Active Dosimeter-Based Estimate of Astronaut Acute Radiation Risk for Real-Time Solar Energetic Particle Events

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Motivation

- **Need to Assess Biological Impacts to Astronauts in Real-Time during Solar Energetic Particle (SEP) Events**
  - Free-space SEP events have an increased impact on exploration mission planning and operations
  - Countermeasures may be necessary to avoid exceeding astronaut permissible exposure limits (PELs)
- **The Solution**
  - Crew organ doses are estimated using onboard dosimeter measurements
  - The organ doses provide input to acute biological response models
  - New operational tool developed to assess acute radiation risk during SEP events in order to inform and determine courses of action during spaceflight missions
  - The tool has been developed specifically for NASA's Orion Multi-Purpose Crew Vehicle (MPCV), but could easily be extended to other vehicles
- **The new operational acute radiation risk model will be utilized on NASA's EM-1 and EM-2 missions**

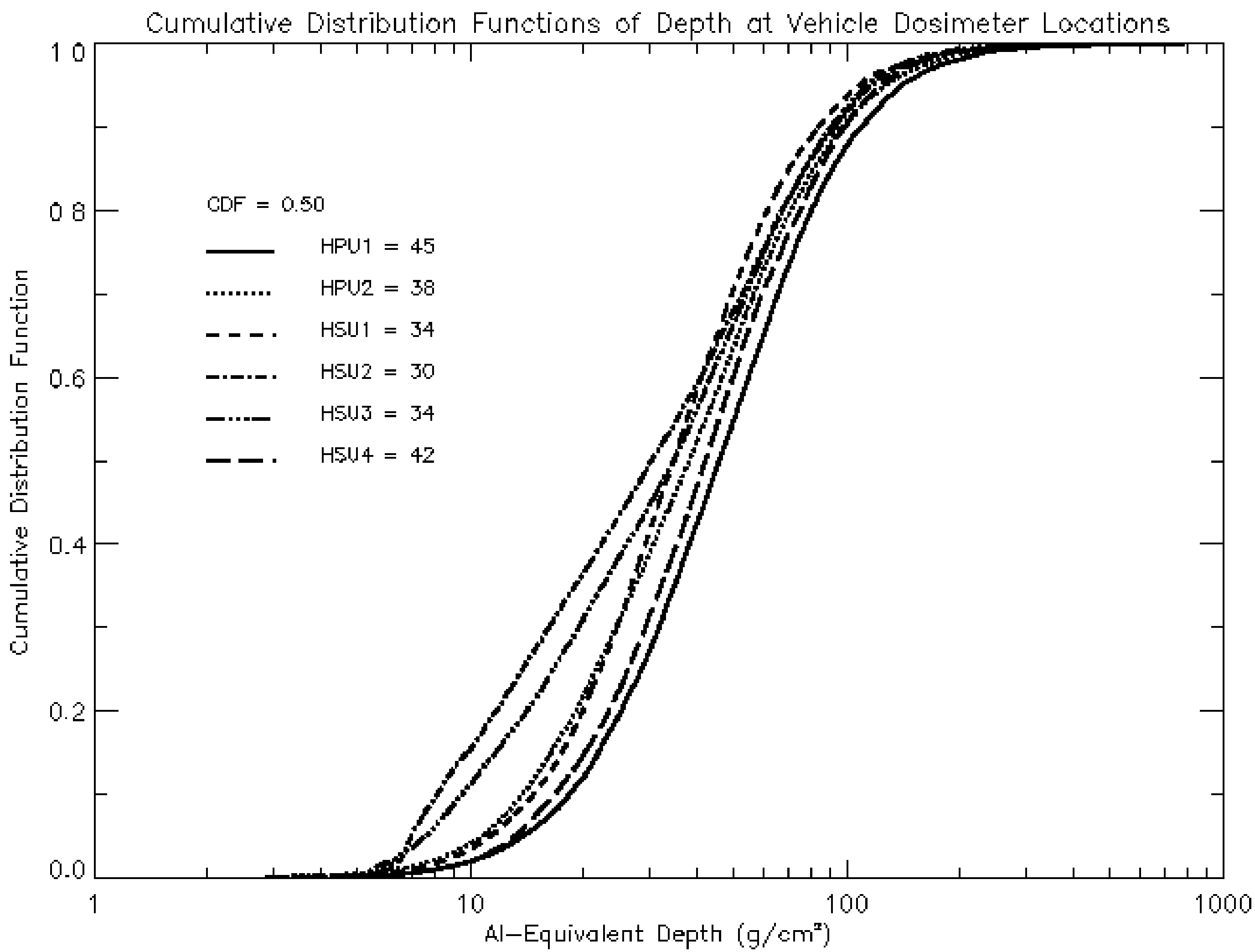
Operational Acute Radiation Risk Tool

- **SEP Organ Dose Model**
  - Infer crew organ doses in vehicle storm-shelter from onboard dosimeter measurements
  - Orion MPCV configured with a distributed dosimeter system called the Hybrid Electronic Radiation Assessor (HERA)
  - EM-1 (uncrewed): 3 x HERA dosimeters
  - EM-2 (crewed): 6 x HERA dosimeters
- **Acute Biological Response Model**
  - Input: BFO dose rates and total BFO dose from the SEP organ dose model
  - Based on codes developed for ARRBOD and HemoDose
  - Includes neurovascular models (nausea and vomiting, fatigue and weakness), hematopoietic models (lymphocyte, granulocyte, leukocyte, and platelets), and a performance degradation algorithm

Outline

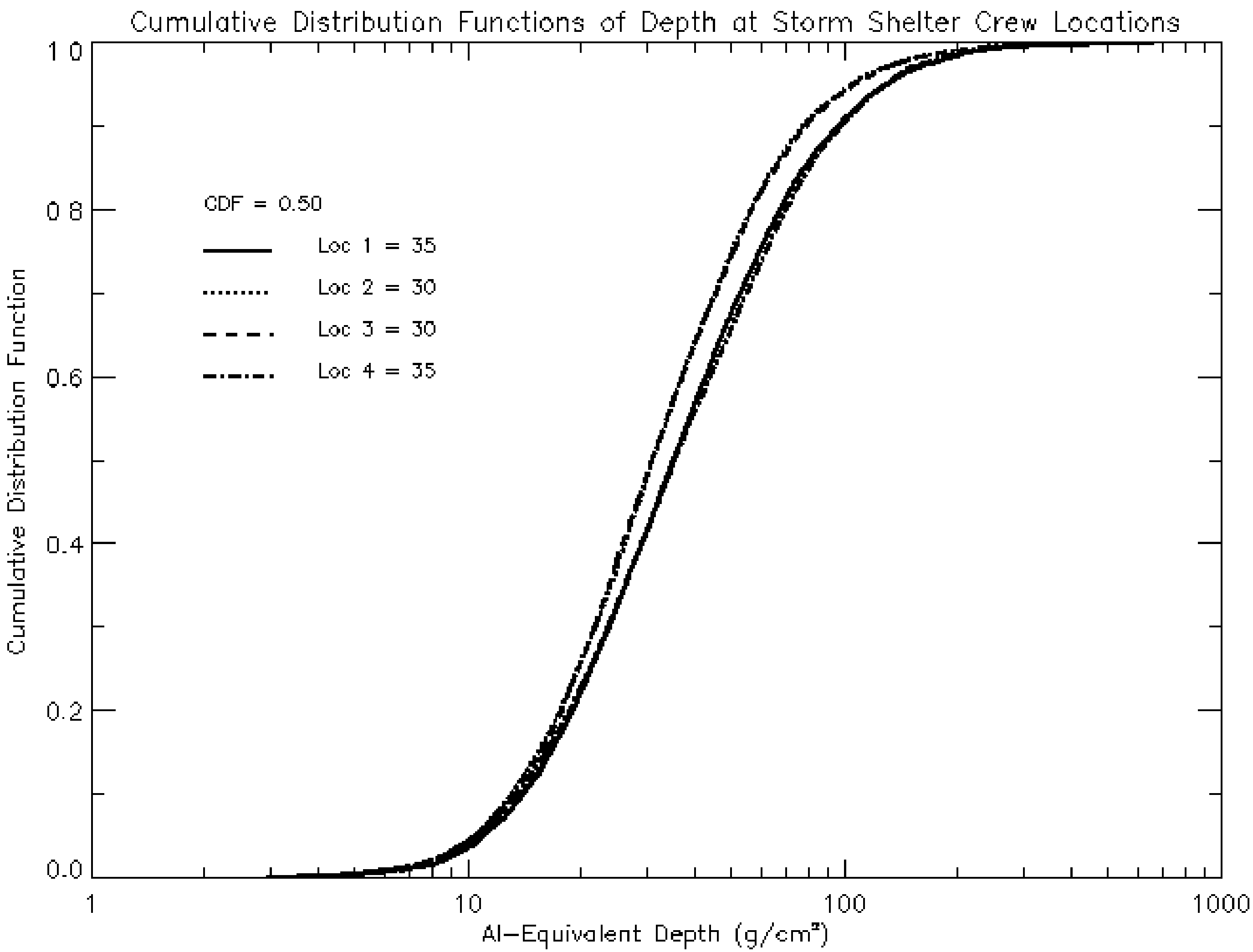
- **Overview of SEP Organ Dose Model**
  - New methodology
- **Analysis of October 1989 SEP Event**
  - NASA is considering using this event in defining requirements of future space exploration habitat design
  - Assess uncertainty of SEP organ dose model
    - EM-2 vehicle dosimeter configuration
    - EM-1 vehicle dosimeter configuration
    - EM-1: combinations of missing dosimeter measurements
  - Map uncertainty in SEP organ dose model into uncertainty in the acute biological responses
- **Summary and Conclusions**

Vehicle Dosimeter Shielding



EM-1: HPU1, HSU1, and HSU2

Storm-Shelter Crew Shielding



SEP Organ Dose Model

1. **Pre-Computed Dose Database for Historical SEP Events**
   - Computed dose in silicon at vehicle dosimeter locations (HZETRN)
   - Computed organ doses at vehicle storm-shelter crew locations (HZETRN)
   - Computed for 65 SEP/GLE events (Tylka fits using double power-law function)
   - **Assumption**: isotropic spatial distribution of SEP protons
2. **Find event in database (index j*) that minimizes the square residual between measured and database averaged dose (in silicon)**
   - Variation in normalized doses with dosimeter location (i.e., variation with depth) is indicative of the spectral shape of the proton energy spectrum
   - Optimal index (j*) is the event in the database that best matches the spectral shape of the (real-time) vehicle radiation environment

Optimal Database Index

$$j^* = \min_j \left\{ \sum_{i=1}^{N_{\text{det}}} \left[\hat{D}_{\text{det}}^{(i)} - \hat{D}_{i,j} \right]^2 \right\}$$

Averaged Measured Dose

$$\hat{D}_{\text{det}}^{(i)} = \frac{D_{\text{det}}^{(i)}}{\sum_{i=1}^{N_{\text{det}}} \tilde{\mathbf{S}}_{\varepsilon,(ii)}^{-1} D_{\text{det}}^{(i)} \Big/ \sum_{i=1}^{N_{\text{det}}} \tilde{\mathbf{S}}_{\varepsilon,(ii)}^{-1}}$$

Averaged Database Dose

$$\hat{D}_{i,j} = \frac{D_{i,j}}{\frac{1}{N_{\text{det}}} \sum_{i=1}^{N_{\text{det}}} D_{i,j}}$$

SEP Organ Dose Model – Cont

3. **Adjust magnitude of doses for the optimal database SEP event (j*) in a way that is consistent with the vehicle dosimeter measurements**
   - Solution of an inverse problem
   - Find linear fit coefficients $\mathbf{x}_s = (\alpha,\beta)^T$

$$\mathbf{x}_s = \mathbf{x}_0 + \left(\tilde{\mathbf{K}}^T \tilde{\mathbf{S}}_\varepsilon^{-1} \tilde{\mathbf{K}}\right)^{-1} \left[\tilde{\mathbf{K}}^T \tilde{\mathbf{S}}_\varepsilon^{-1} \left(\mathbf{y} - \mathbf{F}(\mathbf{x}_0)\right)\right]$$

(Generalized LSQ Solution: Details given elsewhere)

4. **Apply parameters inferred from the vehicle dosimeter measurements (j*,α, β) to the database of organ doses at the storm-shelter crew locations**

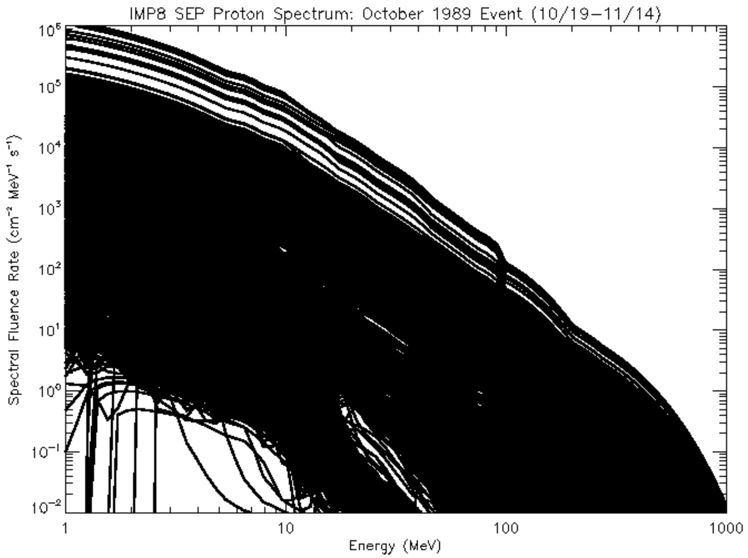
$$H_{\eta,\kappa}^{RT} = \alpha H_{\eta,\kappa,j^*}^{DB} + \beta$$

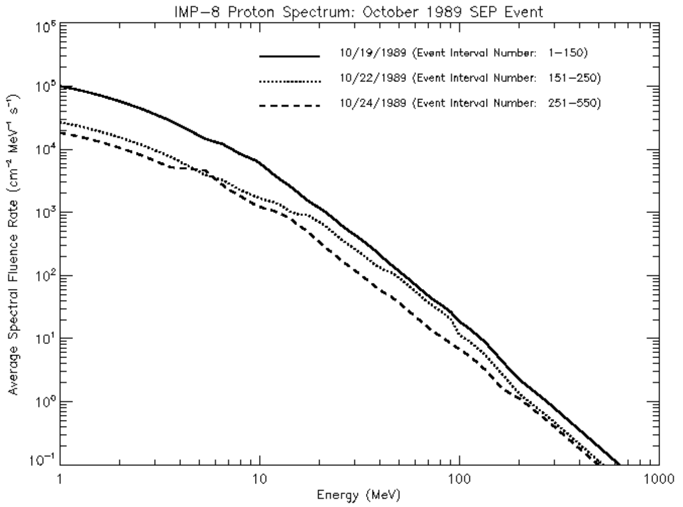
η : Organ Type ($\eta = 1 - 27$)

κ : Crew Location ($\kappa = 1 - 4$)

Analysis of October 1989 SEP Event

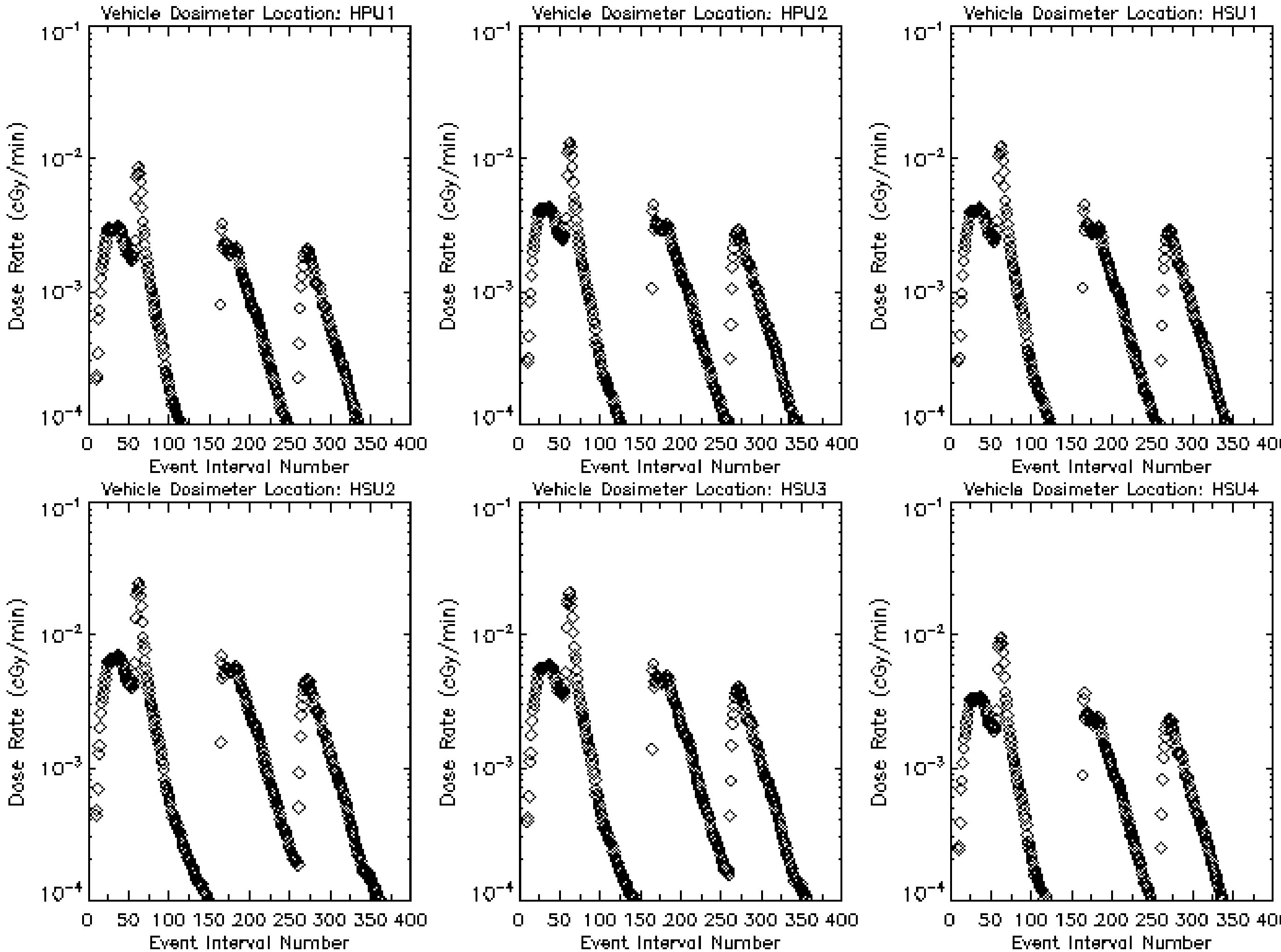
- **October 1989 SEP Event**
  - Start: 08:15 UT on 10/19/89
  - End: 08:15 UT on 10/26/89
  - Consist of three consecutive events which peak on 10/19/89, 10/22/89, and 10/24/89
- **Vehicle Dosimeter Measurements Simulated Using HZETRN**
  - Free-space SEP proton spectra constructed from IMP-8/GME differential flux measurements (~ 1-400 MeV)
  - Absorbed dose in silicon calculated at vehicle dosimeter locations by HZETRN, shielding thicknesses obtained by ray-tracing vehicle CAD model
- **Storm-Shelter Organ Doses Calculated Using HZETRN: Taken as "*True*" Values**
  - Free-space SEP proton spectra same as above
  - Organ doses calculated at storm-shelter crew locations by HZETRN, shielding thicknesses obtained by ray-tracing vehicle CAD model and MAX/FAX human body models
- **Top Right Figure**: free-space SEP spectra, 329 30-minute averaged profiles between event start/end dates
- **Bottom Right Figure**: free-space SEP spectra averaged over the three sub-events





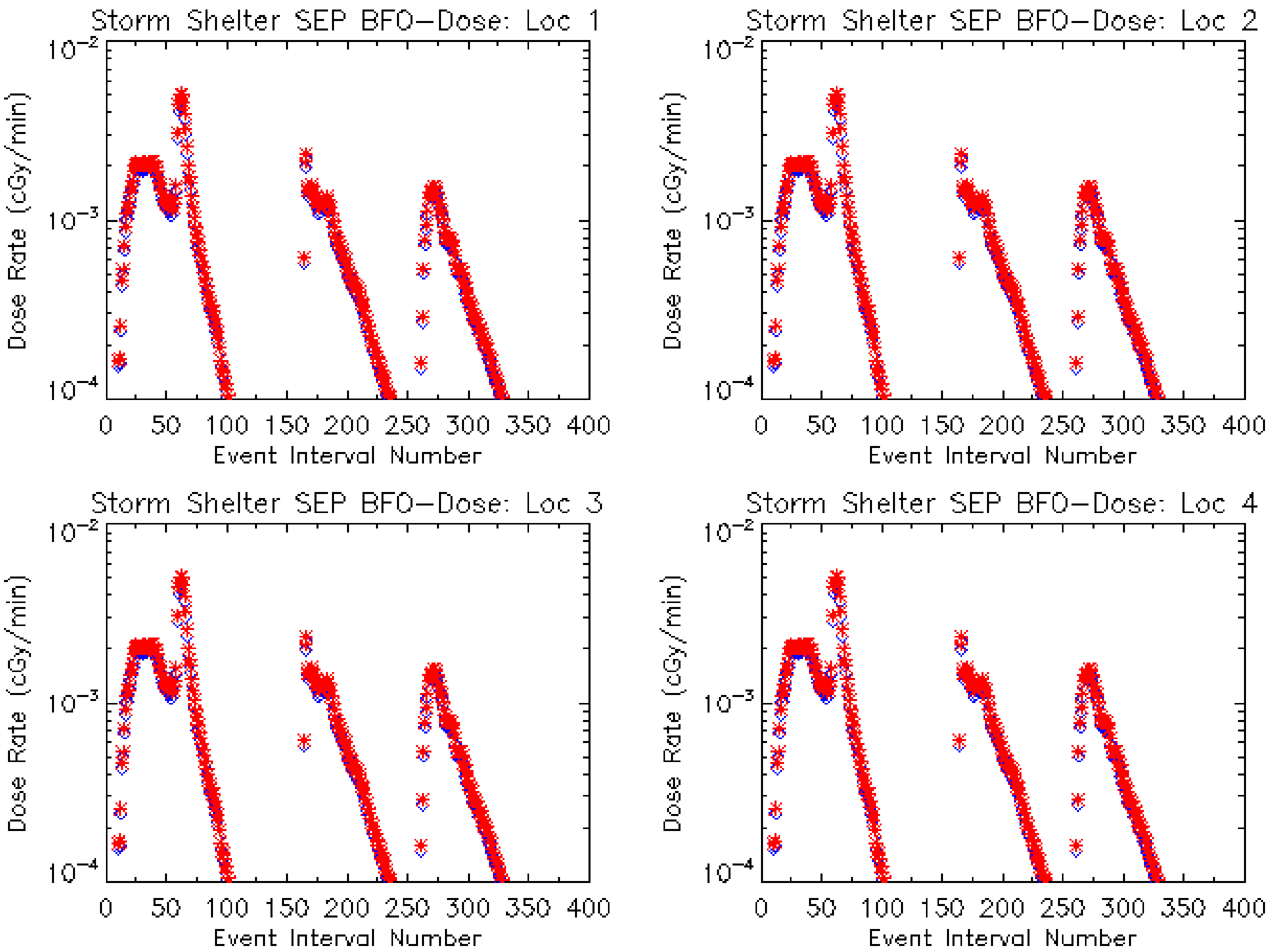
Dose Rates @ Dosimeter Locations

Orion MPCV EM-2 Configuration



BFO Dose Rates @ Crew Locations

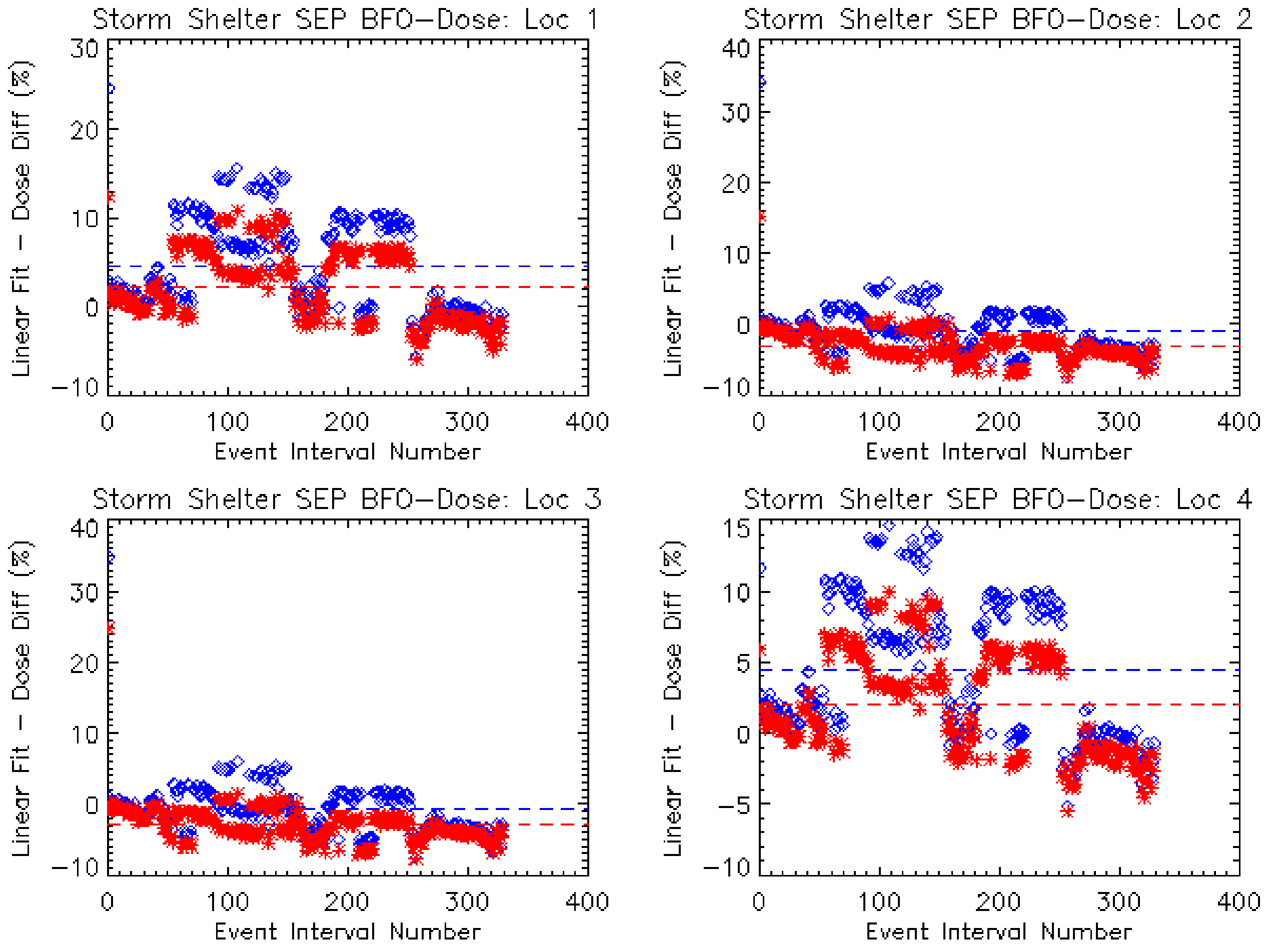
Orion MPCV Storm-Shelter Crew Locations



Blue = Male; Red = Female

BFO Dose Rate Differences

Orion MPCV Storm-Shelter Crew Locations



Blue = Male; Red = Female

SEP Organ Dose Estimate: EM-2

- **Benchmark**: Time-dependent October 1989 Event
- **Total BFO Dose**: 6.4-7.9 cGy, depending on crew location and body type
- **No Systematic Bias**
  - Average error over the event is less than standard deviation (STD) in the model differences over the event
- **Average Model Uncertainty**: 10-15% (STD)
- **Maximum/Minimum Uncertainty**: 25-35%
  - Over any 30-min integration period

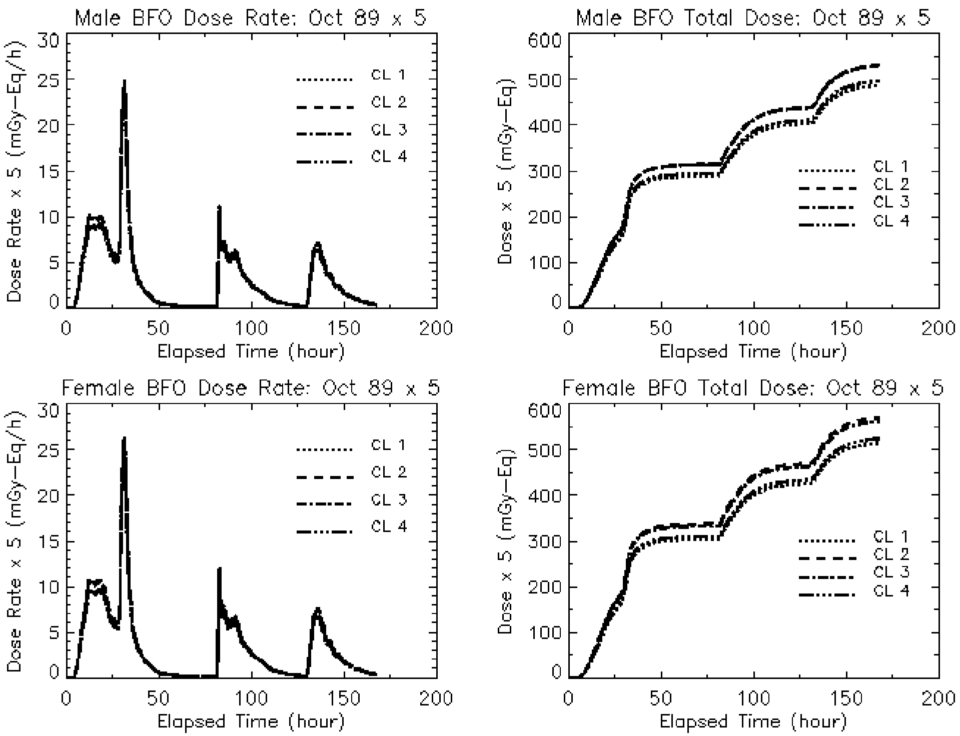
SEP Organ Dose Estimate: EM-1

- **Benchmark**: Time-dependent October 1989 Event
- **No Systematic Bias**
  - Average error over the event is less than standard deviation (STD) in the model differences over the event
  - The average and absolute average error differs by no more than 2% compared to the EM-2 configuration
- **Average Model Uncertainty**: 10-15% (STD)
- **Maximum/Minimum Uncertainty**: 25-35%
  - Over any 30-min integration period
- **Explanation Why EM-1 Error Metrics Roughly Equal EM-2**
  - Information content on vehicle radiation environment is embedded in the dose-depth variation among vehicle dosimeters
  - The EM-1 configuration includes HPU1/HSU2 locations, which correspond to the maximum/minimum average shielding environment of the EM-2 configuration
  - The three additional dosimeters in EM-2 do not introduce enough independent information on the radiation environment to improve estimate of organ doses
  - Main advantage of EM-2 (3 additional dosimeters): Measurement redundancy. May be artifact of isotropic assumption, however.

SEP Organ Dose Estimate: Sub-EM-1

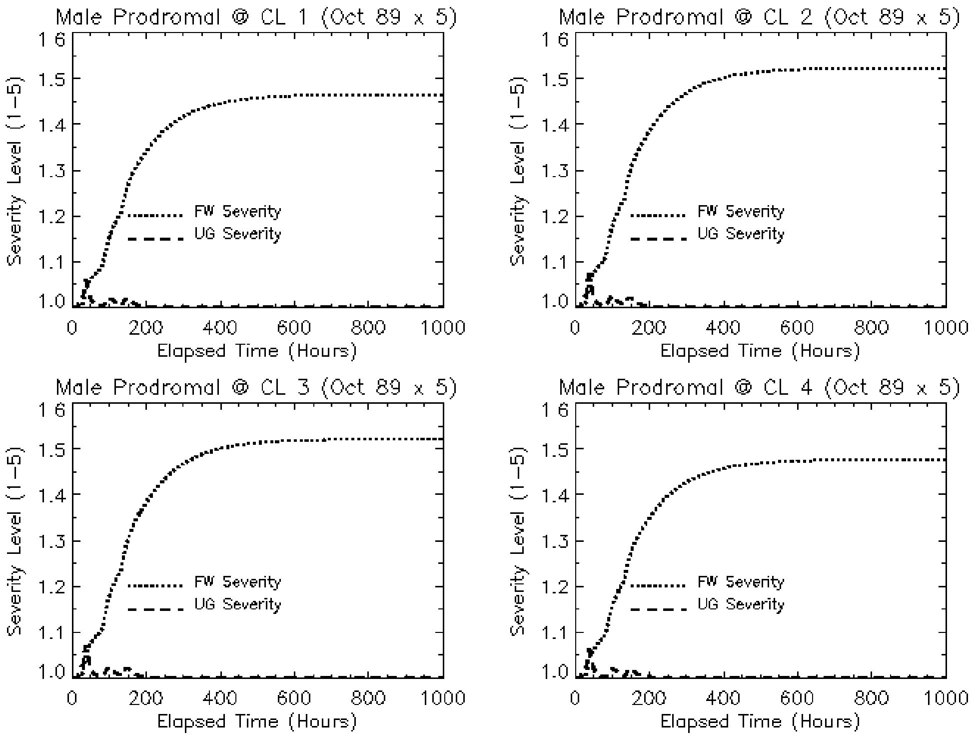
- **Benchmark**: Time-dependent October 1989 Event
- **Comparison for Single Functioning Dosimeter Combinations (i.e. set storm-shelter BFO dose rate to vehicle dosimeter measurement)**
  - Model bias error is over ~ 100% for HSU1 dosimeter location
  - Model bias error is between ~ 300-400% for HSU2 dosimeter location
  - Worst case maximum uncertainty (any 30-min interval) is over a factor of 20 for HSU2 dosimeter location
- **Largest Modeling Errors for Single Functioning HSU1 and HSU2 Dosimeter Locations**
  - Average shielding environment at these locations nearly the same as the average shielding environment at the storm-shelter crew locations
  - In other words, no approximate account for body shielding, yielding significantly overestimated organ doses
- **Best Results for Single Functioning Dosimeter if Located at HPU1**
  - This dosimeter location effectively includes an additional 10-15 g/cm^2 of (body) shielding compared to the storm-shelter crew locations

Input BFO Dose to Biological Model



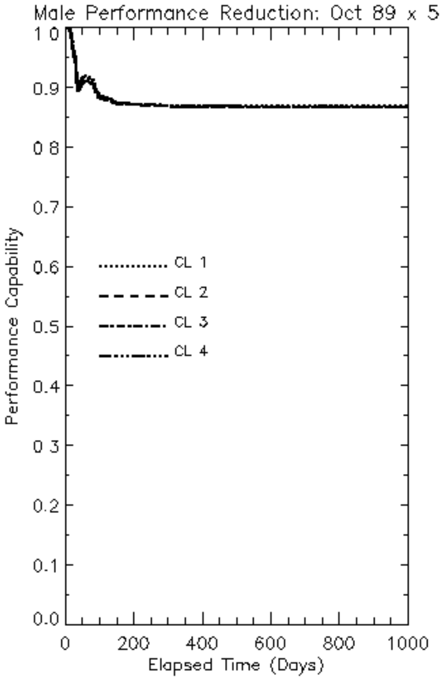
- Dose limits for deterministic effects are given in terms of gray equivalent (Gy-Eq), which is organ dose (Gy) multiplied by the relative biological effectiveness (RBE) for specific end point and radiation quality
- Therefore, scale BFO dose (Gy) from SEP organ dose model by proton RBE = 1.5 to get BFO dose (Gy-Eq)
- Storm-shelter BFO dose (< 120 mGy-Eq) for October 1989 SEP event is well below the threshold for acute effects (500 mGy-Eq)
- Therefore, scale storm-shelter BFO dose by addition factor of 5 to induce a response in acute biological model

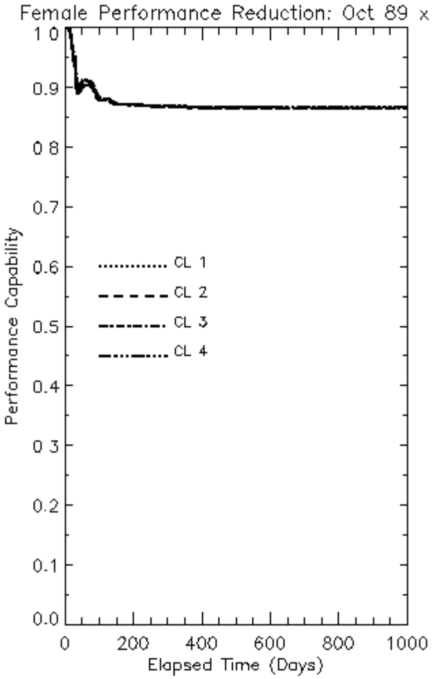
Prodromal Response: 5 x Oct 89



- **Acute Radiation Syndrome**
  - Reduction in hematopoietic stem cell pool in bone marrow, from which originate blood cell types that regulate the immune system, for example.
  - Prodromal responses such as upper gastrointestinal distress (UG) and fatigue and weakness (FW)
- **UG/FW prodromal response** (severity scale: 1-5)
  - No discernable symptoms at level 1
  - UG: peak within 20-40 hours of initial exposure
  - FW: peak after 20 days of initial exposure

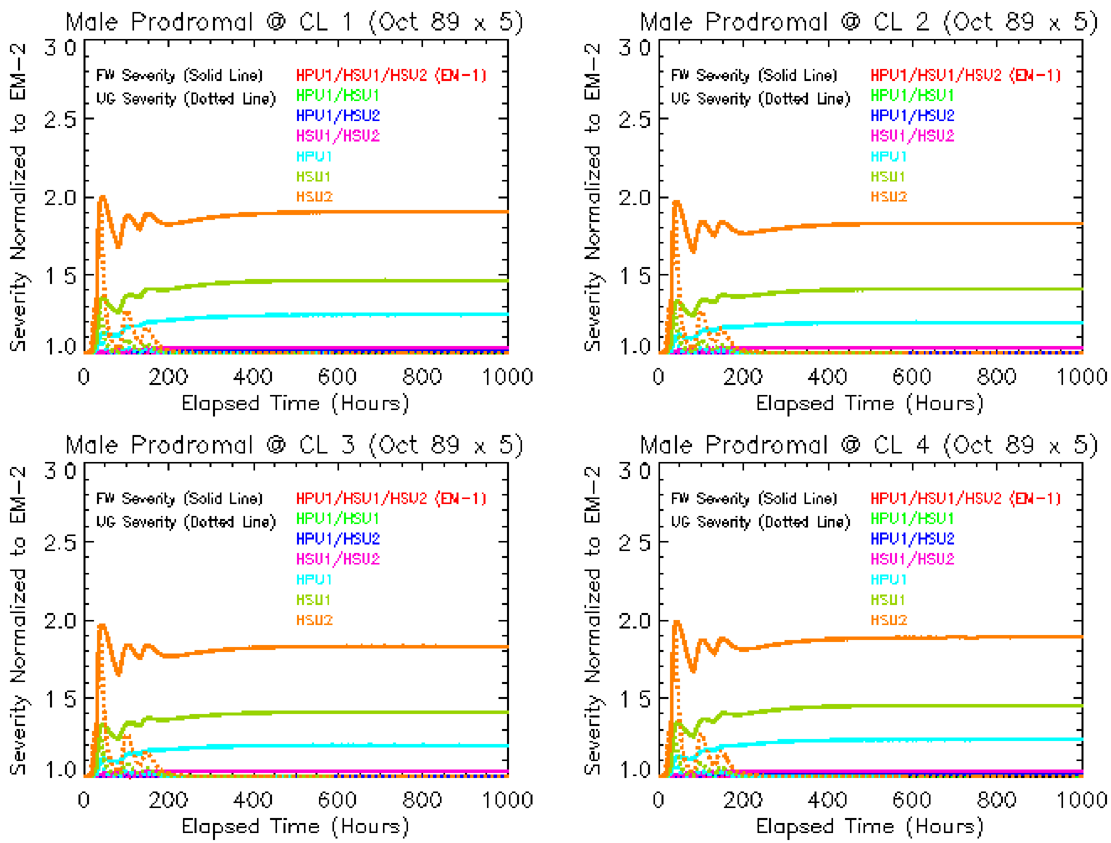
Performance Alteration: 5 x Oct 89





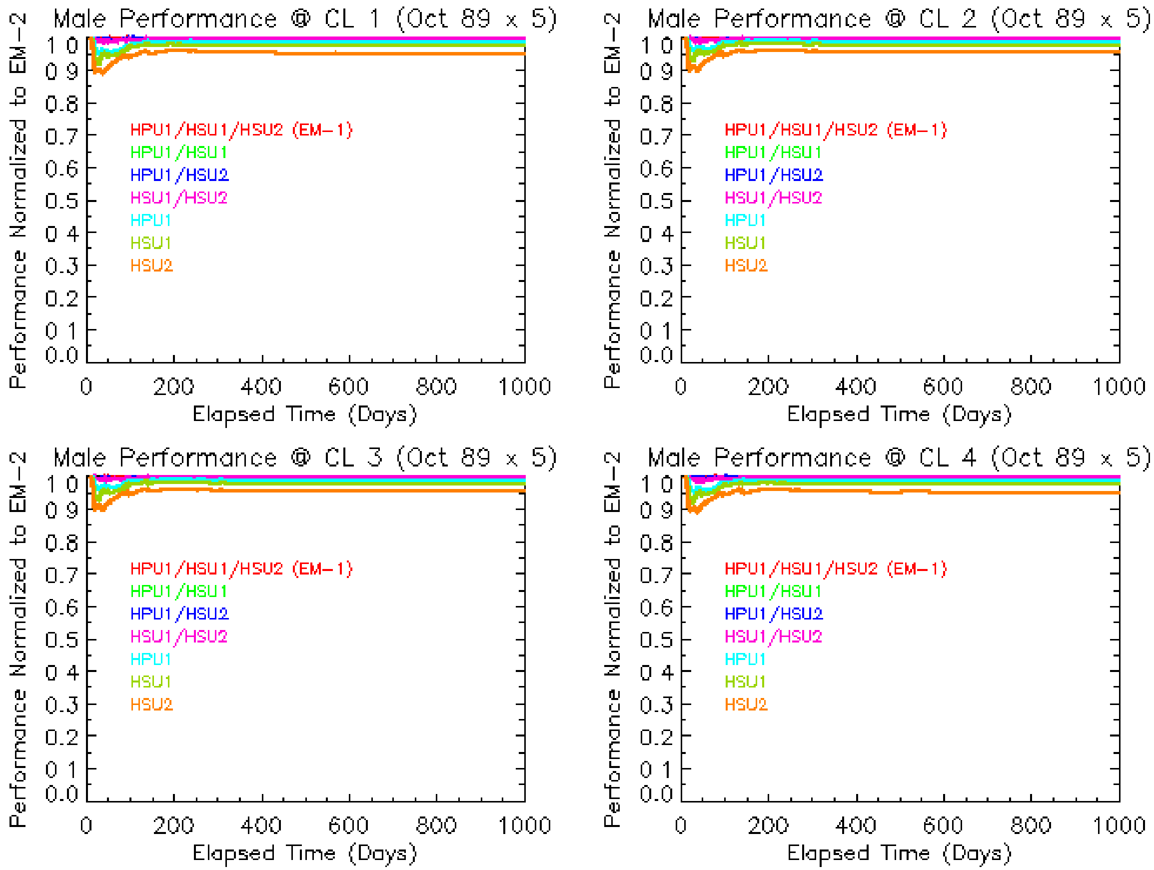
- **Acute Radiation Syndrome**
  - Reduction in hematopoietic stem cell pool in bone marrow, from which originate blood cell types that regulate the immune system, for example.
  - Prodromal responses such as upper gastrointestinal distress (UG) and fatigue and weakness (FW)
- **Performance degradation**
  - Minimum performance capability associated with value of 0.87, indicating typical tasks would take (1.0/0.87) 1.15 (15%) longer
  - The initial time-profile of performance follows the UG response. FW becomes dominate factor in performance as it increases with time and exceeds UG response
  - Note: performance capability better than 0.75 is considered operationally effective in military context

Propagate BFO Dose Uncertainty



- UG/FW prodromal responses for various vehicle dosimeter configurations (EM-1 + combinations of missing EM-1 dosimeter measurements) normalized to results from EM-2 configuration
- Worst case uncertainty: factor 2 with only HSU2 dosimeter functioning

Propagate BFO Dose Uncertainty



- Performance capability response for various vehicle dosimeter configurations (EM-1 + combinations of missing EM-1 dosimeter measurements) normalized to results from EM-2 configurations
- Worst case uncertainty: less than 10% with only HSU2 dosimeter functioning

Summary and Conclusions

- **Operational tool developed for assessing acute radiation risk in real-time during SEP events**
- **Uncertainty in SEP organ dose model**
  - Average event error:
    - 15% (EM-1/EM-2)
    - Factor 4 (HSU2 dosimeter only)
  - Absolute maximum error in 30-minute interval:
    - 35% (EM-1/EM-2)
    - Factor 20 (HSU2 dosimeter only)
- **Uncertainty in biological responses much less than uncertainty in SEP organ dose model**
  - Prodromal (UG/FW) less than factor 2
  - Performance capability less than 10%
- **Acute biological responses in storm-shelter to large SEP event**
  - None for October 1989 event
  - Minimal for 5 x October 1989
  - Crew well shielded by Orion MPCV storm-shelter
- **Next phase of analysis and model development**
  - Assess impact of anisotropic distributions of SEP proton
- **Operational tool will be tested on EM-1 and fully utilized on EM-2**

Backup Slides

SEP Organ Dose: Oct 1989: EM-2

Comparison of Model Estimate of Male BFO Dose Rate at Crew Locations (CL)

Difference (%)	CL 1	CL 2	CL 3	CL 4
Average	4.61	-0.90	-0.83	4.42
Absolute Avg.	5.34	2.47	2.51	5.03
Maximum[a]	24.58	33.98	34.76	14.66
Minimum[a]	-5.64	-7.52	-7.58	-5.14
STD[b]	15.33	13.22	13.52	12.97

Comparison of Model Estimate of Female BFO Dose Rate at Crew Locations (CL)

Difference (%)	CL 1	CL 2	CL 3	CL 4
Average	2.24	-3.13	-2.95	2.07
Absolute Avg.	3.67	3.24	3.17	3.37
Maximum[a]	12.37	15.20	24.80	9.92
Minimum[a]	-5.98	-7.46	-7.66	-5.52
STD[b]	11.73	10.38	11.25	10.16

[a]Max/Min difference for any 30-min interval; [b]Standard deviation over event

SEP Organ Dose: Oct 1989: EM-1

Comparison of Model Estimate of Male BFO Dose Rate at Crew Locations (CL)

Difference (%)	CL 1	CL 2	CL 3	CL 4
Average	6.63	0.09	0.17	6.29
Absolute Avg.	7.43	3.02	3.10	6.97
Maximum[a]	21.57	31.75	32.49	14.76
Minimum[a]	-4.49	-6.73	-6.77	-4.07
STD[b]	15.25	12.91	13.21	12.95

Comparison of Model Estimate of Female BFO Dose Rate at Crew Locations (CL)

Difference (%)	CL 1	CL 2	CL 3	CL 4
Average	3.66	-2.78	-2.51	3.36
Absolute Avg.	5.02	2.87	2.74	4.59
Maximum[a]	10.76	13.99	23.32	9.89
Minimum[a]	-5.07	-7.09	-7.19	-4.68
STD[b]	11.58	9.64	10.47	10.04

[a]Max/Min difference for any 30-min interval; [b]Standard deviation over event

SEP Organ Dose: Oct 1989: Sub-EM-1

Absolute Average Difference (%) Between Model Estimate of BFO Dose Rate at Crew Locations (CL)

	M	M	M	M	F	F	F	F
Location	**CL 1**	**CL 2**	**CL3**	**CL 4**	**CL 1**	**CL 2**	**CL 3**	**CL 4**
HPU1/HSU1[a]	4.80	4.78	4.80	4.50	4.47	4.19	4.33	4.15
HPU1/HSU2[a]	6.73	1.93	1.90	6.21	3.38	5.22	4.91	2.81
HSU1/HSU2[a]	14.97	8.77	8.86	14.49	11.99	5.89	6.23	11.55
HPU1[b]	71.63	60.63	51.03	67.89	59.20	37.64	39.83	44.93
HSU1[c]	143.10	113.36	113.92	137.74	125.41	94.86	98.00	120.74
HSU2[d]	366.15	309.08	310.19	355.34	331.64	272.94	279.21	322.37

[a]Standard deviation of the differences are within 10-15%
[b]Standard deviation of the differences are within 25%
[c]Standard deviation of the differences are within 45%
[d]Standard deviation of the differences are within 150%

SEP Organ Dose: Oct 1989: Sub-EM-1

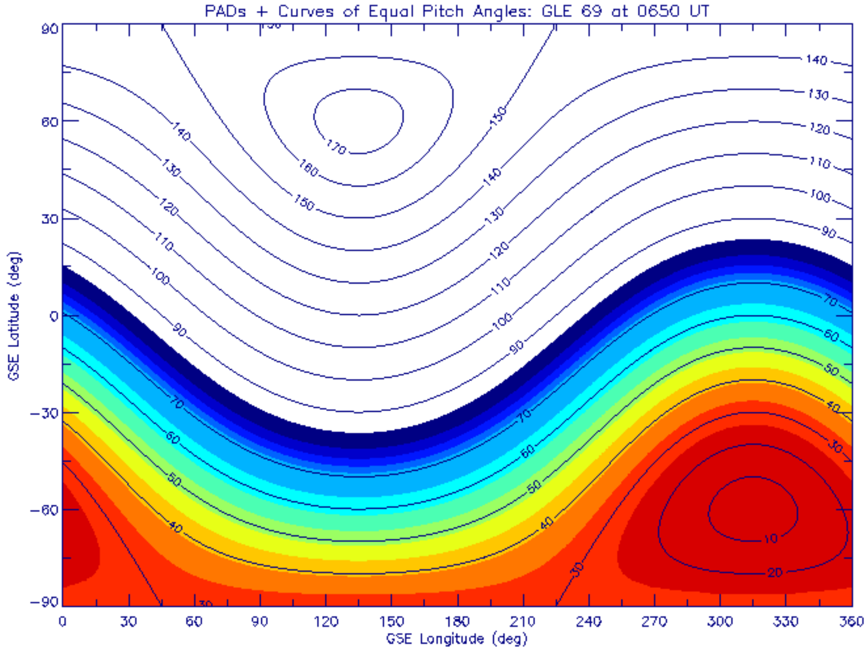
Absolute Maximum Difference (%) Between Model Estimate of BFO Dose Rate at Crew Locations (CL)

	M	M	M	M	F	F	F	F
Location	**CL 1**	**CL 2**	**CL3**	**CL 4**	**CL 1**	**CL 2**	**CL 3**	**CL 4**
HPU1/HSU1[a]	14.66	15.53	15.53	14.26	13.39	14.15	14.35	13.02
HPU1/HSU2[a]	20.40	30.55	31.28	12.83	9.37	13.00	22.24	7.56
HSU1/HSU2[a]	45.85	53.07	54.05	34.06	29.05	28.96	40.33	27.77
HPU1[b]	408.55	355.08	359.93	322.94	292.14	226.95	269.34	246.69
HSU1[c]	732.39	644.86	652.80	592.26	541.84	435.14	504.53	467.45
HSU2[d]	2270.7	2021.4	2044.0	1871.6	1728.0	1424.1	1621.7	1516.1

[a]Standard deviation of the differences are within 10-15%
[b]Standard deviation of the differences are within 25%
[c]Standard deviation of the differences are within 45%
[d]Standard deviation of the differences are within 150%

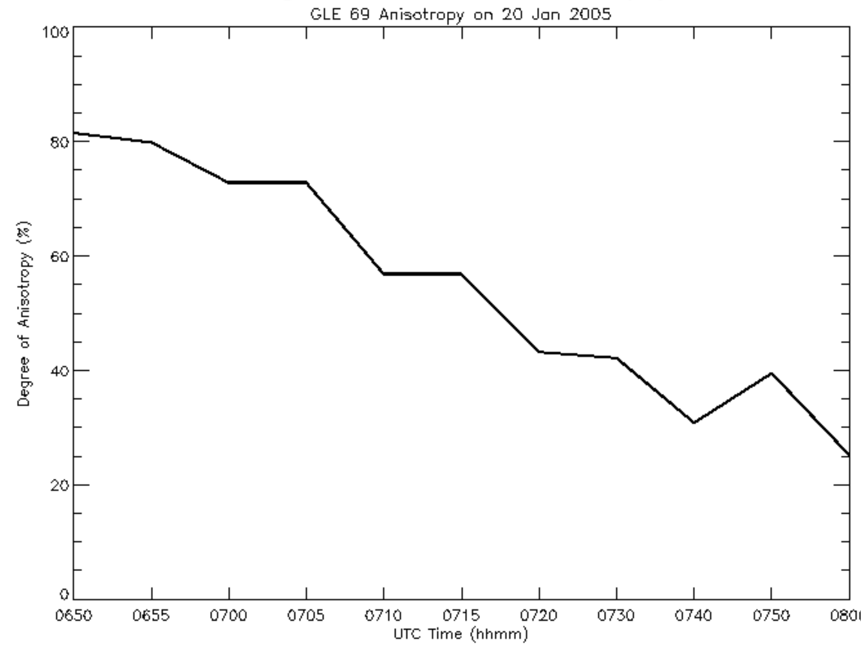
Example SEP Anisotropy: GLE69

Pitch Angle Distribution About Arrival Direction in GSE Coordinates: 06:50 UT



Highly collimated proton beam during initial phase of GLE

Degree of Anisotropy



The anisotropy shown above persisted for an additional 11 hours at 10-30%

GLE69 Parameterization: *Bombardieri et al., Astrophys. J.,* ***682****, 1315-1327, 2008*

Effect of Anisotropy

- **Effect of Anisotropy**
  - Database of pre-computed doses (at vehicle dosimeter locations and at the storm-shelter crew locations) assume an isotropic spatial distribution of SEP protons
  - For large SEP (GLE) events, the initial protons arrive as a highly collimated beam (directed along IMF)
    - This spatial anisotropy persists in time up through and past the peak flux
    - Thus, most of the accumulated SEP dose is delivered by a highly anisotropic distribution of protons
  - In principle, for a highly anisotropic SEP event, the dose-depth variation in the pre-computed database of Si-doses at the vehicle dosimeter locations, which were assumed to be isotropically distributed in space, will not represent the dose-depth variation in the actual vehicle dosimeter measurements
  - How will the explicit assumption of spatial isotropy in the pre-computed database of dose quantities translate into error in the estimated storm-shelter crew organ doses for large (anisotropic) SEP events?
    - Unknown