Minimizing Astronauts' Risk from Space Radiation during Future Lunar Missions

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Outline

- Future Space Radiation Environment for Lunar Missions
  - GCR
  - SPE
- Analysis of Directional Shielding Provided by Lunar Transfer Vehicle (LTV) Geometry during Interplanetary Transfer
- Organ Dose Calculation inside LTV by Idealization of the Actual Motion of Astronauts
- Organ Dose Calculation inside Rover during EVA
- SPE Shelter Optimization in Consideration of Mass Constraint and Maximizing Protection

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.

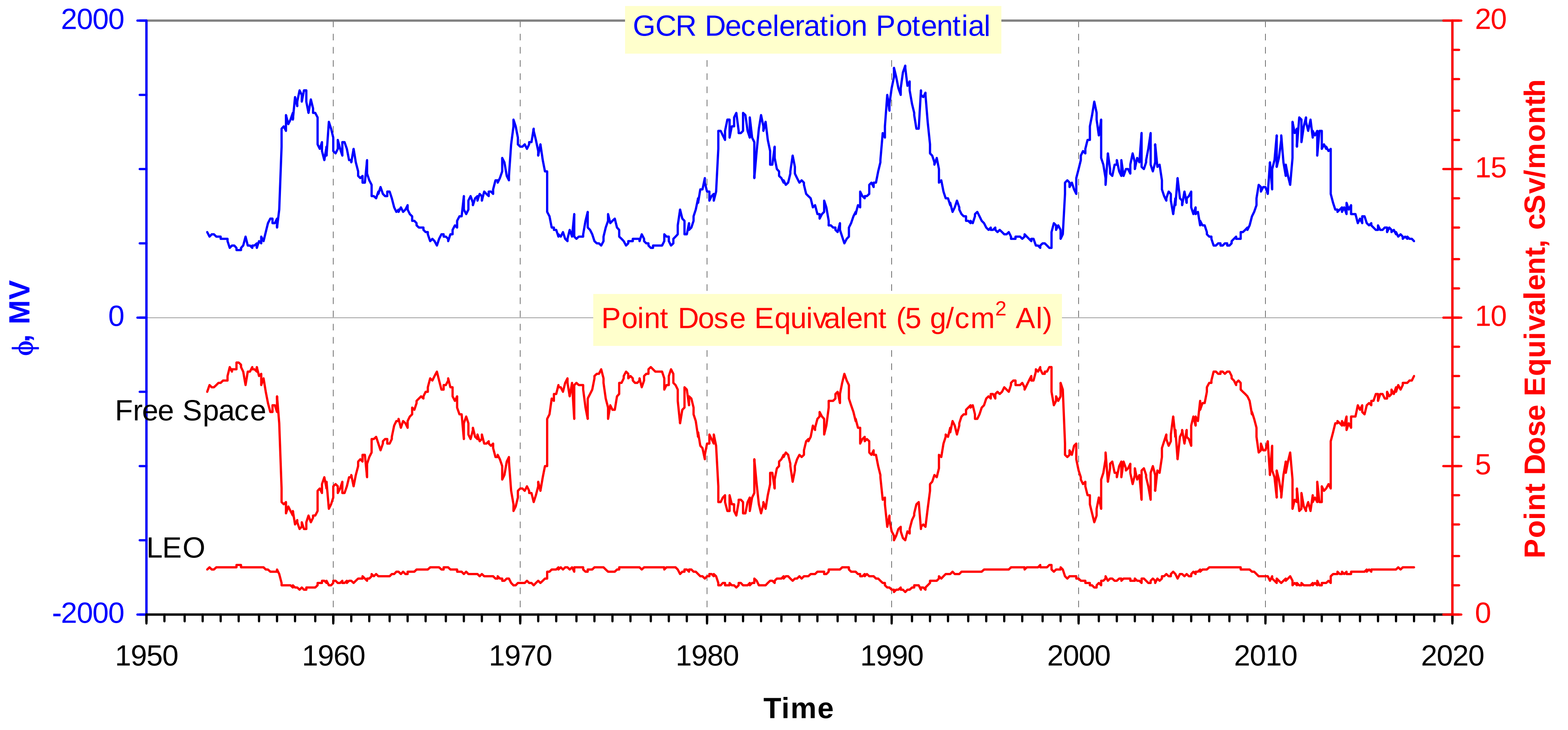
→ We develop a practical approach to predicting GCR environment.

- 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 mission period are major operational problems for planning space missions and protecting humans during missions.

→ We calculate probabilities of large SPEs occurring 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, A., 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, M. and Smart, D., 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.

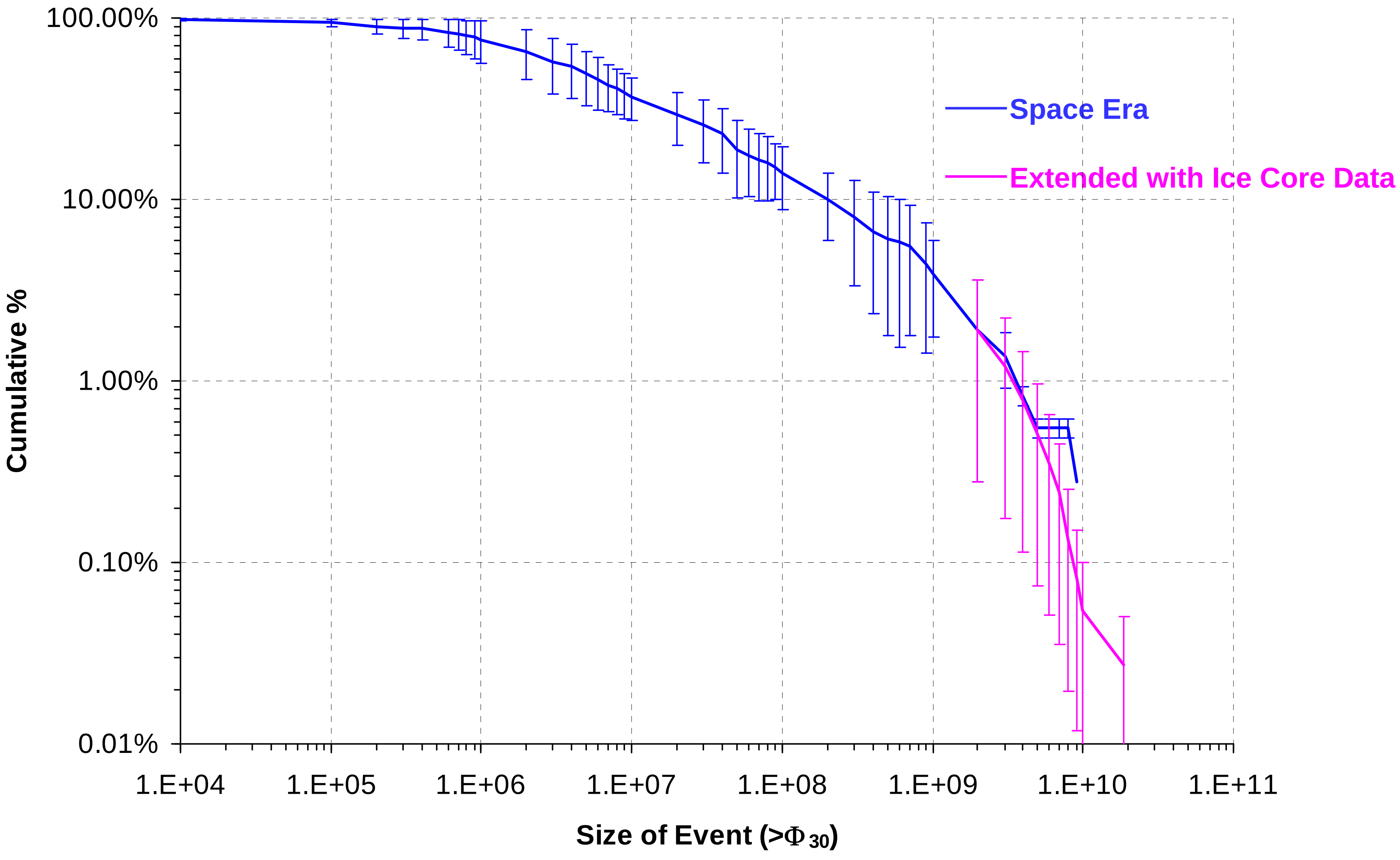
(7) Freier, P. S. and Webber, W. R., "Exponential Rigidity Spectrums for Solar-Flare Cosmic Rays," *J. Geophys. Res*., Vol. 68, No. 6, 1963, pp. 1605-1629.

(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.

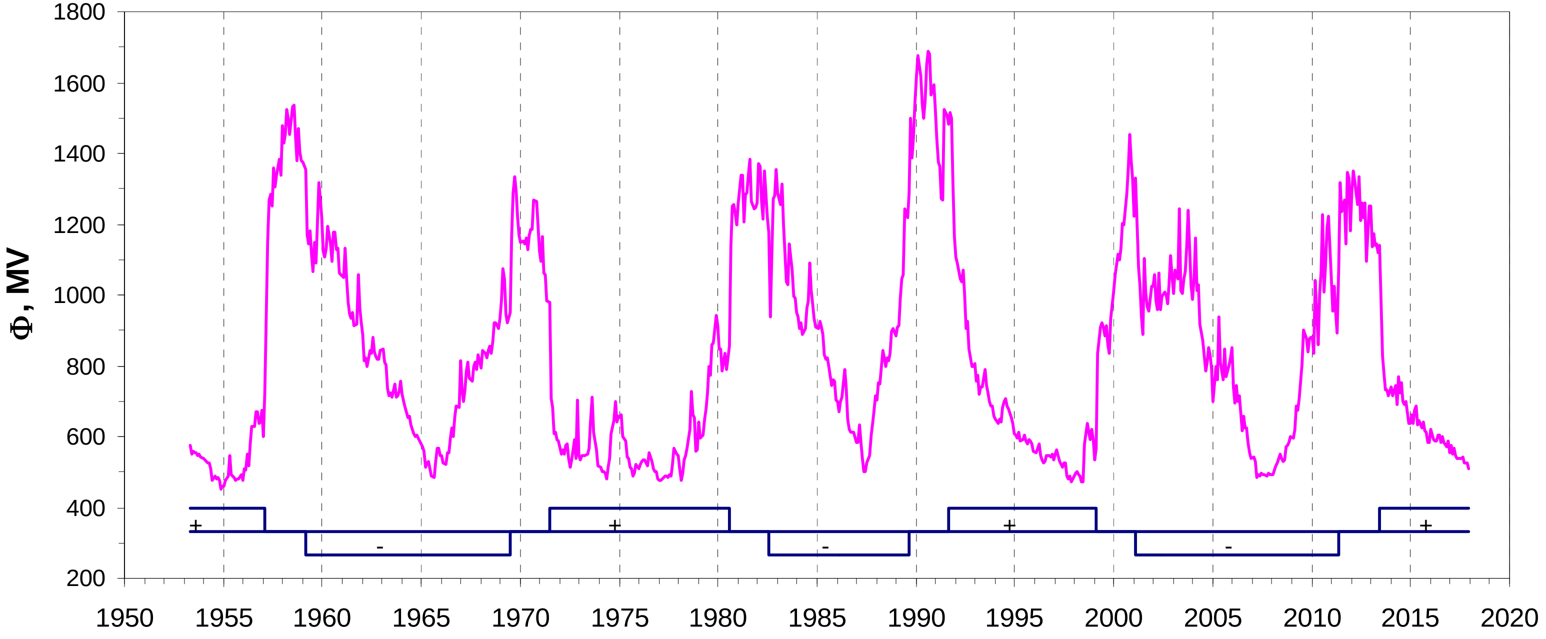
(9) Kim, M. Y., Cucinotta, F. A., and Wilson, J. W., A temporal forecast of radiation environments for future space exploration missions, Radiat. and Environ. Biophys., **46**, No. 2, pp. 95-100, June 2007.

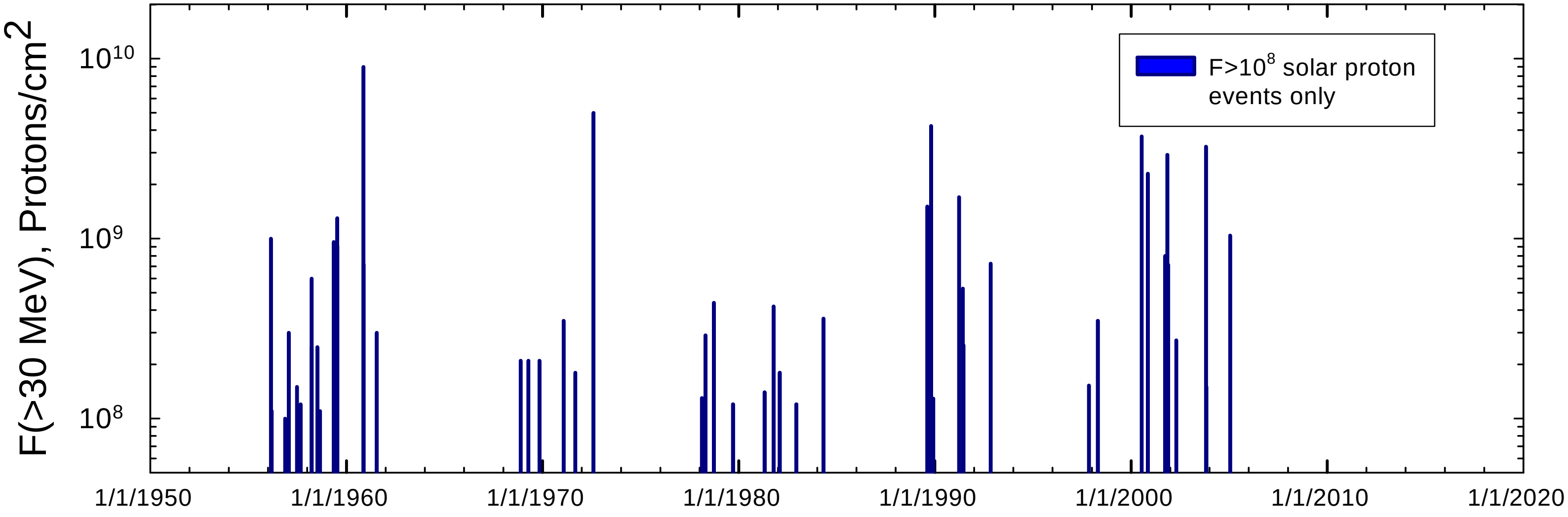
(10) Xapsos *et al*., *IEEE Trans. Nuc. Sci.* **47**(6), 2218-2223, 2000.

Cumulative Distributions of Sample SPE Populations

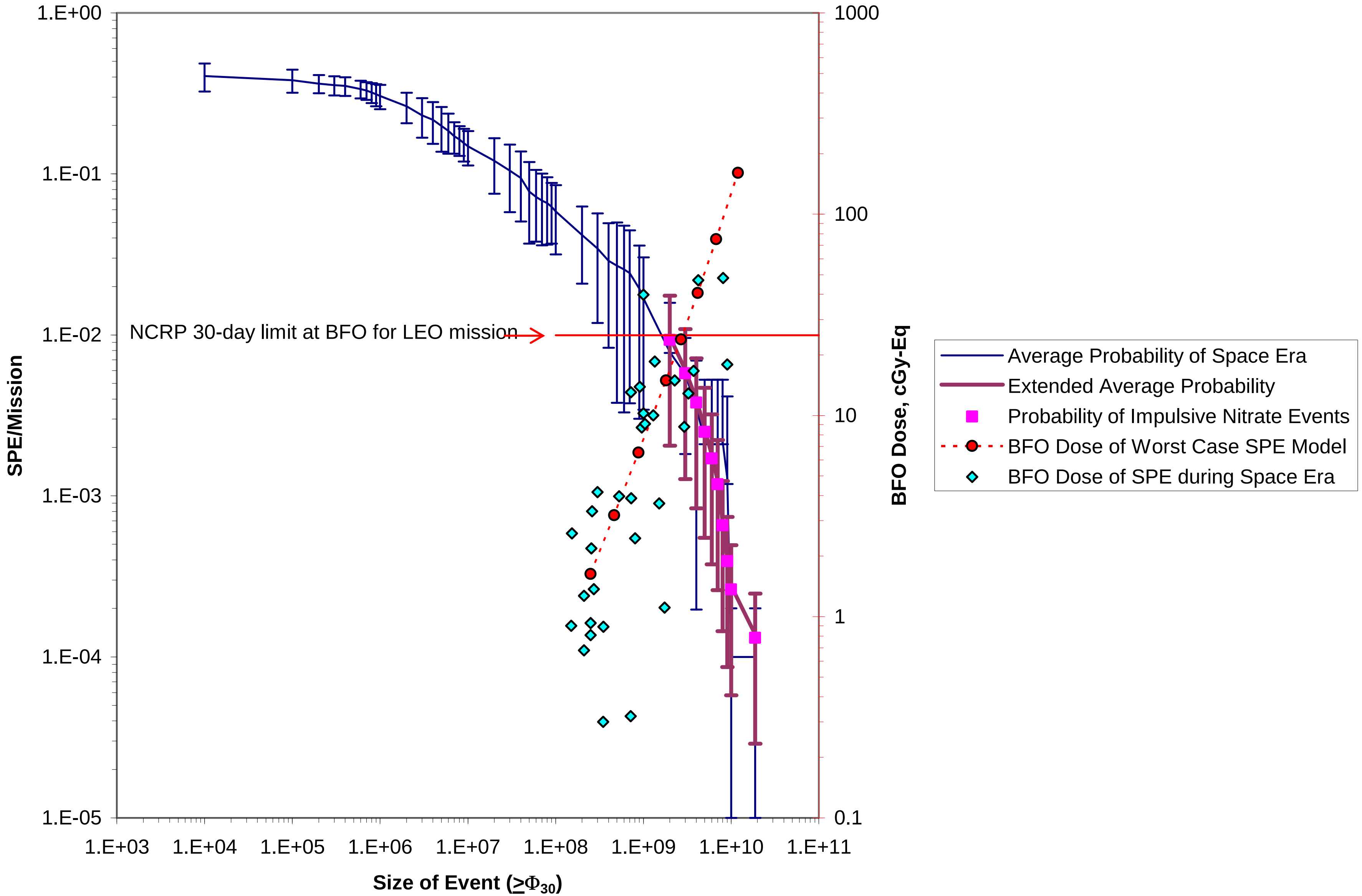


GCR Deceleration Potential

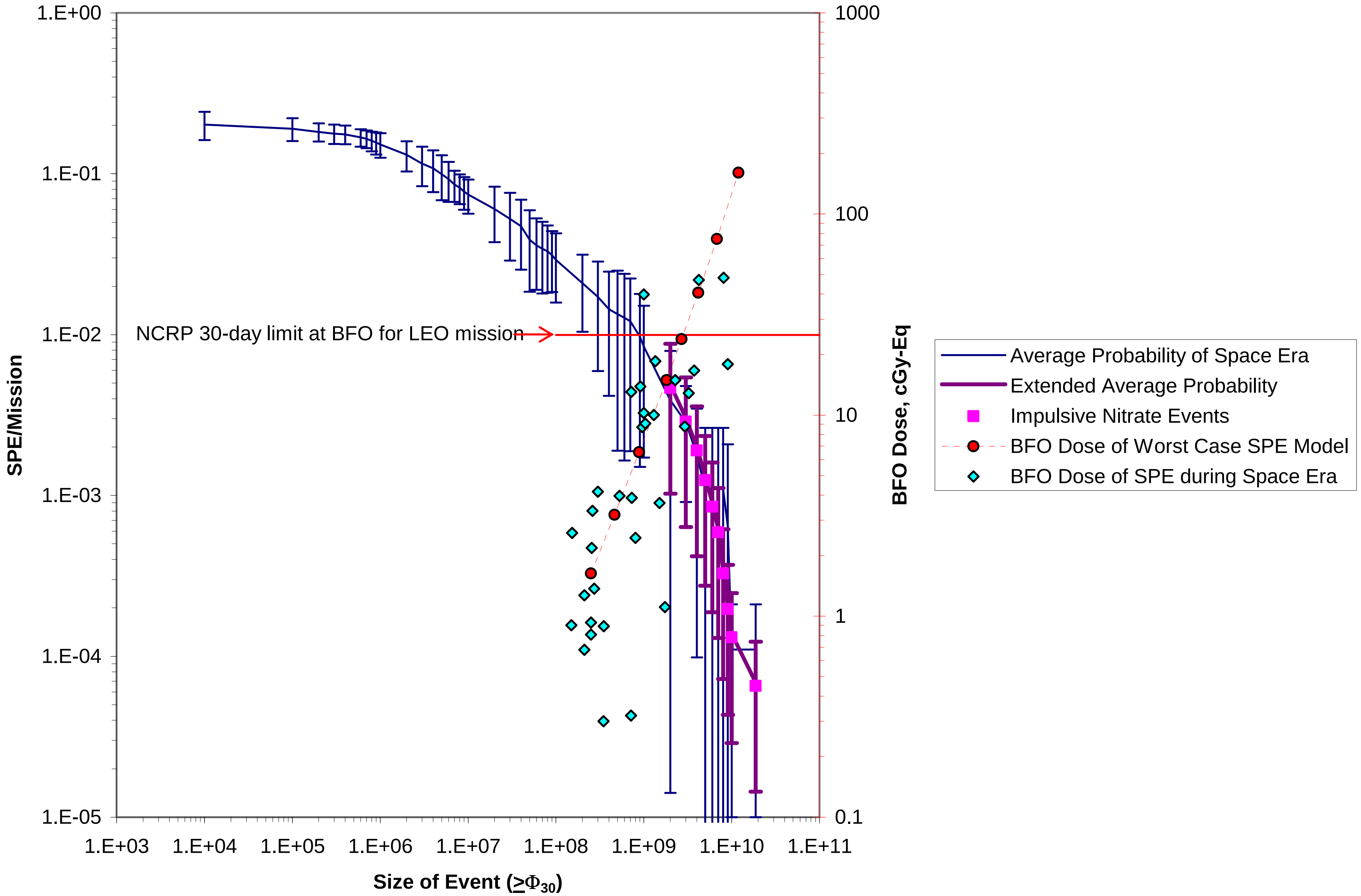




SPE Probability in 2-Week Mission and BFO Exposure Level inside a Typical Equipment Room in Free Space



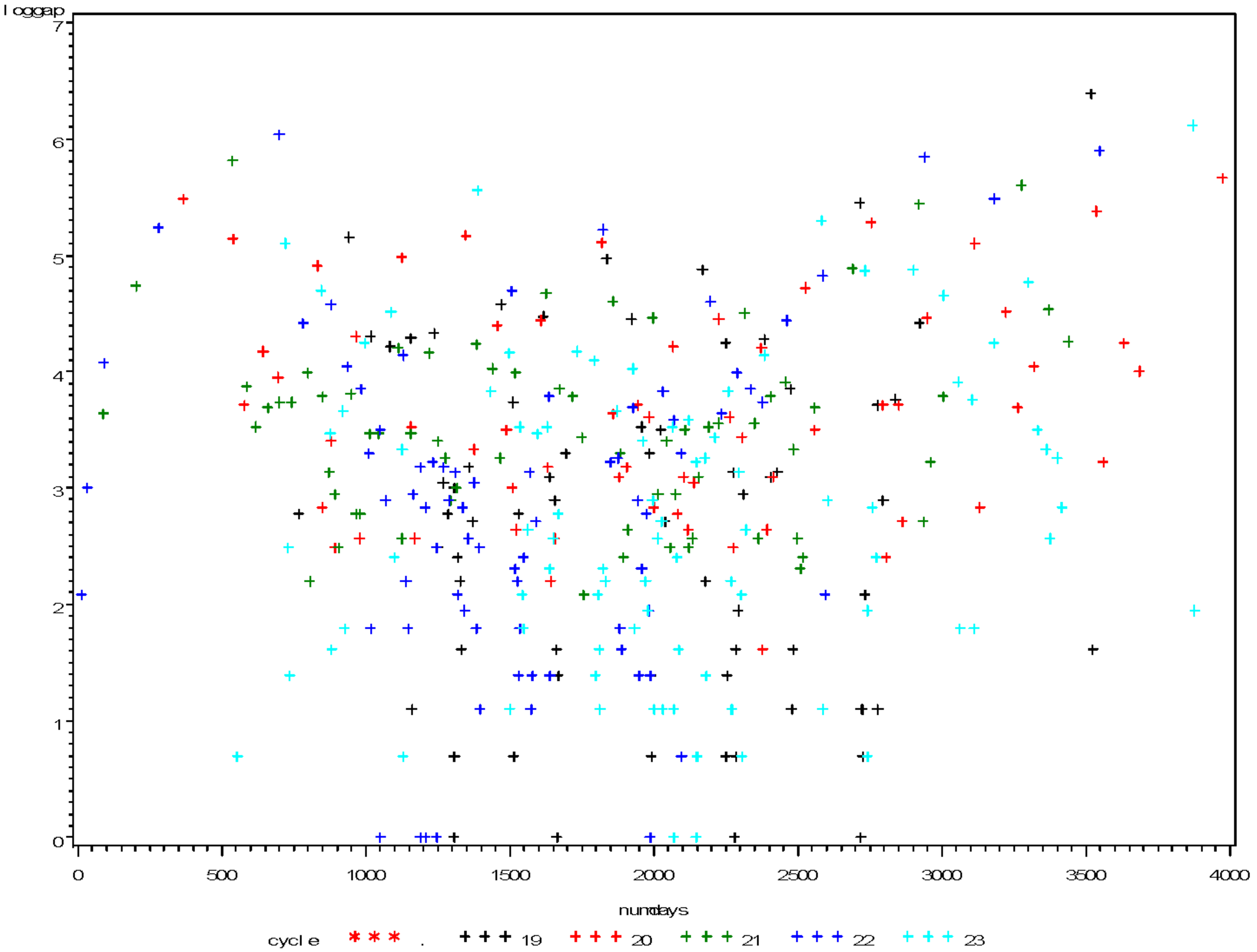
SPE Probability in 1-Week Mission and BFO Exposure Level inside a Typical Equipment Room in Free Space



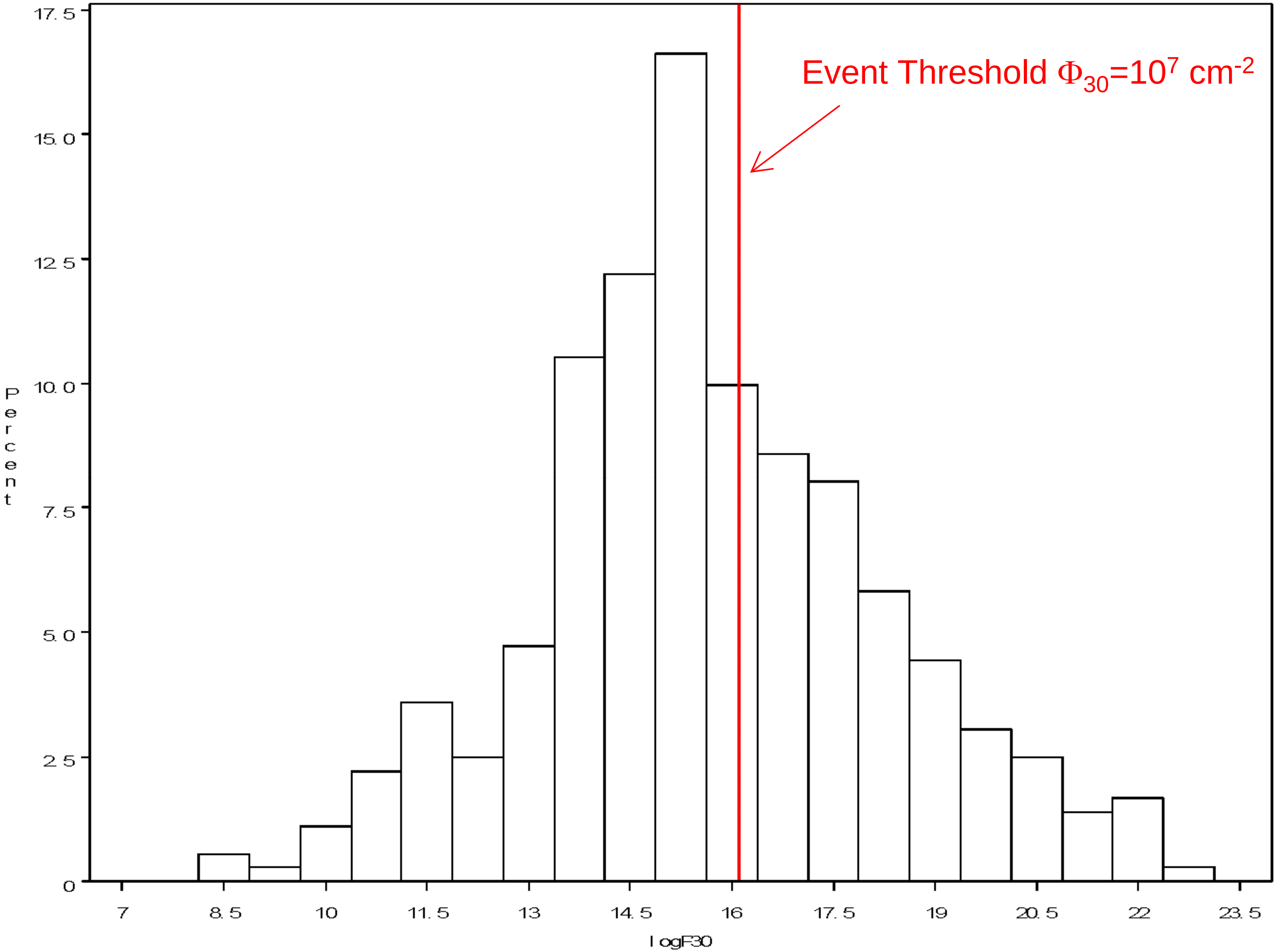
Probability of SPE with $\Phi_{30} > 2 \times 10^9$ cm^{-2} in 1-Week Mission

	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 %

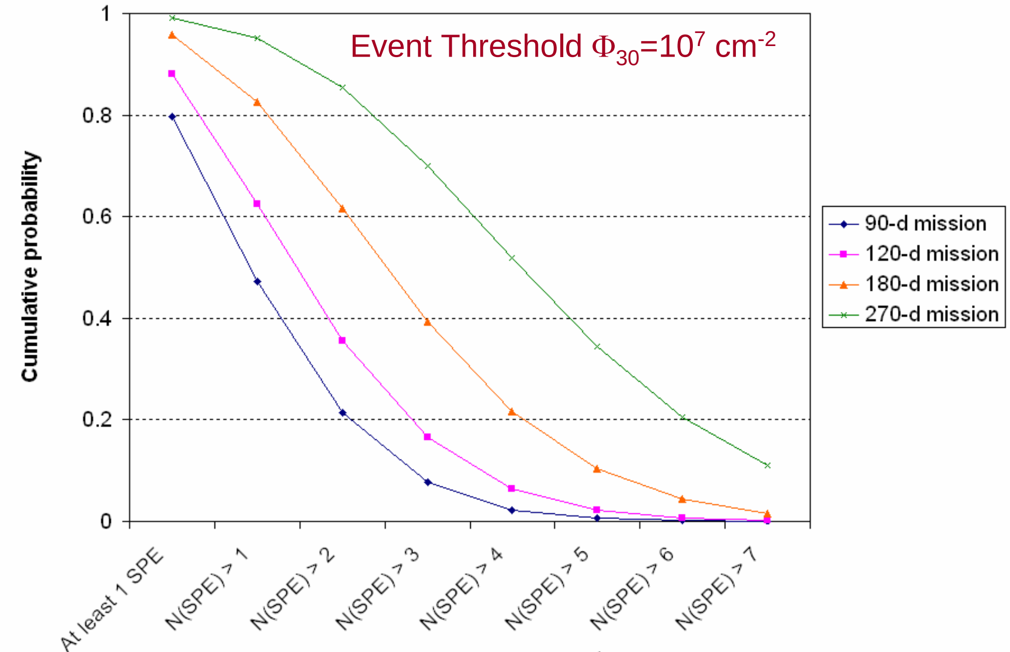
Hazard Model of SPE Gap Times

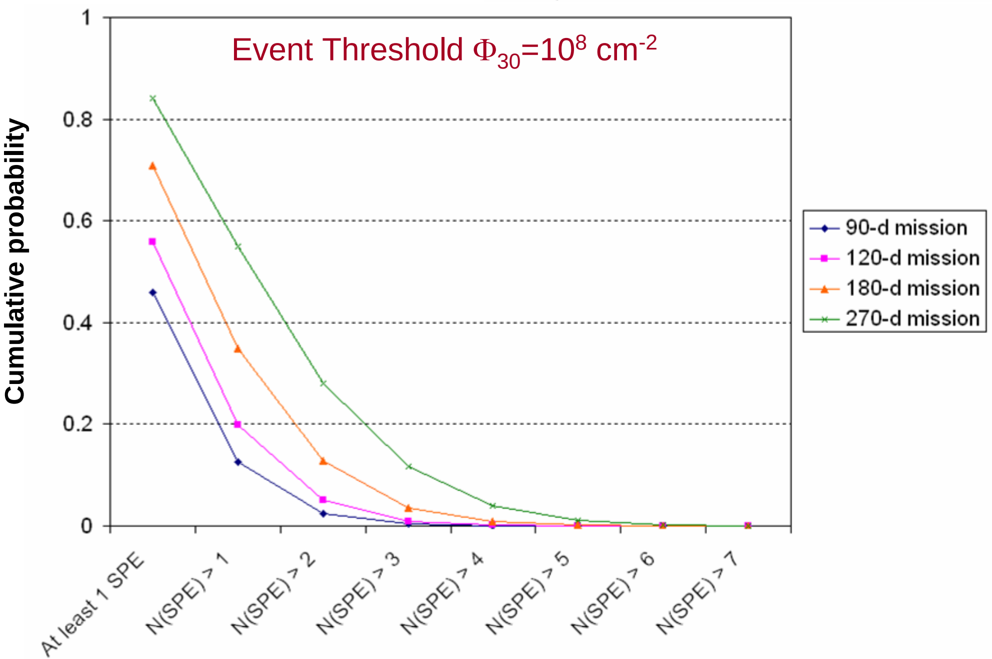


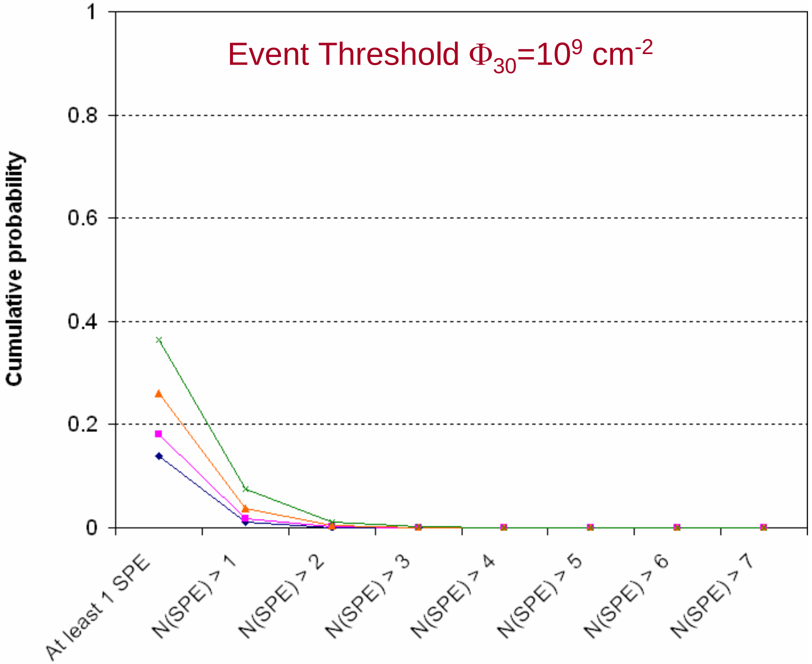
Histogram of Event Size, log(Φ_{30})



Cumulative Probability during a Given Mission Period



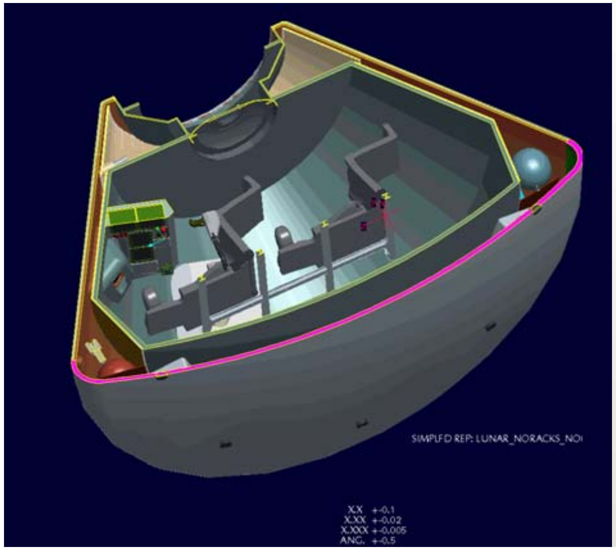


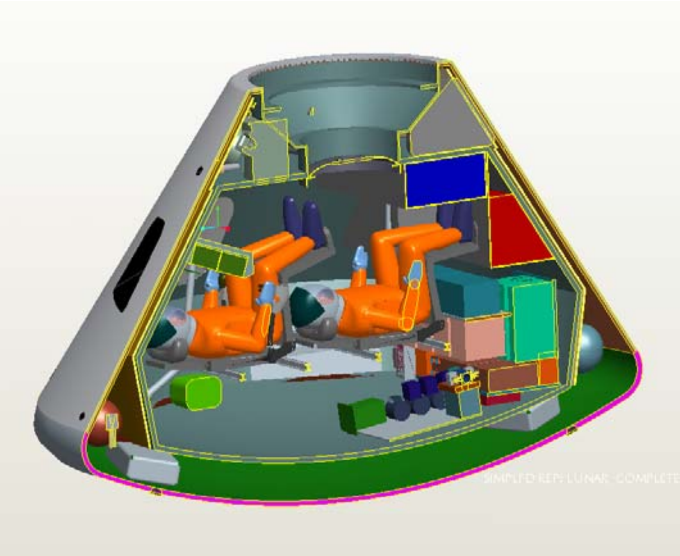


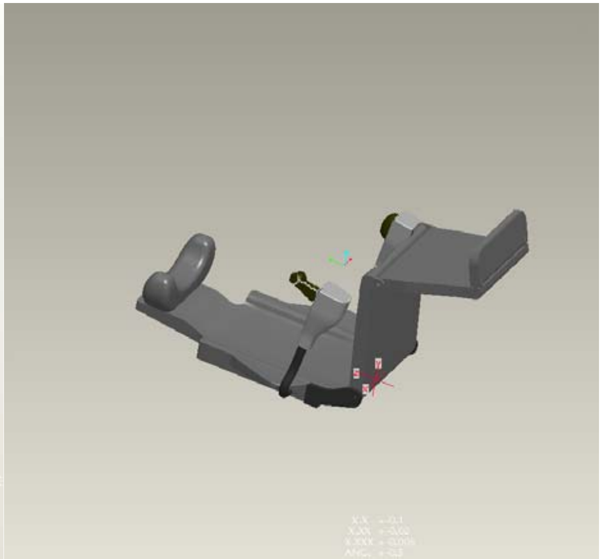
LTV Geometry
and
Directional Point Dose
from 1972 SPE
at 4 DLOCs

Structural Distribution Model Using ProE™

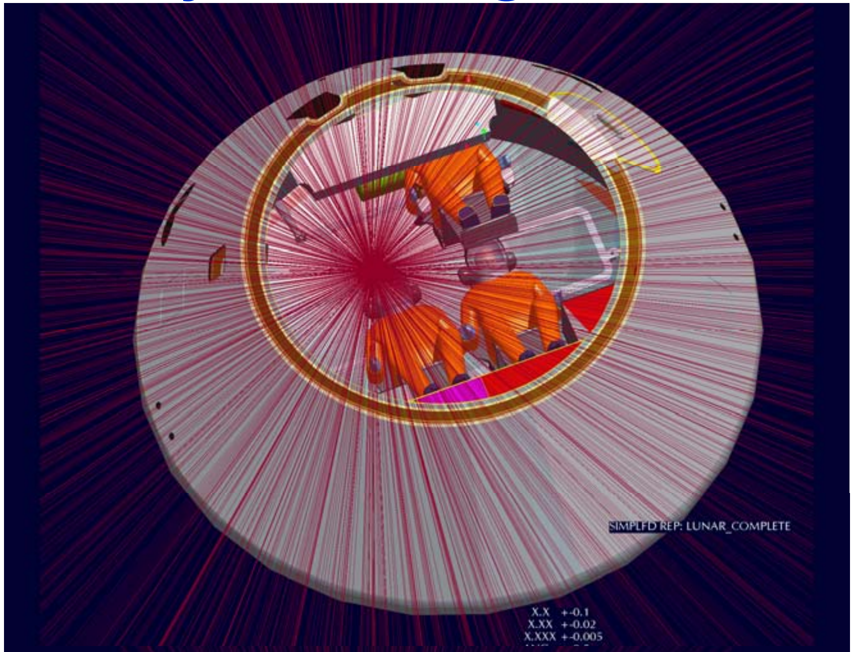
Various Composition Layers for Lunar Transfer Vehicle

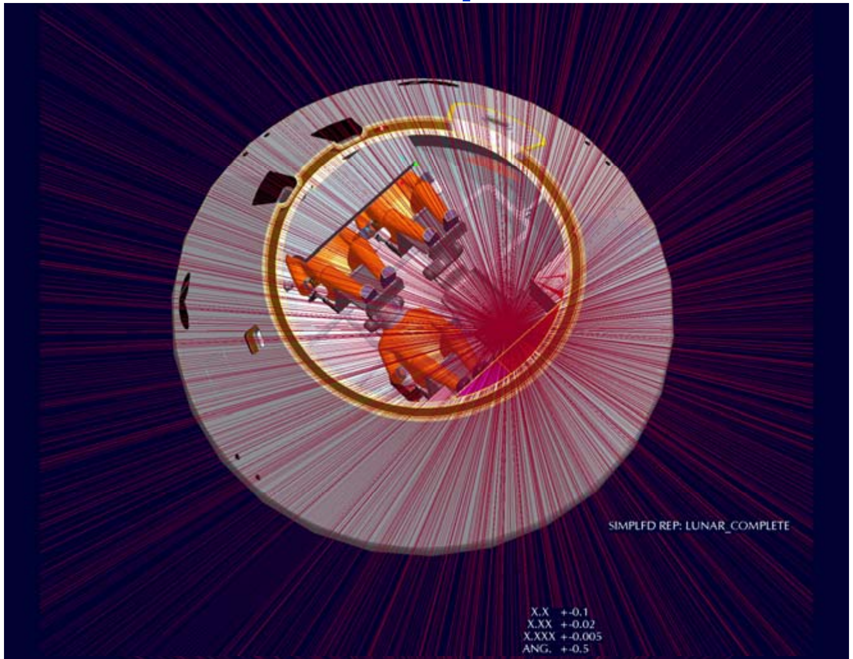


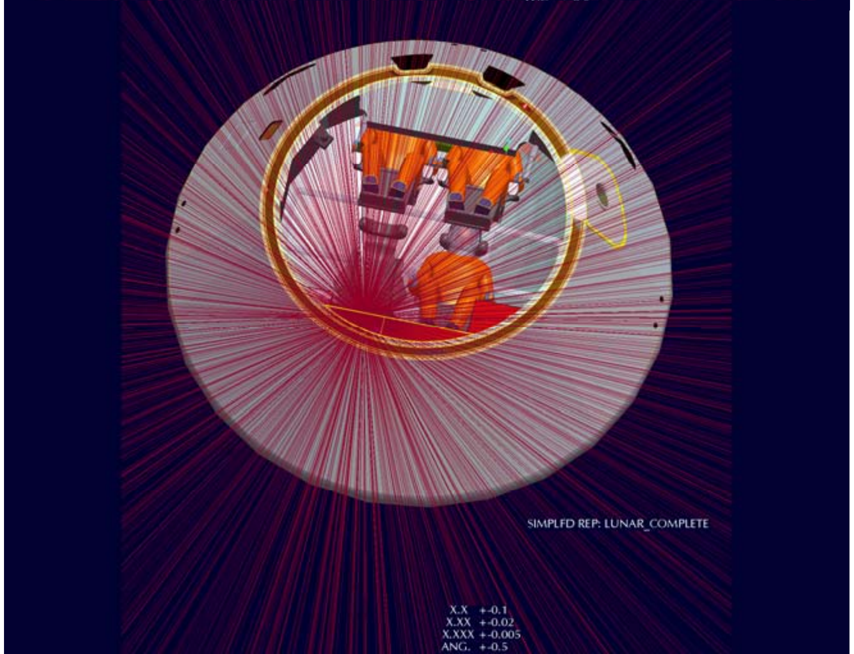


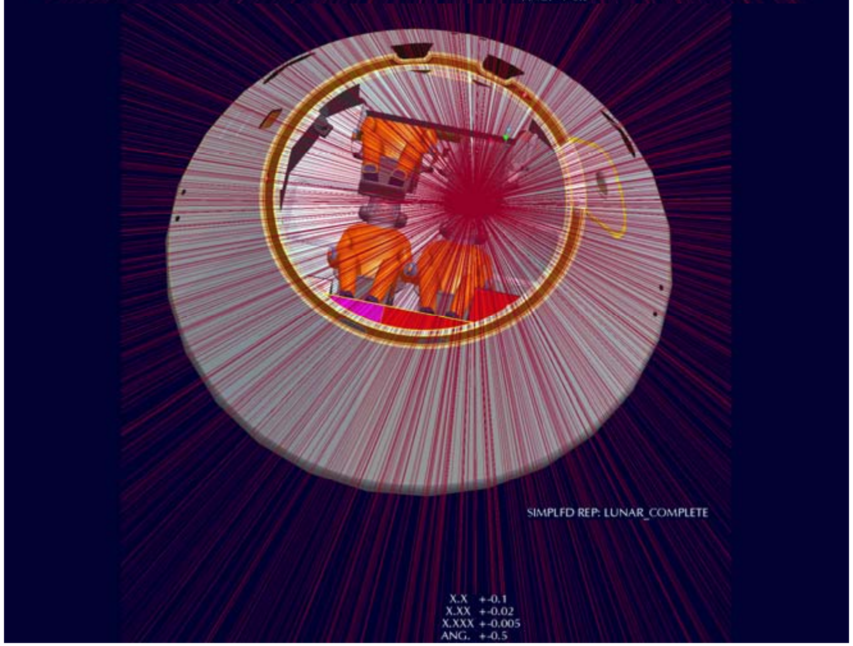


Ray Tracings at 4 DLOCs inside Spacecraft

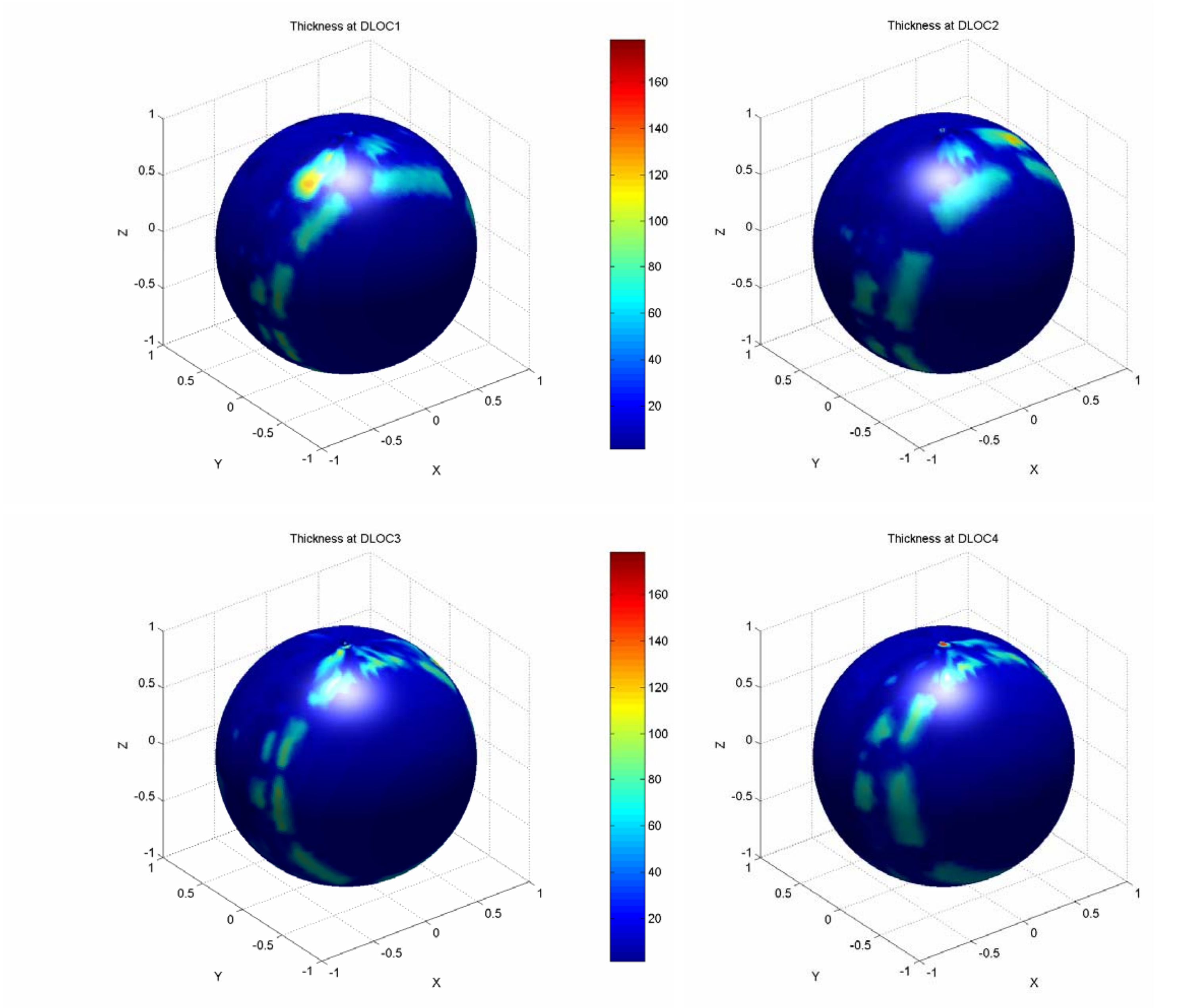


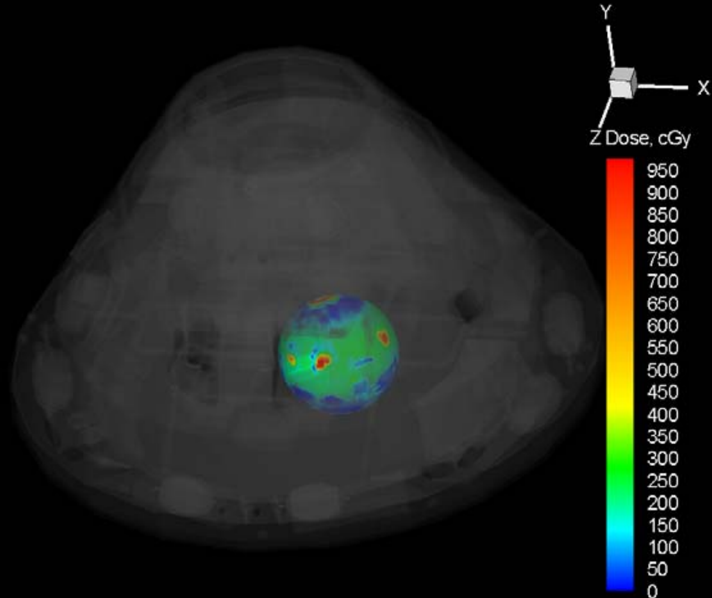




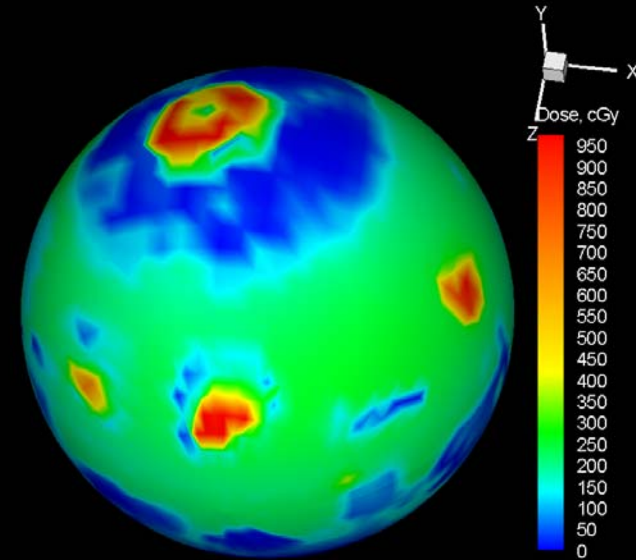


Shielding Distributions at 4 DLOCs inside LTV

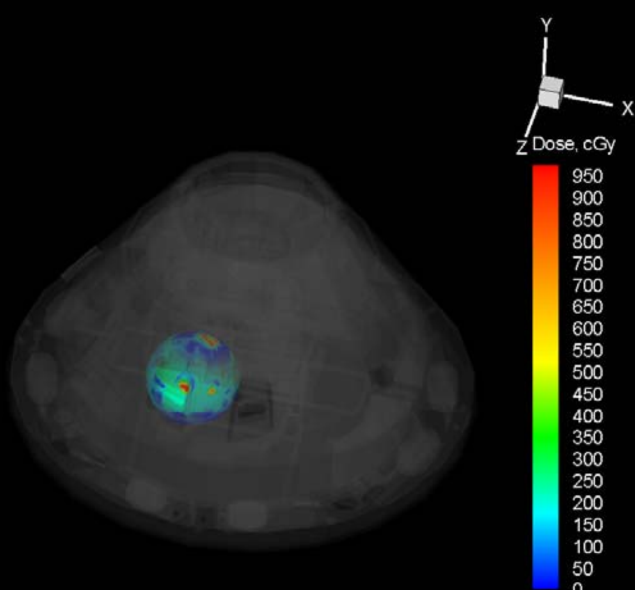




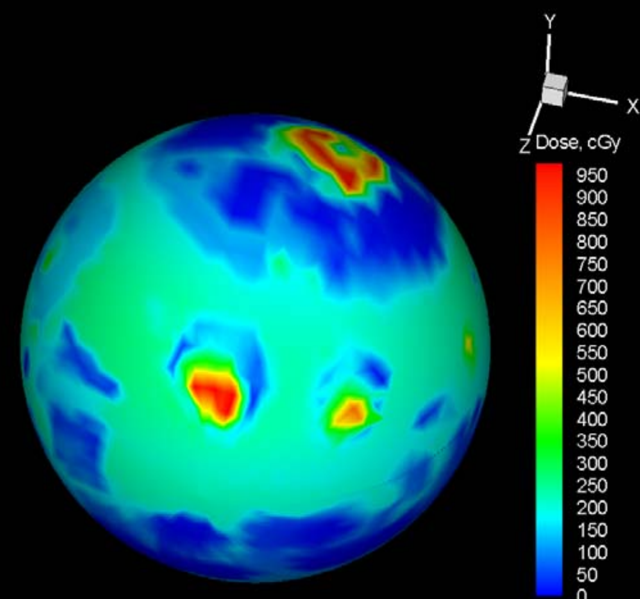
Lunar Transfer Vehicle Concept
DLOC1 Aug 1972 SPE



Lunar Transfer Vehicle Concept
DLOC1 Aug 1972 SPE

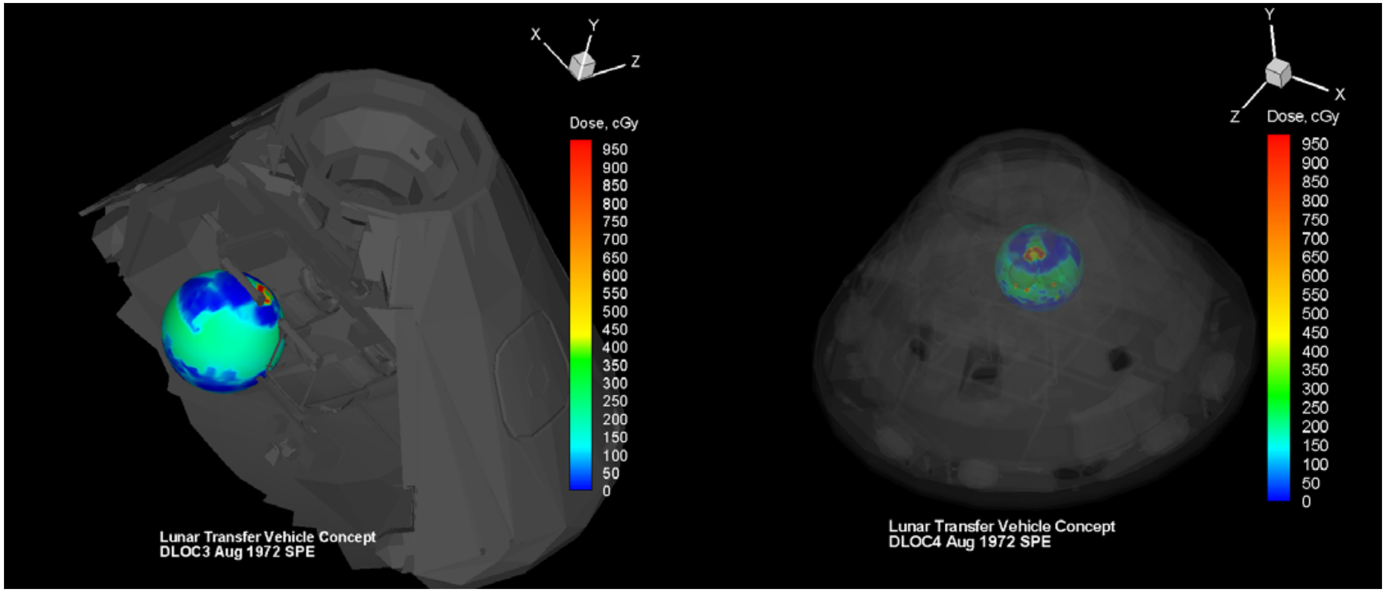


Lunar Transfer Vehicle Concept
DLOC2 Aug 1972 SPE



Lunar Transfer Vehicle Concept
DLOC2 Aug 1972 SPE

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



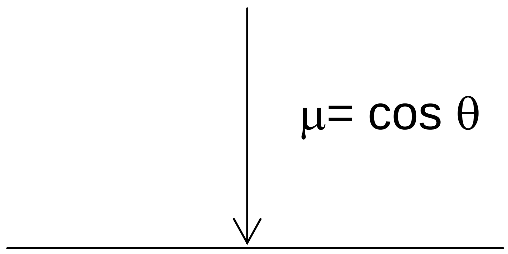
Organ Dose Calculation inside LTV
with Idealization of the Actual Motion of Astronauts

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):

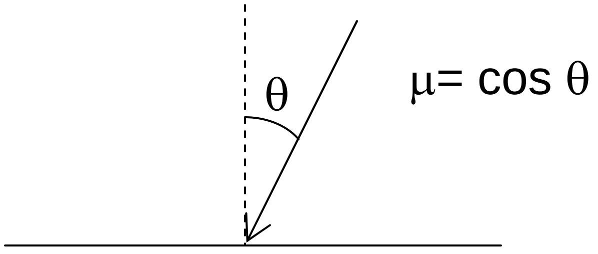
  $p(\mu)$ = constant



<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

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

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

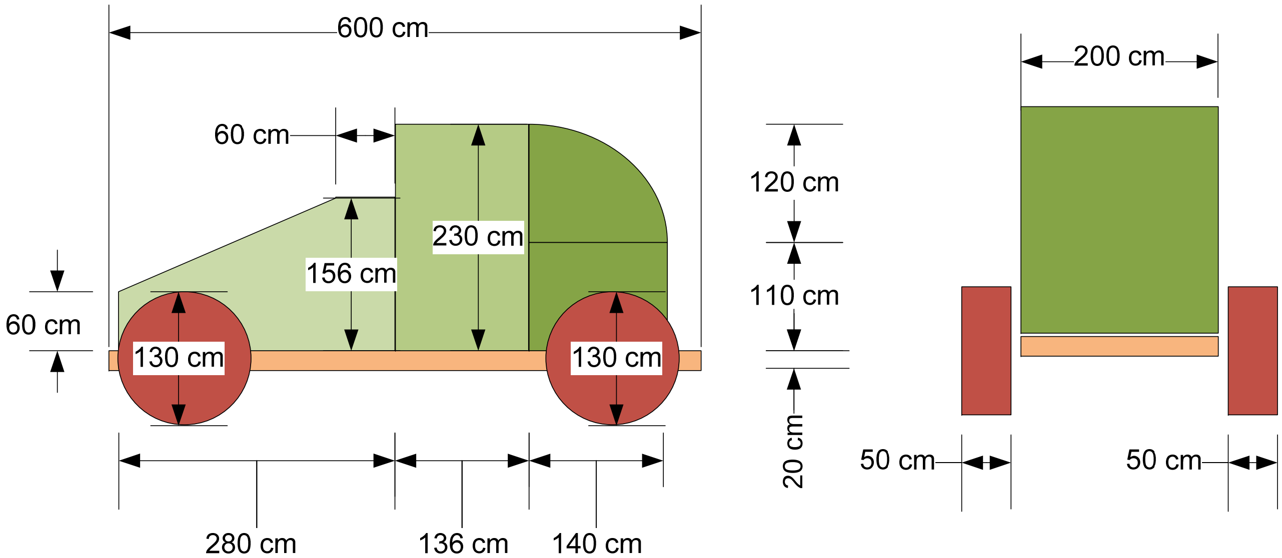
Organ Dose Quantities for Two Orientations

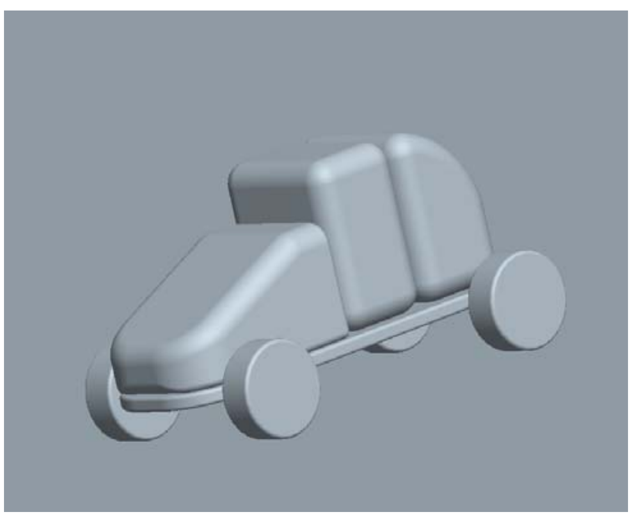
August 1972 SPE

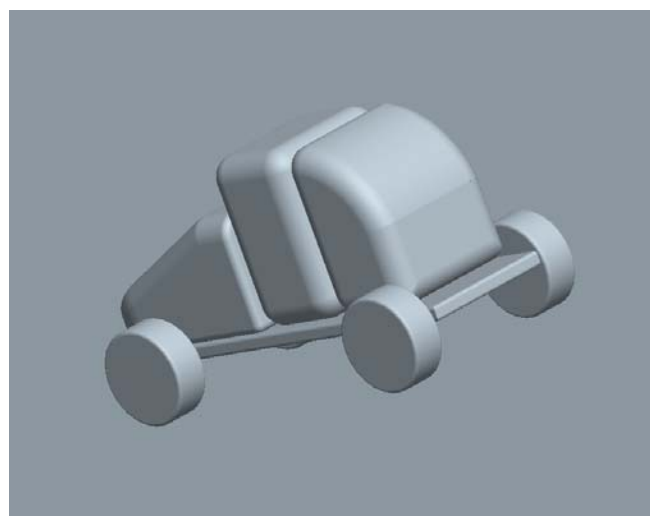
		Random orientation				Aligned orientation			
		DLOC1	**DLOC2**	**DLOC3**	**DLOC4**	**DLOC1**	**DLOC2**	**DLOC3**	**DLOC4**
X-coordinate, cm		43.18	-43.18	40.64	-40.64	43.18	-43.18	40.64	-40.64
Y-coordinate, cm		119.38	119.38	119.38	119.38	119.38	119.38	119.38	119.38
Z-coordinate, cm		52.71	52.71	-79.34	-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 Concepts for EVA

Initial Rover Design

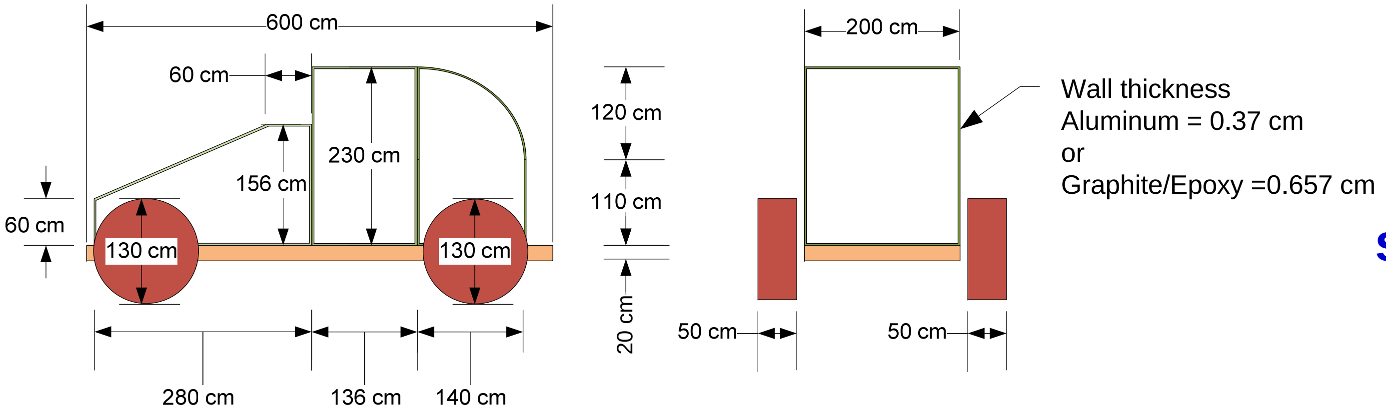




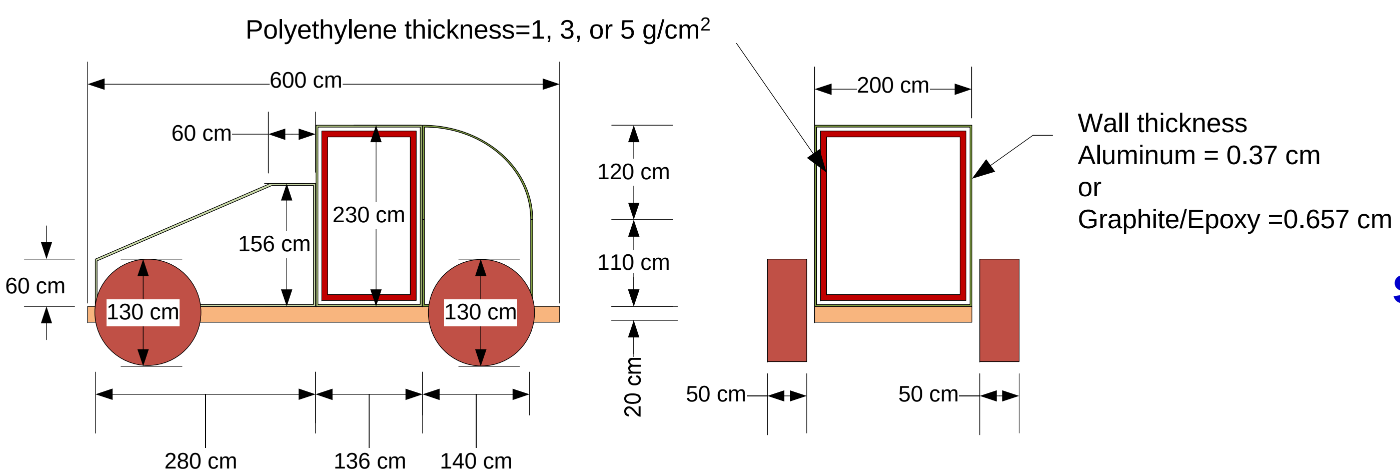


- Three sections of rover: front, center, and back.
- Wall thickness: 1 g/cm^2

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



Rover without polyethylene shield in central section



Rover with polyethylene shield in central section

SPE Shelter Concepts on Rover

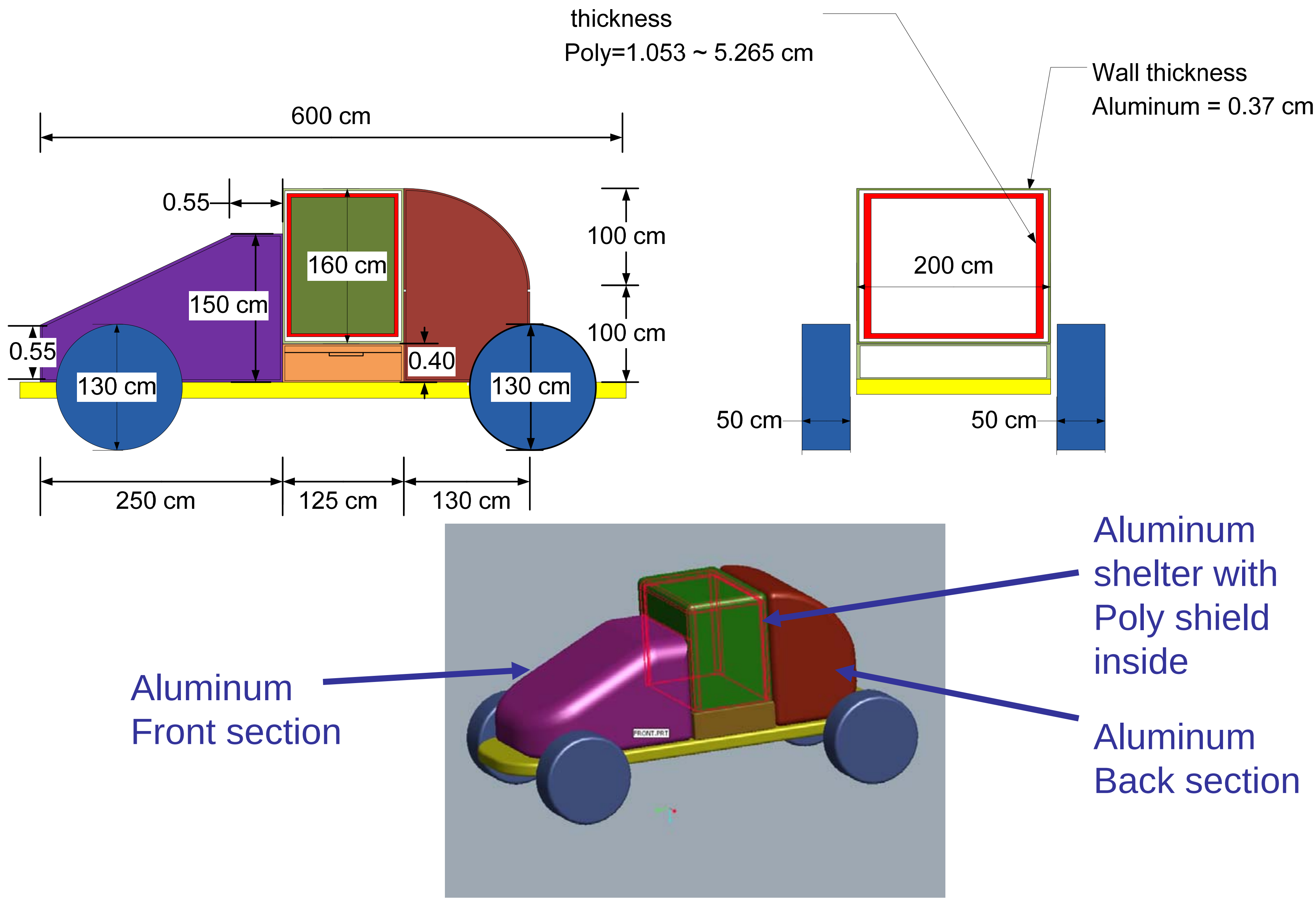
Rover section	Section mass of 1 g/cm^2, kg	Rover mass, kg		Polyethylene SPE shelter thickness, g/cm^2	Polyethylene shelter mass, kg	Total mass, kg
Front	201	554		1	166	720
Center	188			3	490	1044
Back	165			5	800	1354

EVA Exposure (in cSv) Analysis on Lunar Surface from August 1972 SPE Based on the Initial Rover Design

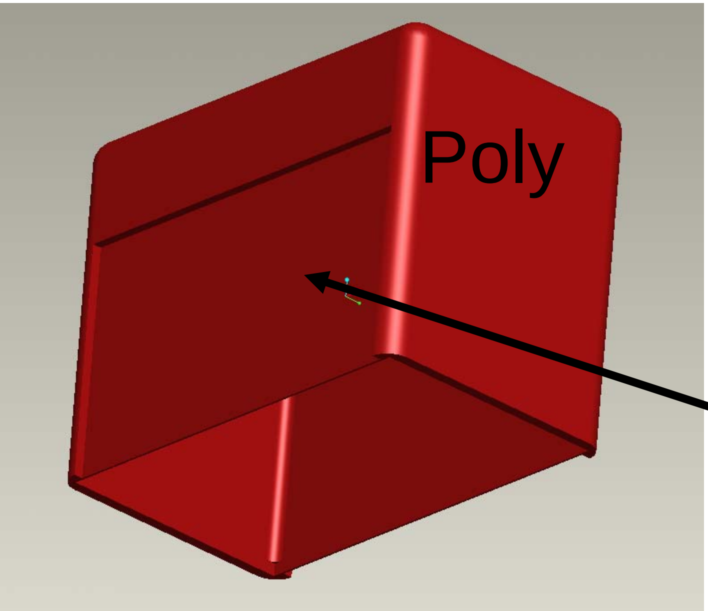
Organ dose, cSv	Polyethylene thickness of SPE shelter in the rover							
	0 g/cm^2		1 g/cm^2		3 g/cm^2		5 g/cm^2	
	Al Rover	Graphite/ Epoxy Rover	Al Rover	Graphite/ Epoxy Rover	Al Rover	Graphite/ Epoxy Rover	Al Rover	Graphite/ Epoxy Rover
Skin			358.05	320.48	116.20	107.92	49.99	47.09
Eye			277.52	252.14	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	89.02	80.20	51.94	48.27	23.10	21.85	11.88	11.36
Rover mass	554 kg		720 kg		1044 kg		1354 kg	

Optimization of Rover Design

New Rover Design

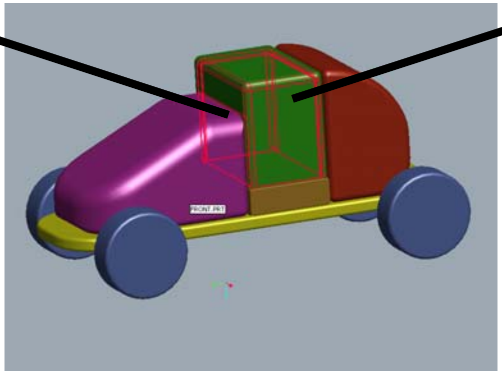


Polyethylene Weight Optimization



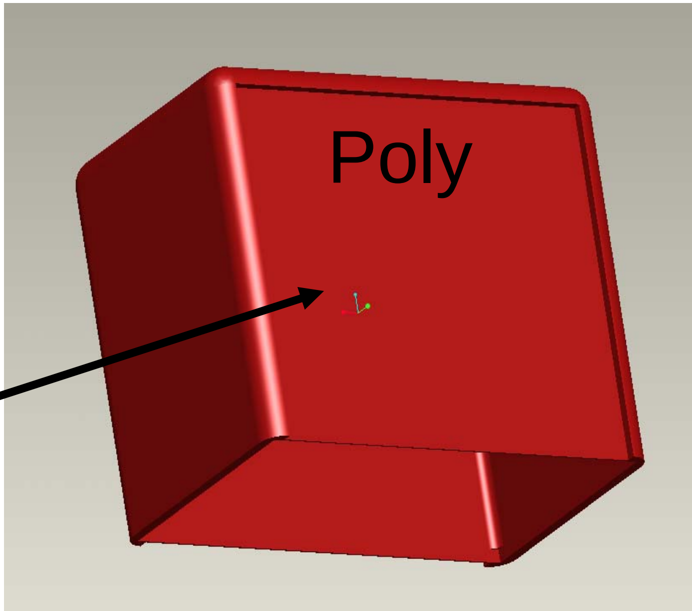
Poly thickness is reduced in the front side of the poly shelter where it is protected by the front section of the rover.

Reduction is from 5.265 to 1.053 cm



Poly in shelter section is made 155 cm tall

Without bottom layer

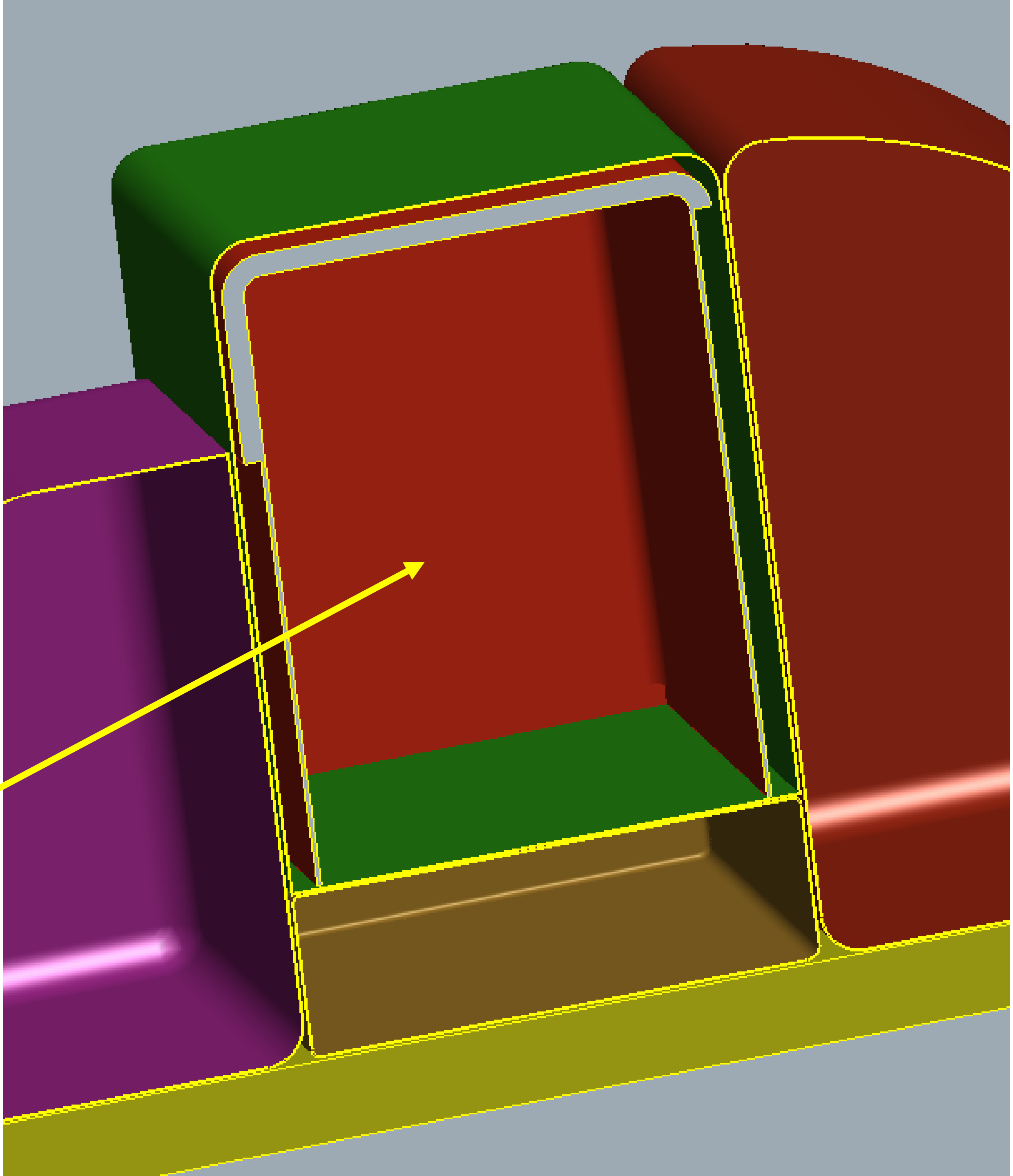


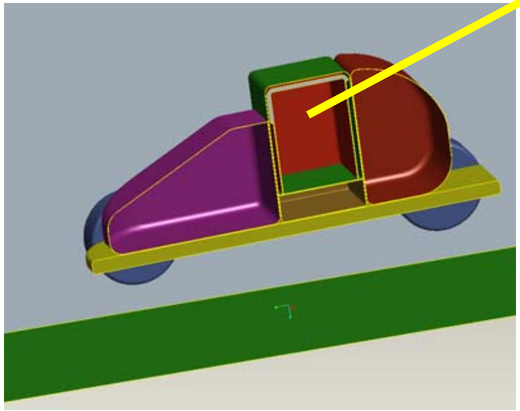
Poly thickness is reduced in the back side of the poly shelter where it is protected by the back section of the rover

Reduction is from 5.265 to 1.053 cm

- 50% poly weight reduction while maintaining almost the same shielding protection.
  - Poly weight was reduced from 799 kg to 378Kg.

Cross Section of Vehicle showing the poly shield thickness optimization inside shelter





Mass of Rover of 1 g/cm^2-thick Pressurized Vehicle with Various SPE Shelter Concept Based on the New Rover Design

Rover section	Section mass, kg	Rover mass, kg		Polyethylene SPE shelter thickness, g/cm^2	SPE shelter mass, kg	Total mass, kg
Front	180	554		1	166	**721**
Center bottom	73			3	490	**1044**
Center top	148			5	557	**1112**
Back	154			Optimized	378	**933**

EVA Exposure (in cSv) Analysis on Lunar Surface from August 1972 SPE Based on the New Rover Design for Optimization

- Aluminum Rover -

Organ dose, cSv	Polyethylene thickness of SPE shelter in the rover				
	No shelter	1 g/cm^2	3 g/cm^2	5 g/cm^2	Optimized Shelter (0-5 g/cm^2)
Skin	929.49	331.10	104.03	43.84	66.83
Eye	549.56	258.71	90.33	39.75	58.88
Avg. BFO	49.13	32.96	16.30	8.83	11.61
Stomach	15.89	11.57	6.50	3.90	4.87
Colon	38.39	26.48	13.61	7.58	9.83
Liver	26.54	18.40	9.59	5.44	6.99
Lung	30.79	21.51	11.30	6.41	8.23
Esophagus	29.26	20.46	10.76	6.12	7.85
Bladder	17.55	12.44	6.75	3.96	5.01
Thyroid	52.61	35.55	17.72	9.63	12.65
Chest	407.73	207.59	75.88	34.04	49.80
Gonads	157.98	90.03	36.54	17.37	24.55
Front brain	97.68	63.06	29.45	15.26	20.56
Mid brain	41.69	29.13	15.23	8.56	11.05
Rear brain	94.58	61.31	28.78	14.96	20.12
Point dose	2310.87	739.66	222.85	90.97	141.55
Whole body effective dose	86.63	49.12	21.09	10.61	14.54
Rover mass	554 kg	721 kg	1044 kg	1112 kg	933 kg

EVA Exposure (in cSv) Analysis on Lunar Surface from August 1972 SPE Based on the New Rover Design for Optimization

- Graphite/Epoxy Composite Rover -

Organ dose, cSv	Polyethylene thickness of SPE shelter in the rover				
	No shelter	1 g/cm^2	3 g/cm^2	5 g/cm^2	Optimized Shelter (0-5 g/cm^2)
Skin	723.45	296.07	96.54	41.26	59.45
Eye	477.47	234.72	84.21	37.52	52.94
Avg. BFO	46.06	31.11	15.54	8.49	10.9
Stomach	15.15	11.09	6.29	3.81	4.67
Colon	36.17	25.11	13.03	7.31	9.27
Liver	25.04	17.47	9.2	5.27	6.62
Lung	29.09	20.44	10.84	6.2	7.8
Esophagus	27.65	19.44	10.33	5.92	7.44
Bladder	16.64	11.87	6.51	3.86	4.78
Thyroid	49.38	33.59	16.91	9.27	11.88
Chest	361.52	189.48	70.87	32.16	44.97
Gonads	143.46	83.19	34.34	16.5	22.45
Front brain	90.93	59.17	27.94	14.6	19.12
Mid brain	39.39	27.67	14.59	8.27	10.44
Rear brain	88.12	57.56	27.32	14.32	18.73
Point dose	1688.81	658	205.96	85.23	124.85
Whole body effective dose	77.88	45.59	19.94	10.14	13.44
Rover mass	554 kg	721 kg	1044 kg	1112 kg	933 kg

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.
- Using detailed distribution of directional risk assessment, better risk mitigation can be made for more efficient protection inside a habitable volume/shelter/spacecraft during future lunar missions.
- A large SPE similar to August 1972 event can be shielded to the whole body effective dose <150 mSv by an optimized SPE shelter on rover during EVA on lunar surface.