Space Radiation Risk Assessment for Future Lunar Missions

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Abstract

For lunar exploration mission design, radiation risk assessments require the understanding of future space radiation environments in support of resource management decisions, operational planning, and a go/no-go decision. The future GCR flux was estimated as a function of interplanetary deceleration potential, which was coupled with the estimated neutron monitor rate from the Climax monitor using a statistical model. A probability distribution function for solar particle event (SPE) occurrence was formed from proton fluence measurements of SPEs occurred during the past 5 solar cycles (19-23). Large proton SPEs identified from impulsive nitrate enhancements in polar ice for which the fluences are greater than 2 $\times$ 109 protons/cm2 for energies greater than 30 MeV, were also combined to extend the probability calculation for high level of proton fluences. The probability with which any given proton fluence level of a SPE will be exceeded during a space mission of defined duration was then calculated. Analytic energy spectra of SPEs at different ranks of the integral fluences were constructed over broad energy ranges extending out to GeV, and representative exposure levels were analyzed at those fluences. For the development of an integrated strategy for radiation protection on lunar

exploration missions, effective doses at various points inside a spacecraft were calculated with detailed geometry models representing proposed transfer vehicle and habitat concepts. Preliminary radiation risk assessments from SPE and GCR were compared for various configuration concepts of radiation shelter in exploratory-class spacecrafts.

Problem

- The continuous galactic cosmic radiation (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.

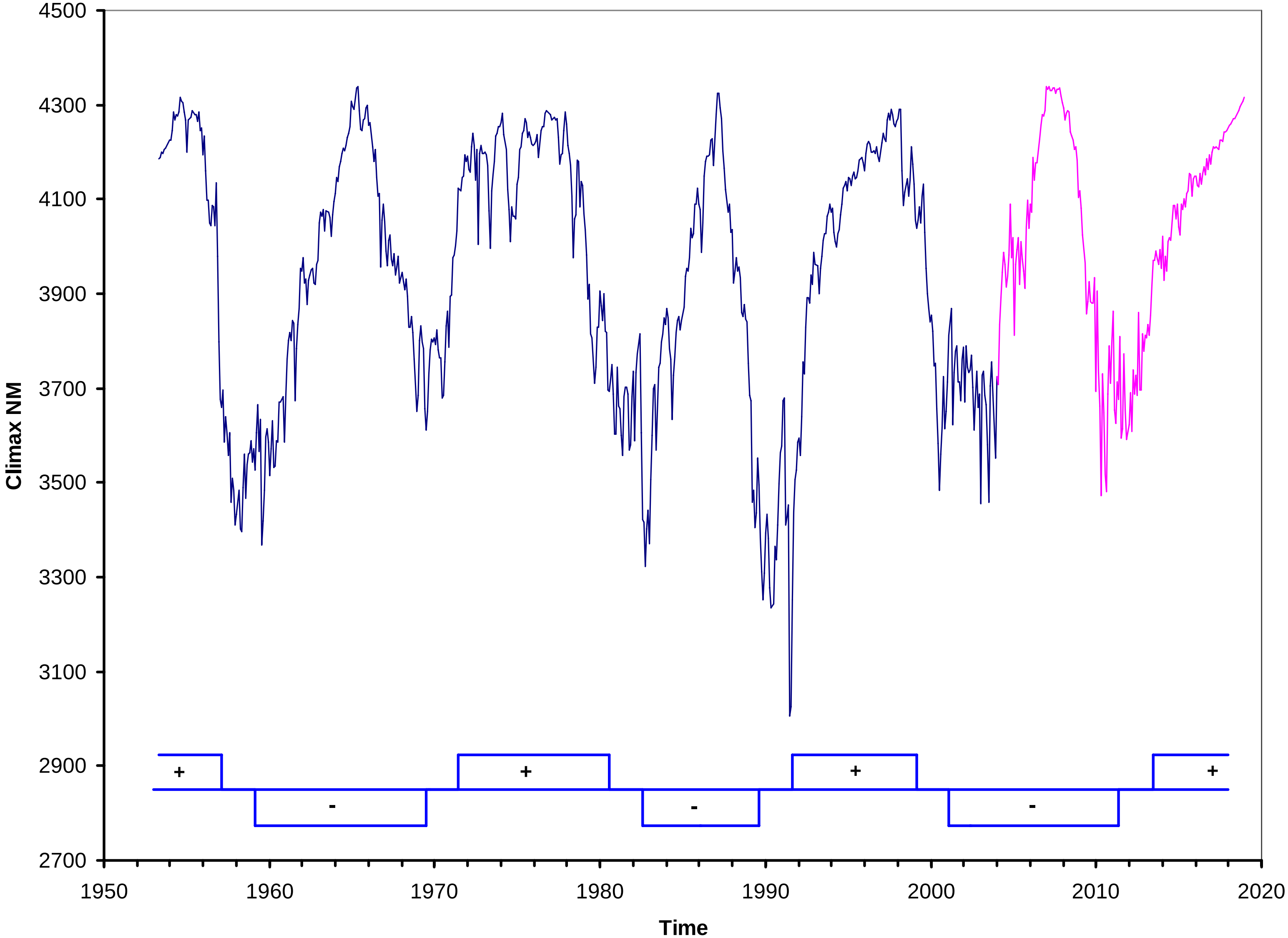
→ A practical approach of expected GCR environment

- 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.

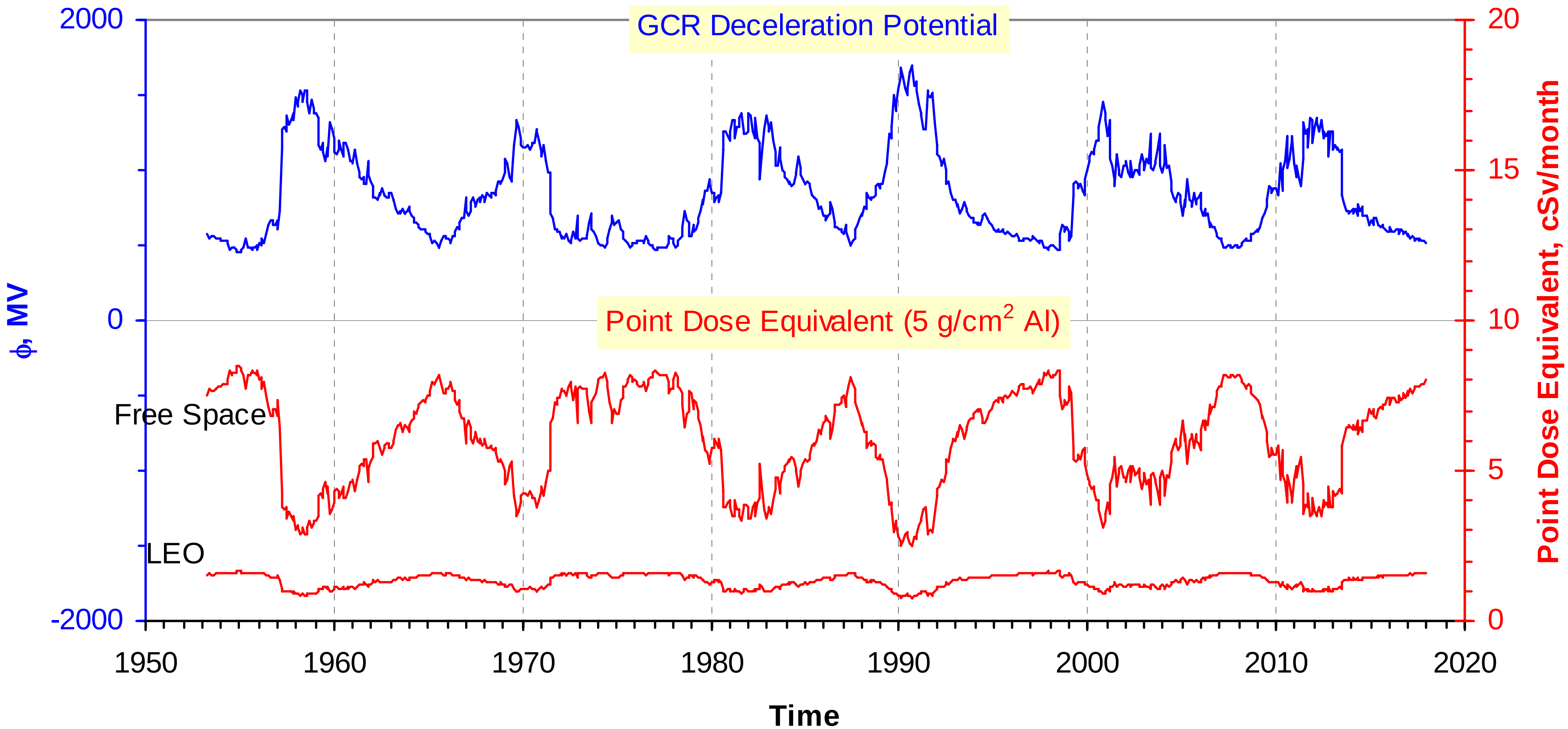
→ A probability of large SPE during the mission periods.

To develop an integrated strategy for radiation protection on lunar exploration missions

Climax Neutron Monitor Rate Measurements and Projection to Solar Cycles 23 and 24



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)

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

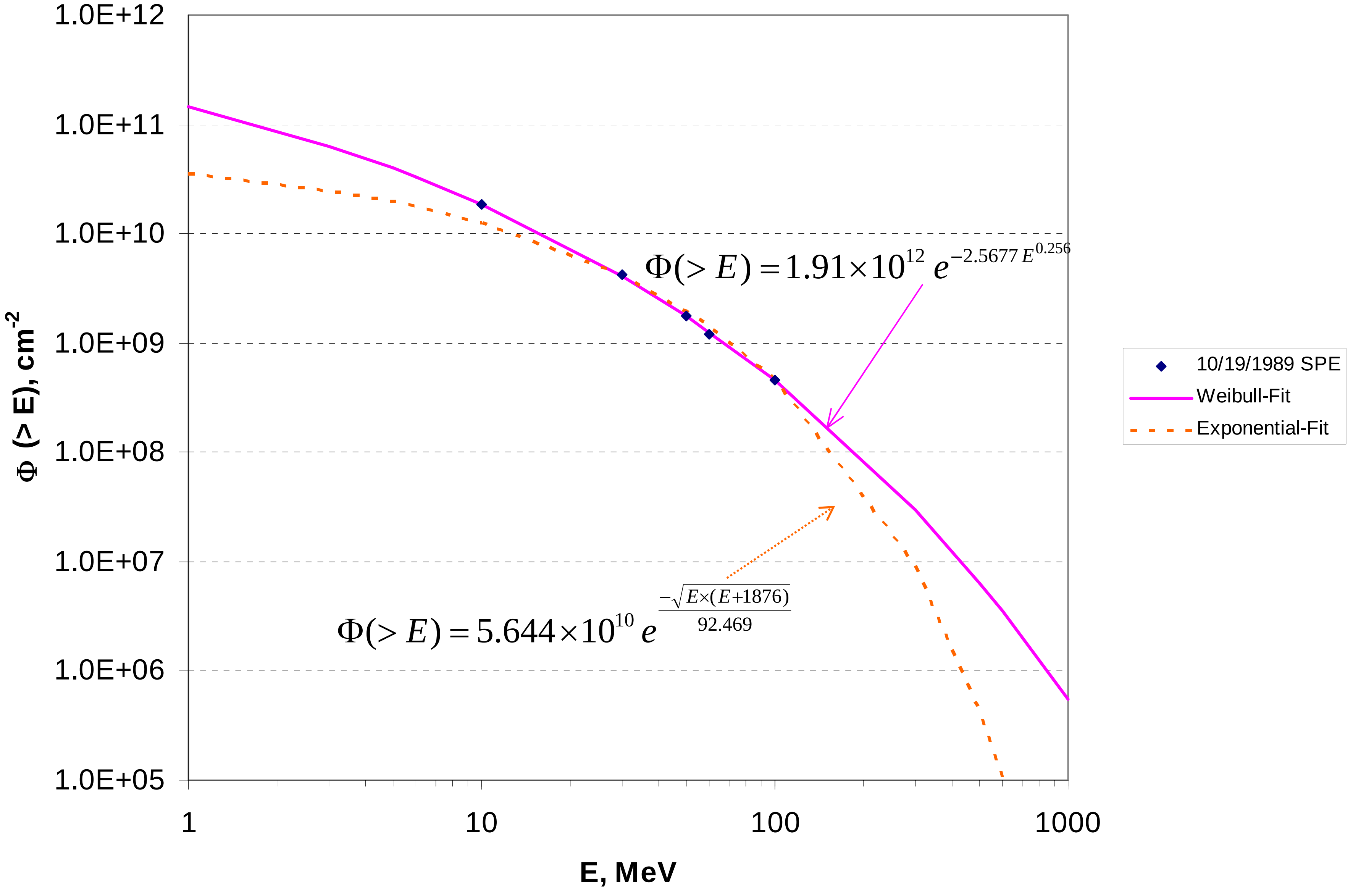
(2) Feynman, Armstrong, Dao-Gibner, and Silverman, J. Spacecraft, **27**, No. 4, pp. 403-410, July-August, 1990.

(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.

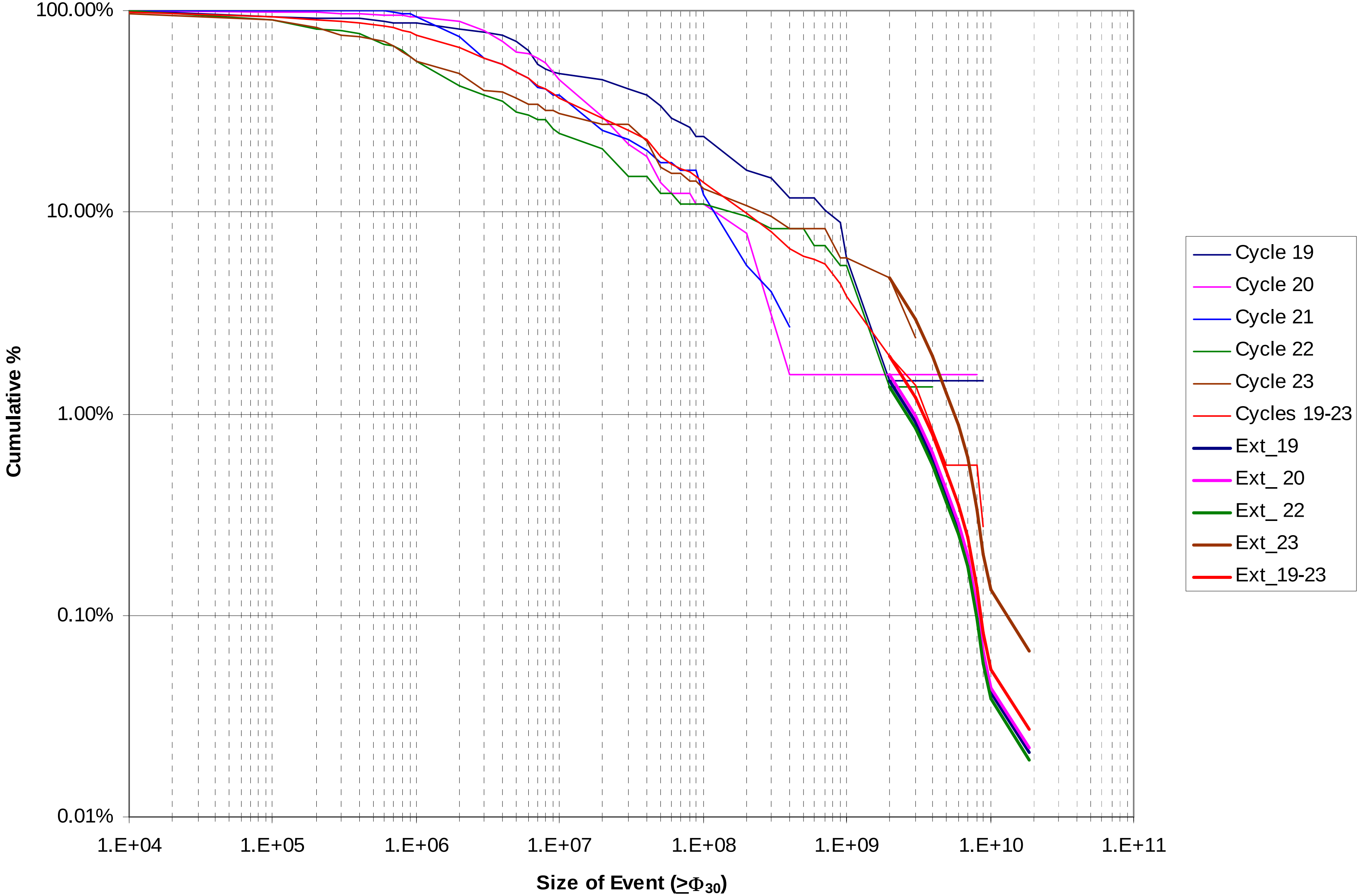
(5) McCracken, K. G., Dreschhoff, G. A. M., Zeller, E. J., Smart, D. F., and Shea, M. A., Solar cosmic ray events for the period 1561-1994, 1. Identification in polar ice, 1561-1950. J. Geophys. Res., **106**, No. A10, 21585-21598, October 1, 2001.

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

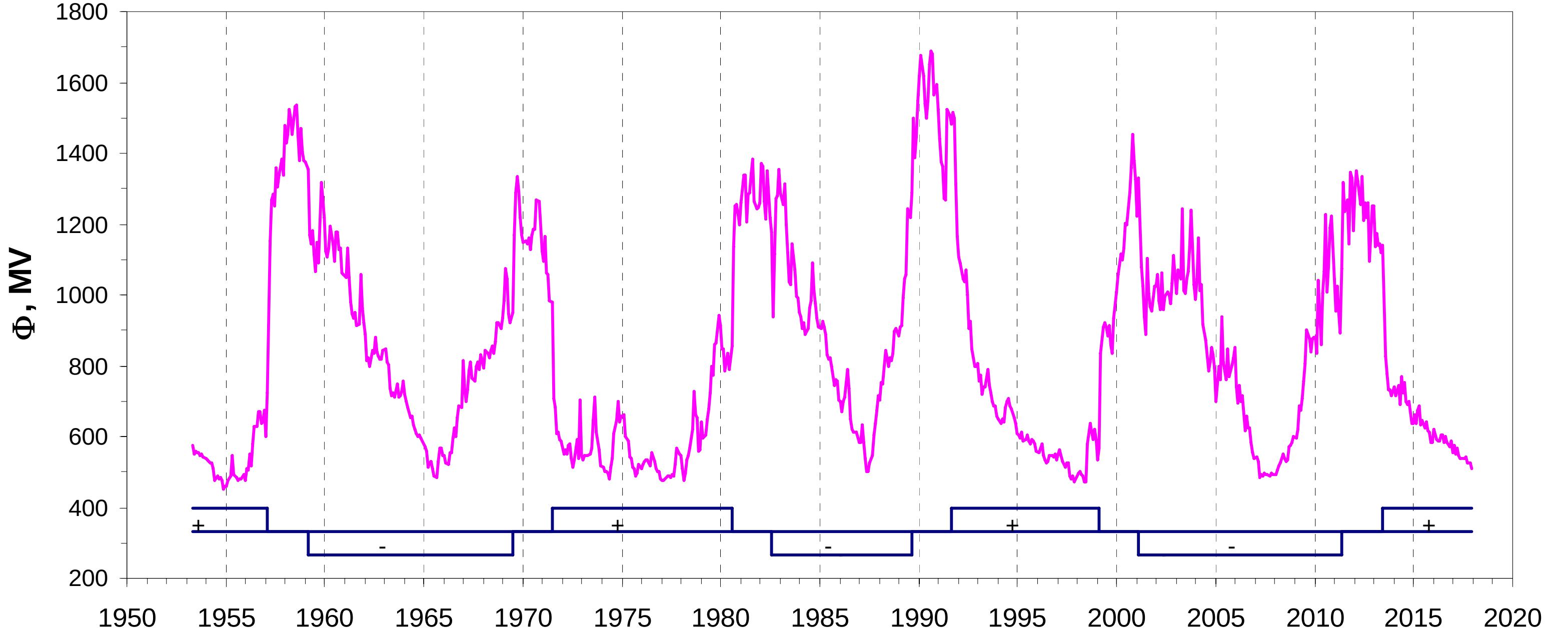


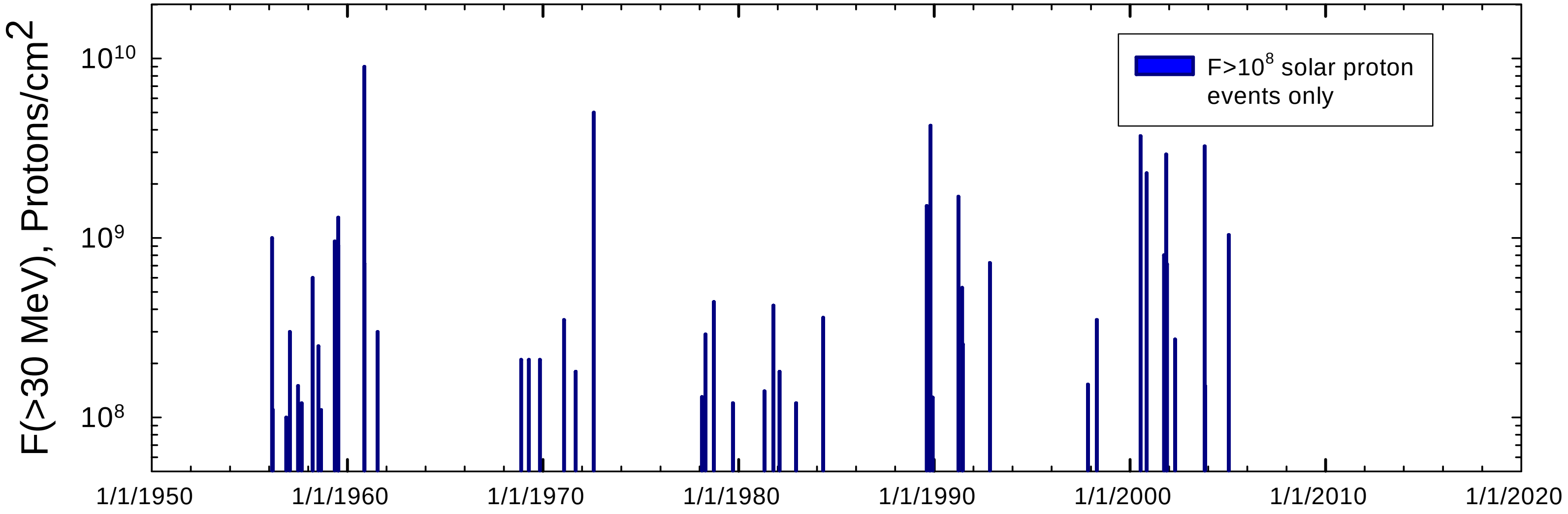
1.0E+12
1.0E+11
1.0E+10
1.0E+09
1.0E+08
1.0E+07
1.0E+06
1.0E+05
1
10
100
1000
E, MeV
Φ (> E), cm^-2
$\Phi(>E) = 1.91\times10^{12}\, e^{-2.5677\,E^{0.256}}$
$\Phi(>E) = 5.644\times10^{10}\, e^{\frac{-\sqrt{E\times(E+1876)}}{92.469}}$
10/19/1989 SPE
Weibull-Fit
Exponential-Fit

Extended Cumulative Distributions of 5 Sample SPE Populations

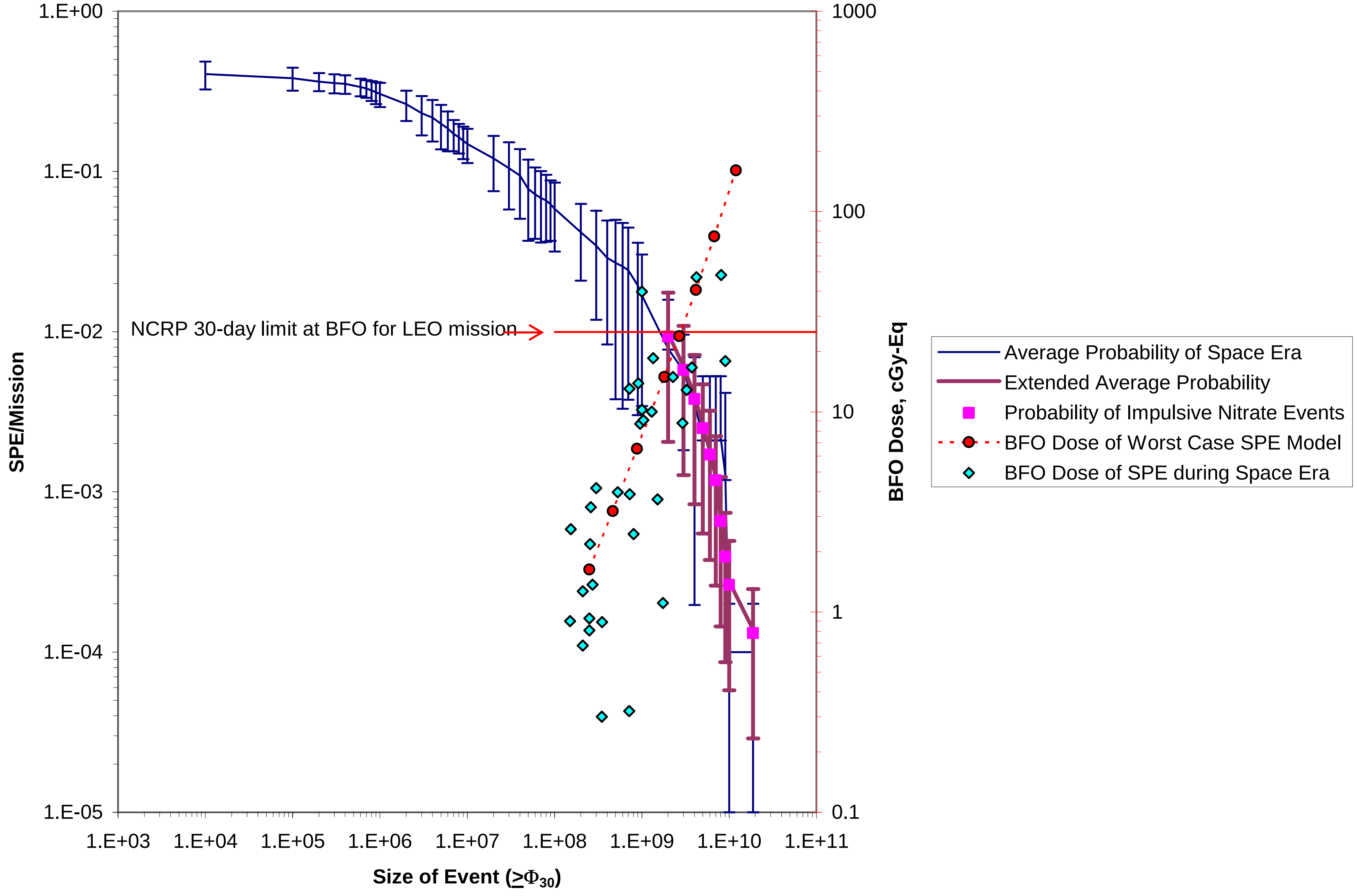


GCR Deceleration Potential

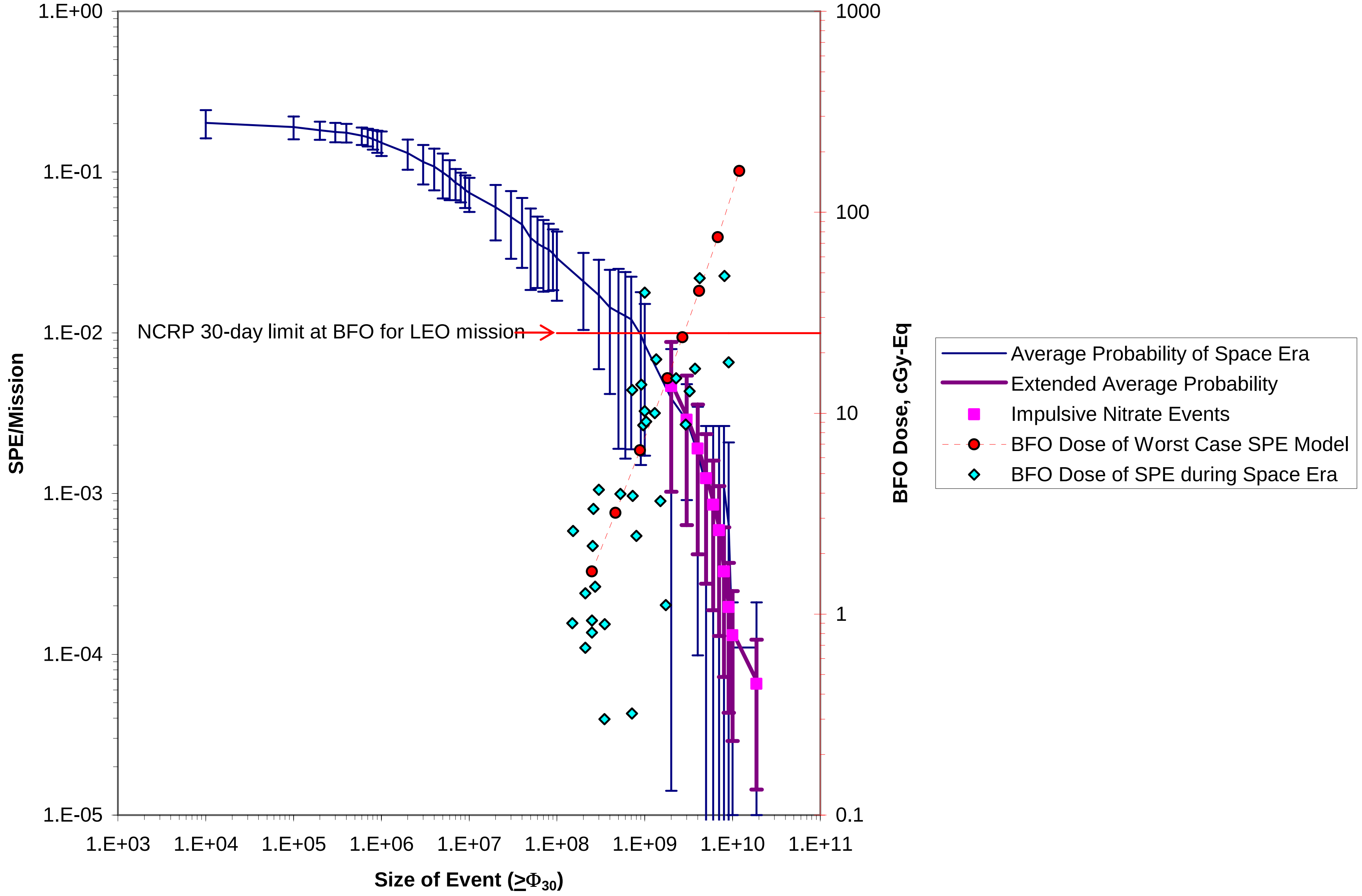




SPE Probability in 2-Week Mission and BFO Exposure Level inside a Typical Equipment Room in Free Space



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

- Calculation using the sample SPE population distributions in space era :

  $P_{\Phi_{30} \geq 2 \times 10^9 \text{ cm}^{-2}} = 0.391\% \pm 0.40\%$

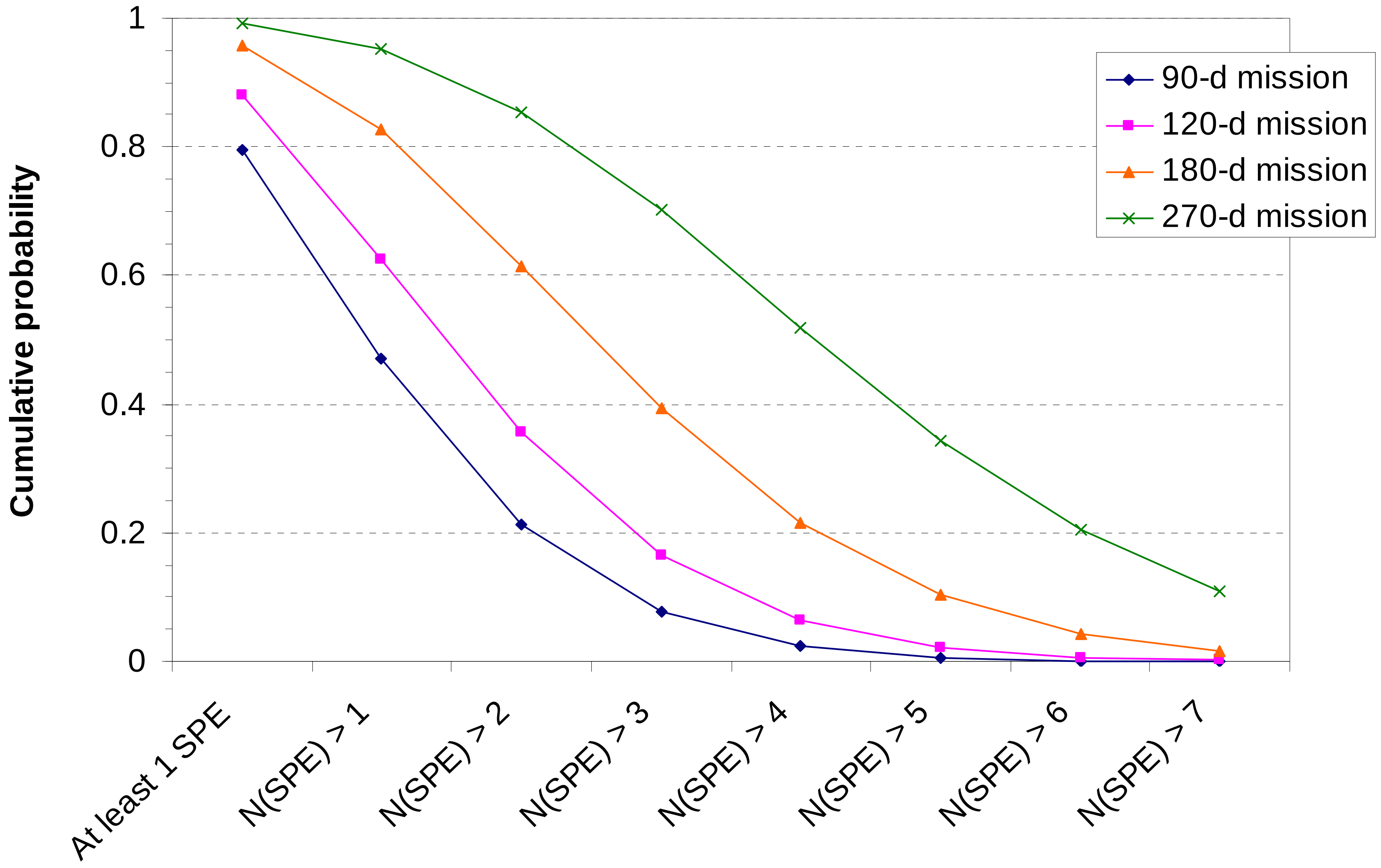
- Calculation using the data in the interval 1561-1950 with the extended SPE population distributions and the correction of seasonal effect:

  $P_{\Phi_{30} \geq 2 \times 10^9 \text{ cm}^{-2}} = 0.489\% \pm 0.387\%$

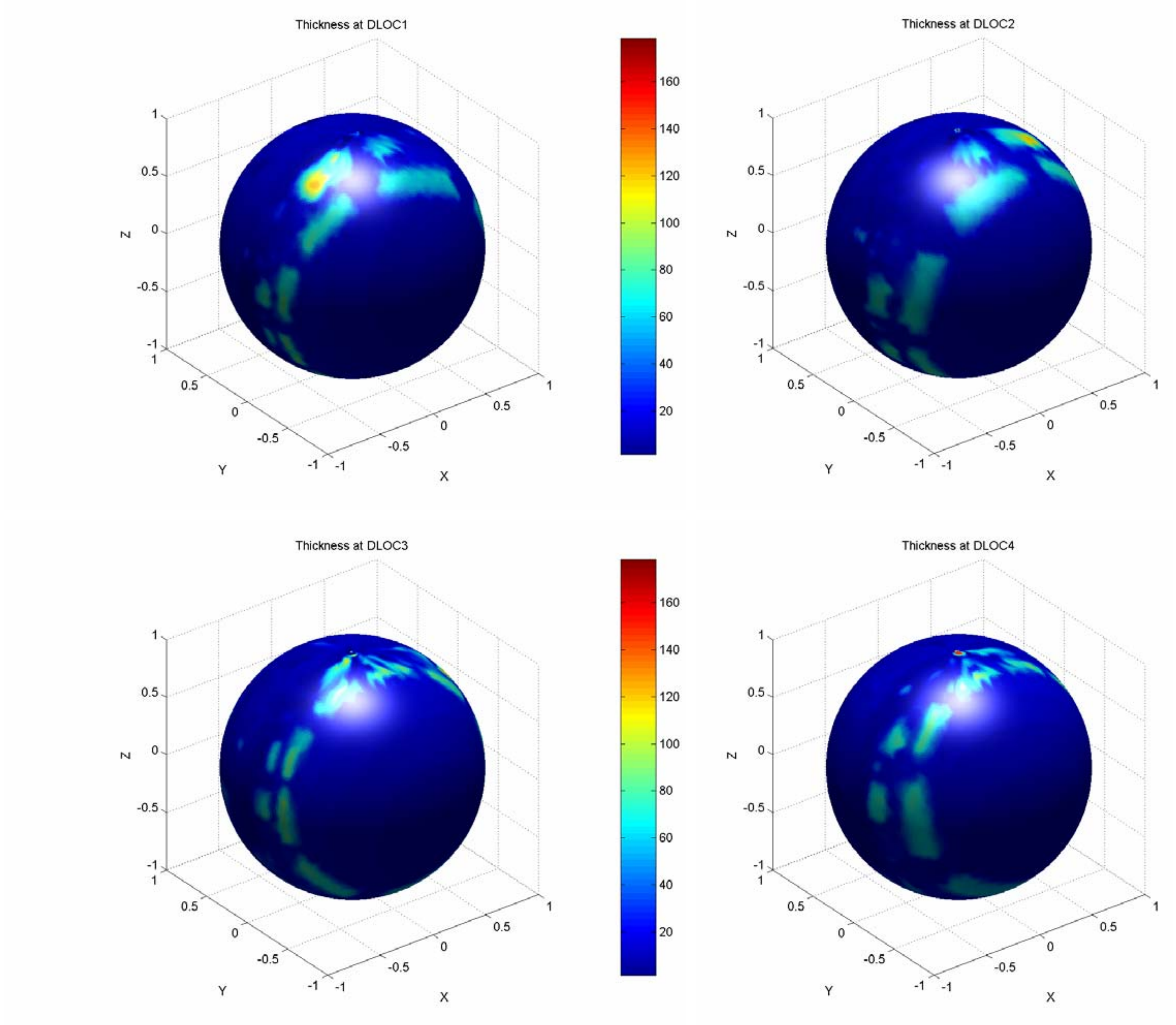
- Observed probability in the interval 1561-1950 with the correction of seasonal effect:

  $P_{\Phi_{30} \geq 2 \times 10^9 \text{ cm}^{-2}} = 0.466\%$

Probability of SPE during a Given Mission Period
Event Threshold $\Phi_{30} > 10^7$ cm^{-2}



Shielding Distributions at 4 Locations of Spacecraft



Organ Dose Quantities for Two Orientations

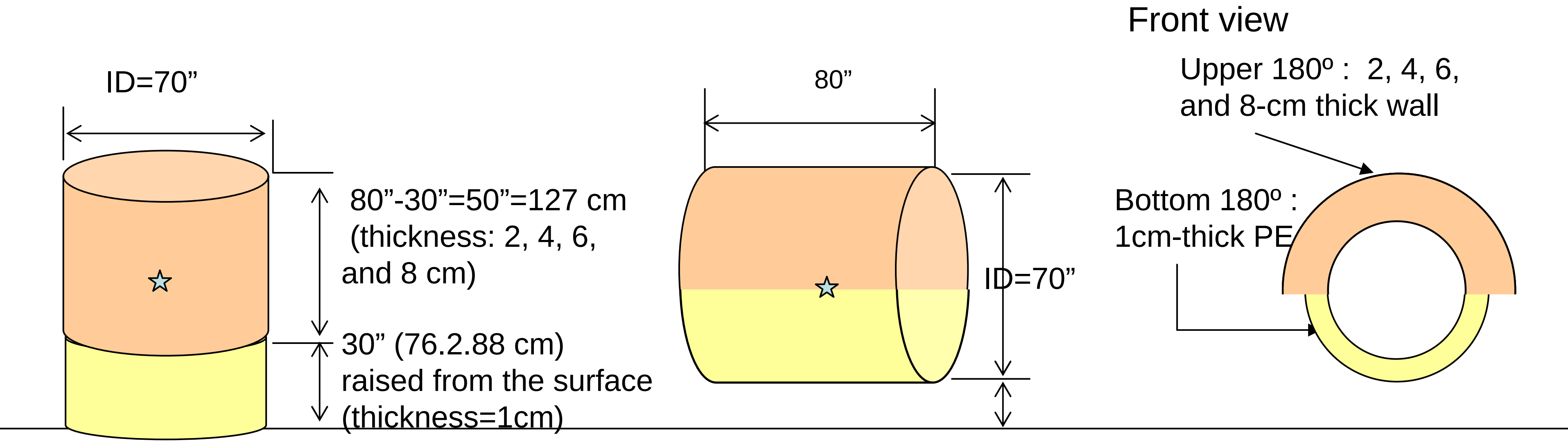
August 1972 SPE

		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

SPE Shelter Concepts on Rover

Vertical Configuration

Horizontal Configuration



EVA Exposure Inside Cylindrical Polyethylene Shelter on Lunar Surface from August 1972 SPE (One Crew Member)

Polyethylene cylinder shelter thickness (ID=70”, H=80”)	E, cSv							
	Horizontal Orientation				Vertical Orientation			
	Mass, kg	Astro	Suit	MARKIII	Mass, kg	Astro	Suit	MARKIII
2 cm (1.84 g/cm^2)	229	51.90	52.03	52.21	242	53.49	53.47	53.19
4 cm (3.68 g/cm^2)	389	24.76	24.88	25.16	429	25.06	25.03	24.83
6 cm (5.52 g/cm^2)	556	13.37	12.96	12.80	624	12.39	12.38	12.25
8 cm (7.35 g/cm^2)	729	8.22	8.36	8.74	825	7.74	7.73	7.64
5 g/cm^2 polyethylene sphere (ID=80”)	684	19.48			684	19.48		

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 SPE by Xapsos et al. (*IEEE Trans. Nuc. Sci.* **47**(6), 2218-2223, 2000) are analyzed with differential energy spectra from Weibull distribution function.

- A probability of SPE at a given fluence level is obtained for various mission periods.

- Detailed distribution of directional risk assessment shows better protection for risk mitigation inside a habitable volume/shelter/spacecraft during future exploration missions.