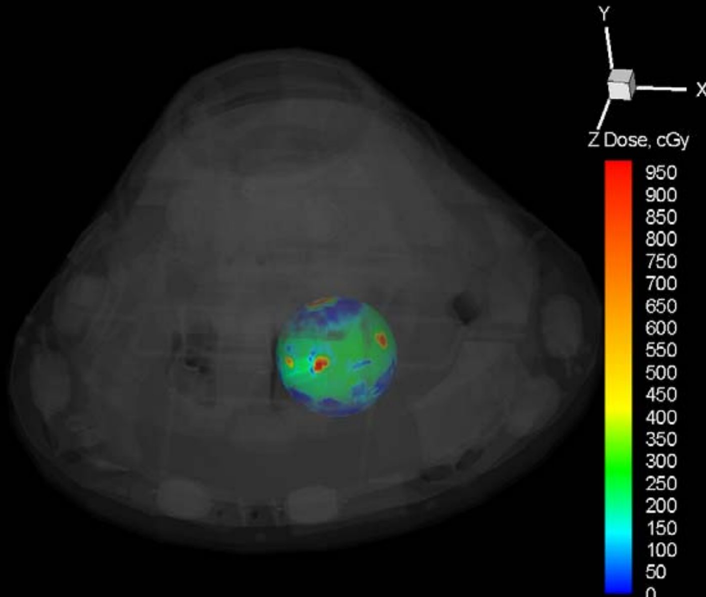
θ = polar angle of a ray

ϕ = azimuth angle of a ray

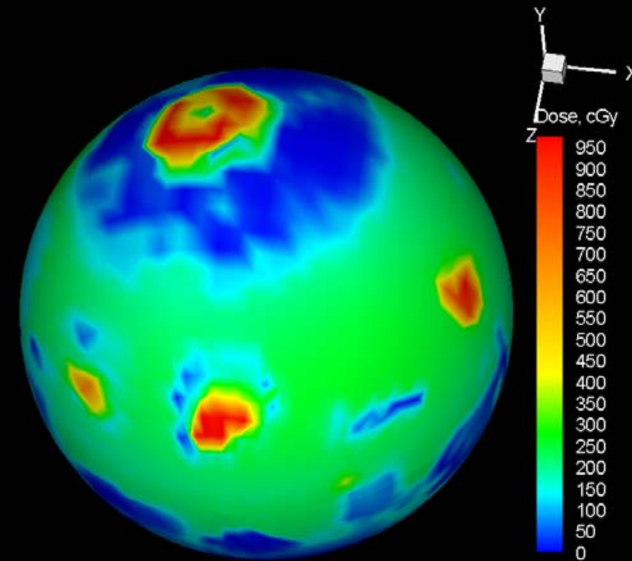
$X(\theta,\phi)$ = the integrated thickness of shielding by spacecraft of a ray

$Y(\theta,\phi)$ = the thickness of body shielding of a ray

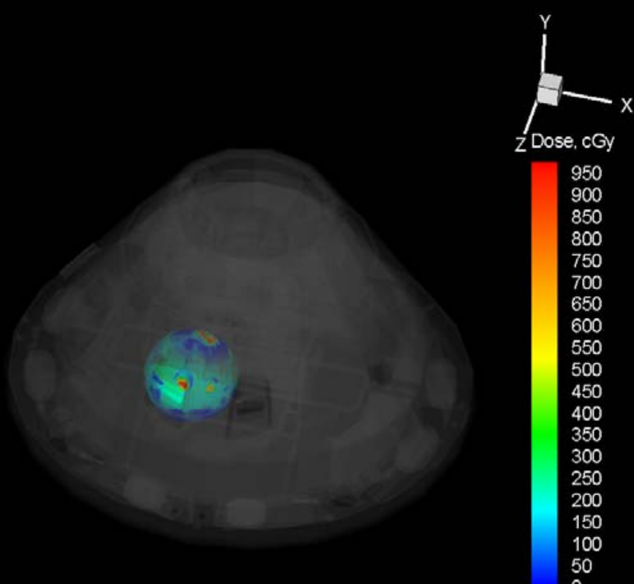
Distributions of Dose from 1972 SPE at 4 DLOCs inside Spacecraft



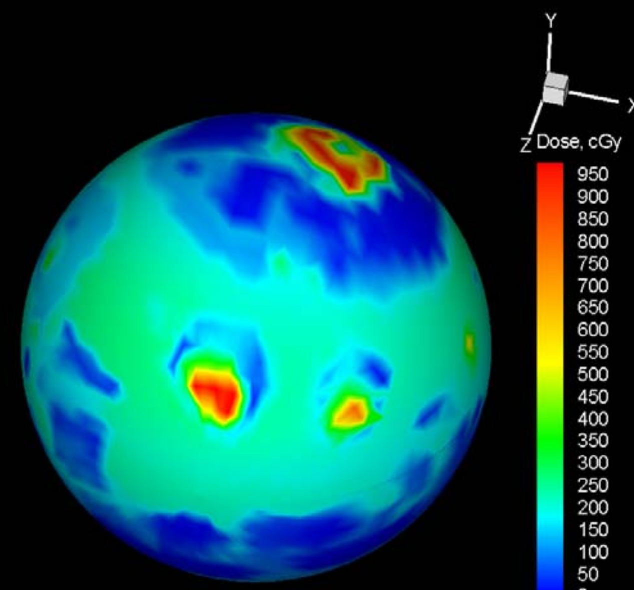
Lunar Transfer Vehicle Concept
DLOC1 Aug 1972 SPE



Lunar Transfer Vehicle Concept
DLOC1 Aug 1972 SPE

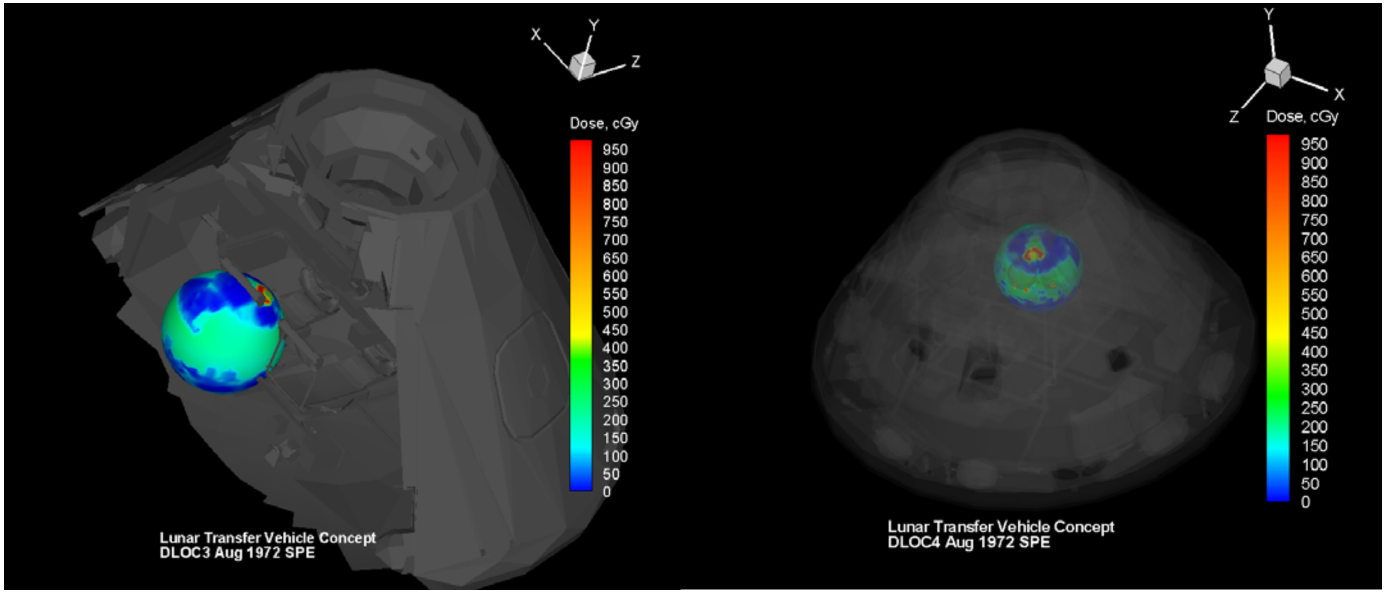


Lunar Transfer Vehicle Concept
DLOC2 Aug 1972 SPE



Lunar Transfer Vehicle Concept
DLOC2 Aug 1972 SPE

Directional Dose Distribution inside Spacecraft Various Composition Layers for Exploration-Class Spacecraft

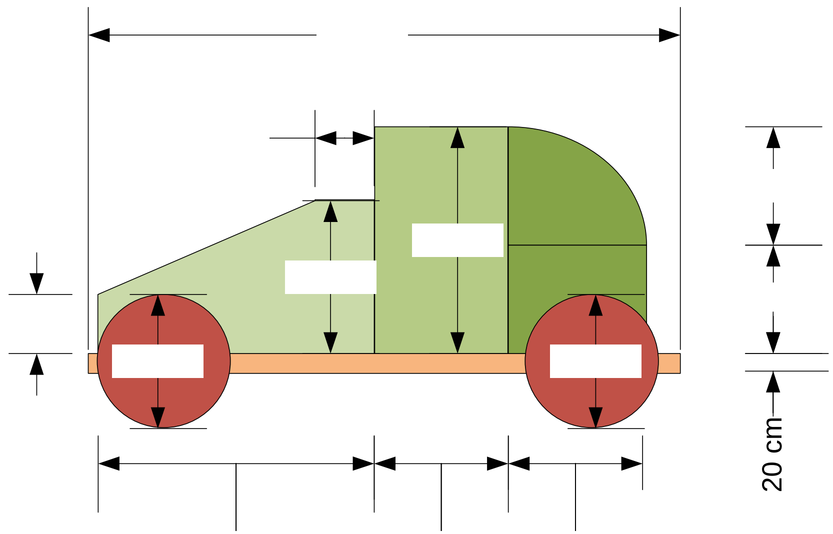


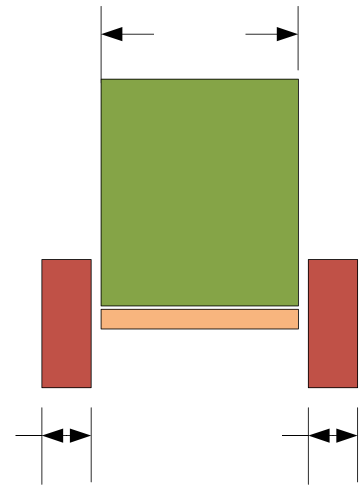
Organ Dose Quantities for Two Orientations

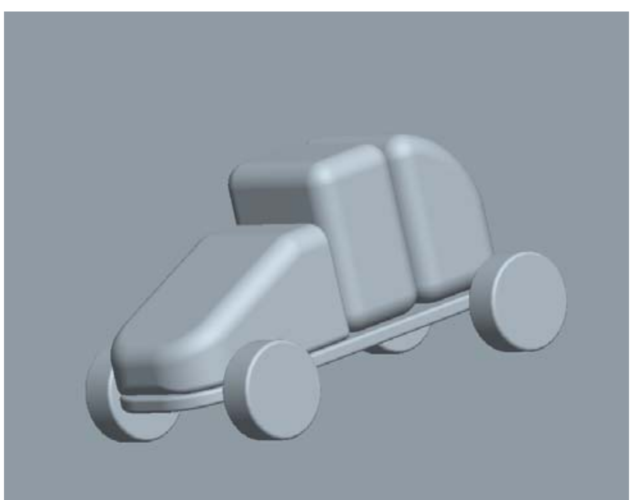
August 1972 SPE

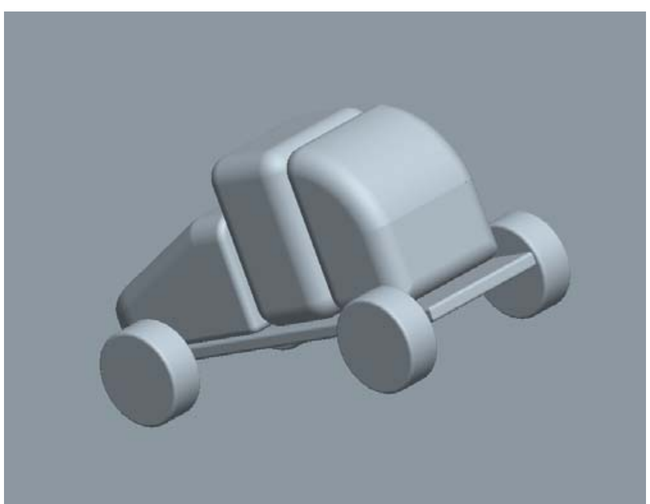
		Random orientation				Aligned orientation			
		DLOC1	**DLOC2**	**DLOC3**	**DLOC4**	**DLOC1**	**DLOC2**	**DLOC3**	**DLOC4**
X-coordinate, cm		43.18	-43.18	40.64	-40.64	43.18	-43.18	40.64	-40.64
Y-coordinate, cm		119.38	119.38	119.38	119.38	119.38	119.38	119.38	119.38
Z-coordinate, cm		52.71	52.71	-79.34	-79.34	52.71	52.71	-79.38	-79.38
Al-Eq x_{avg}, g/cm^2		15.18	15.08	15.85	15.33	15.18	15.08	15.85	15.33
x_{min} - x_{max}		0 - 102.07	0 - 105.50	0 – 83.21	0 - 85.79	0 - 102.07	0 - 105.50	0 – 83.21	0 - 85.79
	Avg skin	126.61	121.07	104.08	108.59	150.92	135.41	111.45	114.45
	Eye	86.76	84.36	73.58	77.06	89.71	89.94	81.62	79.72
	Avg BFO	16.91	16.82	15.2	15.88	18.14	18.20	16.05	15.98
	Stomach	7.38	7.37	6.77	7.03	6.94	6.89	6.59	6.63
	Colon	14.42	14.36	13.04	13.6	14.46	14.36	12.67	12.79
	Liver	10.37	10.33	9.41	9.8	9.43	9.60	8.92	9.23
CAM	**Lung**	12.16	12.12	11.04	11.5	12.09	11.61	11.30	10.73
organ	**Esophagus**	11.61	11.57	10.54	10.98	11.25	10.78	10.52	9.93
dose, cSv	**Bladder**	7.54	7.53	6.9	7.17	7.64	7.25	6.98	6.84
	Thyroid	18.39	18.31	16.55	17.28	18.55	18.15	16.47	16.79
	Chest	72.23	70.58	61.85	64.83	74.88	73.95	67.60	66.37
	Gonads	35.27	34.74	30.76	32.24	37.72	32.64	31.19	27.74
	Front brain	29.54	29.32	26.31	27.53	28.72	27.60	25.32	25.32
	Mid brain	16.2	16.15	14.68	15.3	15.52	15.56	14.05	15.03
	Rear brain	28.93	28.72	25.79	26.98	27.49	27.96	24.98	27.84
Effective dose eq, cSv		21.45	21.16	18.89	19.75	22.42	21.09	19.43	18.64
Point dose eq, cSv		254.68	242.74	207.92	216.83	253.48	241.76	205.76	211.88

Rover Design



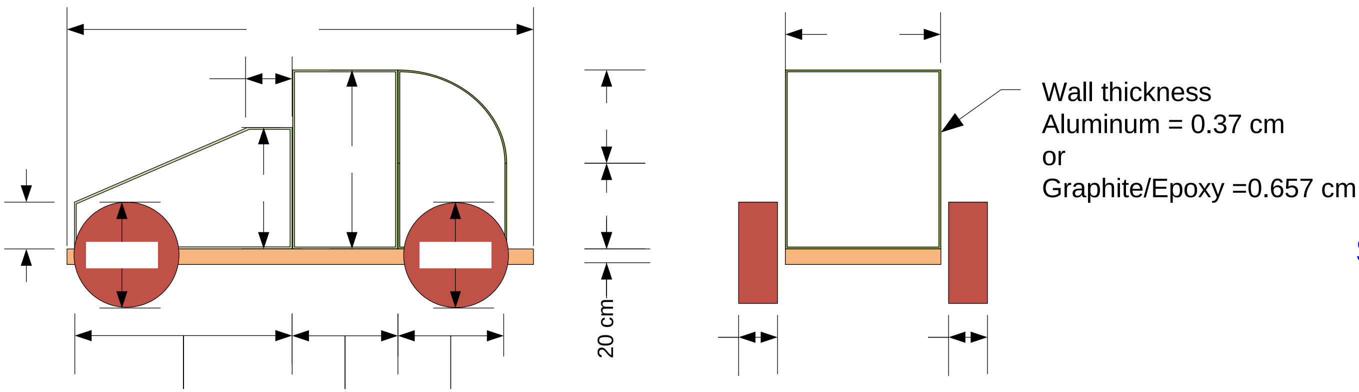




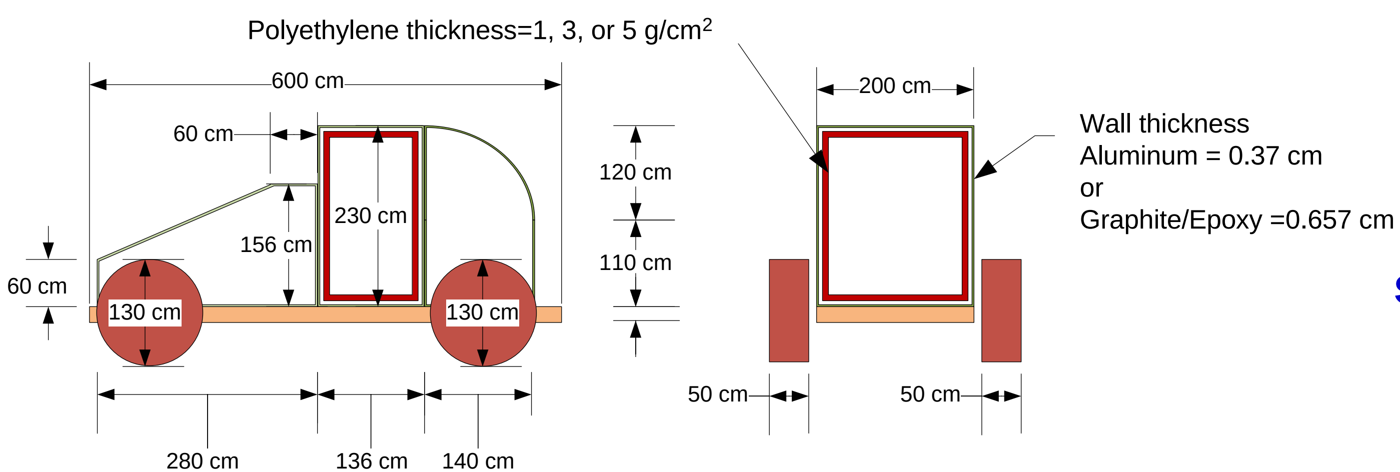


- Three sections of rover: front, center, and back.
- Wall thickness: 1 g/cm^2

Schematic Drawings of Rover *With* and *Without* Polyethylene Shelter in the Center Section



Rover without polyethylene shield in central shelter



Rover with polyethylene shield in central shelter

SPE Shelter Concepts on Rover

Rover section	Section mass of 1 g/cm^2, kg	Rover mass, kg		Polyethylene SPE shelter thickness, g/cm^2	Polyethylene shelter mass, kg	Total mass, kg
Front	201			1	166	720
Center	188	554		3	490	1044
Back	165			5	800	1354

EVA Exposure (in cSv) Inside Polyethylene Shelter for Two Rover Concepts on Lunar Surface from August 1972 SPE

Organ	Polyethylene thickness of SPE shelter in the rover					
	1 g/cm^2		3 g/cm^2		5 g/cm^2	
	Al Rover	Graphite/Epoxy Rover	Al Rover	Graphite/Epoxy Rover	Al Rover	Graphite/Epoxy Rover
Skin	358.05	320.48	116.20	107.92	49.99	47.09
Eye	277.52	252.14	100.40	93.69	45.17	42.66
Avg. BFO	34.46	32.58	17.69	16.88	9.81	9.44
Stomach	12.00	11.51	6.97	6.74	4.27	4.17
Colon	27.61	26.21	14.72	14.10	8.39	8.10
Liver	19.17	18.23	10.36	9.94	6.01	5.82
Lung	22.40	21.32	12.20	11.70	7.08	6.85
Esophagus	21.30	20.27	11.62	11.15	6.76	6.54
Bladder	12.93	12.35	7.26	7.00	4.35	4.24
Thyroid	37.13	35.14	19.22	18.35	10.70	10.30
Chest	221.87	202.84	84.16	78.68	38.61	36.51
Gonads	95.46	88.38	40.27	37.88	19.59	18.62
Front brain	66.16	62.20	32.12	30.50	17.05	16.33
Mid brain	30.33	28.85	16.45	15.77	9.47	9.15
Rear brain	64.30	60.48	31.38	29.81	16.72	16.01
Point dose	801.89	713.90	249.65	230.94	104.10	97.61
Whole body effective dose	51.94	48.27	23.10	21.85	11.88	11.36

Summary

- A temporal forecast of GCR has been derived from the GCR deceleration potential (ϕ) - Point dose equivalent in interplanetary space is influenced by solar modulation by a factor of 3.
- Relationship between large SPE occurrence and ϕ is clearly shown.
- Exposure levels of 34 big SPEs and worst-case SPEs:
  - Most SPEs lead to small BFO doses in an unshielded typical equipment room (< 12.5 cGy-Eq on lunar surface).
- Probabilities of one and multiple SPEs with event size thresholds are obtained for various mission durations.
- Detailed distribution of directional risk assessment shows better protection for risk mitigation inside a habitable volume/shelter/spacecraft during future lunar missions.
- A large SPE similar to August 1972 event can be shielded to an effective dose <150 mSv by an SPE shelter on rover during EVA on lunar surface.