Estimation of Effective Doses for Radiation Cancer Risks on ISS, Lunar and Mars Missions with Space Radiation Measurements

Myung-Hee Y. Kim
Wyle Laboratories, Houston, Texas, 77058

and

Francis A. Cucinotta
NASA Johnson Space Center, Houston, Texas, 77058

10th WRMISS, September 7-9, 2005, NIRS, Chiba, Japan

Phantom Torso Experiment (PTE)
NASA Operational Radiation Protection Program

- Radiation protection practices define the effective dose as a weighted sum over major sites for radiation cancer risks
  - Crew personnel dosimeter does not make direct measurement of effective dose
    - **TLDs measure rad-dose at skin**
    - **They do not account for radiation quality or organ shielding by body**
  - Transport codes and biodosimetry use skin-dose measurement (TLD rad-dose) to estimate effective doses for ISS (STS is similar)

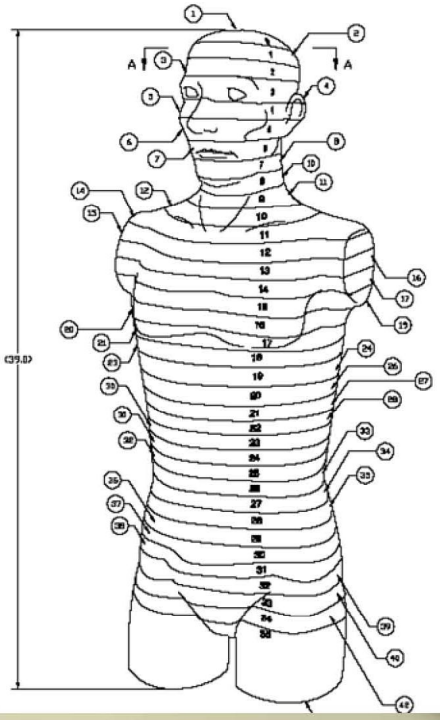
Phantom Torso Experiment (PTE)
NASA Operational Radiation Protection Program

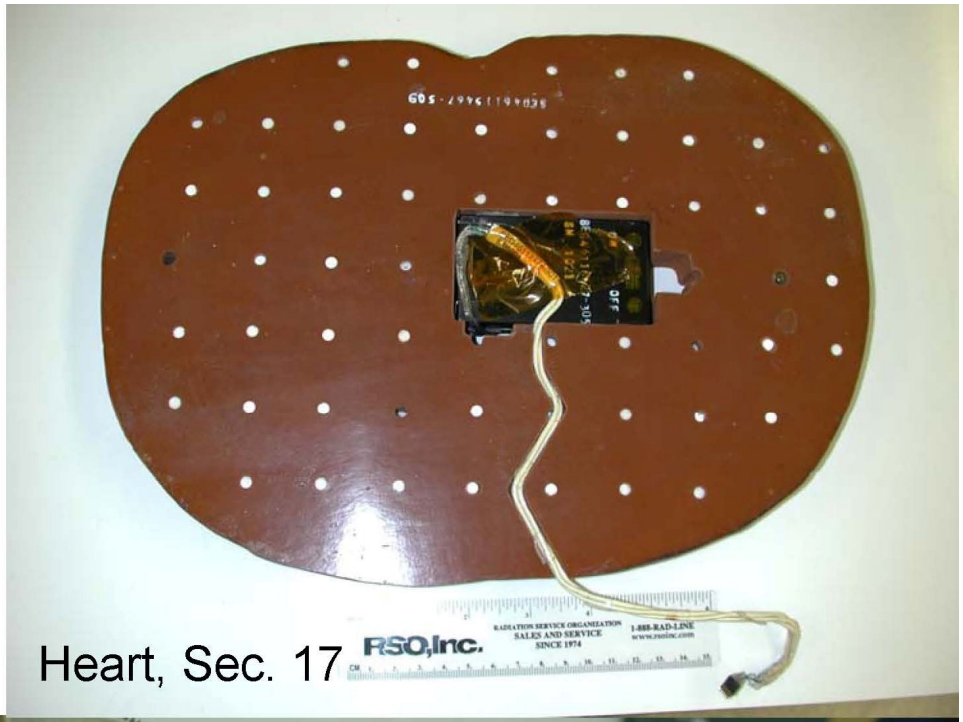
- PTE considers
  - Variation in organ doses (TLD-dose) for many tissue sites
  - Absorption and changes in radiation quality with tissue shielding
  - Tests of space radiation transport codes used to estimate organ and effective doses in NASA's Operational Radiation Protection Program

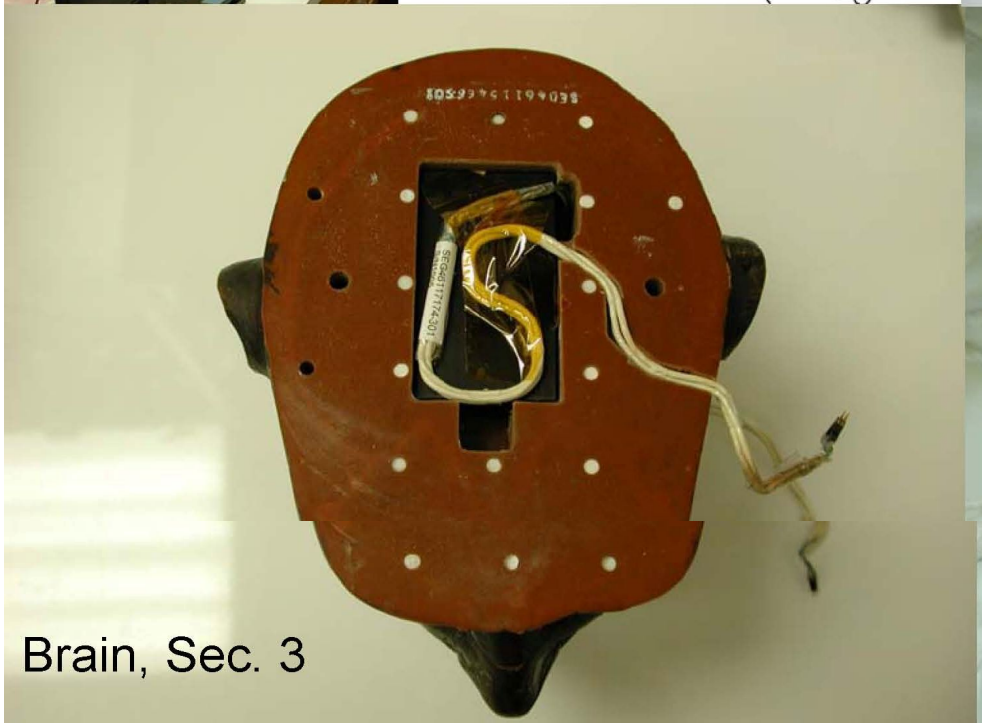
- PTE objectives:
  - Map dose distribution inside the human phantom
  - Separate the contribution of GCR and trapped particles at the fixed organ locations
  - Assess the accuracy of radiation transport models
  - → Relate rad-dose measurements at skin to BFO doses for effective dose and radiation cancer risk estimation

Components of PTE

- Rando phantom torso simulating a standard male with correct bone and tissue structure
  - Sectioned into 34 equal slices of 1 inch thickness
- TLD Dosimeters
  - Phantom slices include many ¼-inch-diameter holes filled with TLDs (passive dosimeters), which are analyzed post mission
    - Number of TLDs = 358
- Tissue Equivalent Proportional Counter
  - Active dosimeter provides time-resolved data on lineal energy spectra on surface of PTE
- Small Active Dosimeters (Silicon)
  - Active silicon detectors placed at Phantom cut-outs of 5 tissue sites to measure LET spectra
    - Brain, thyroid, heart, stomach, and colon
- Charged-particle detector
  - Measures charged-particle Z, E spectra near PTE

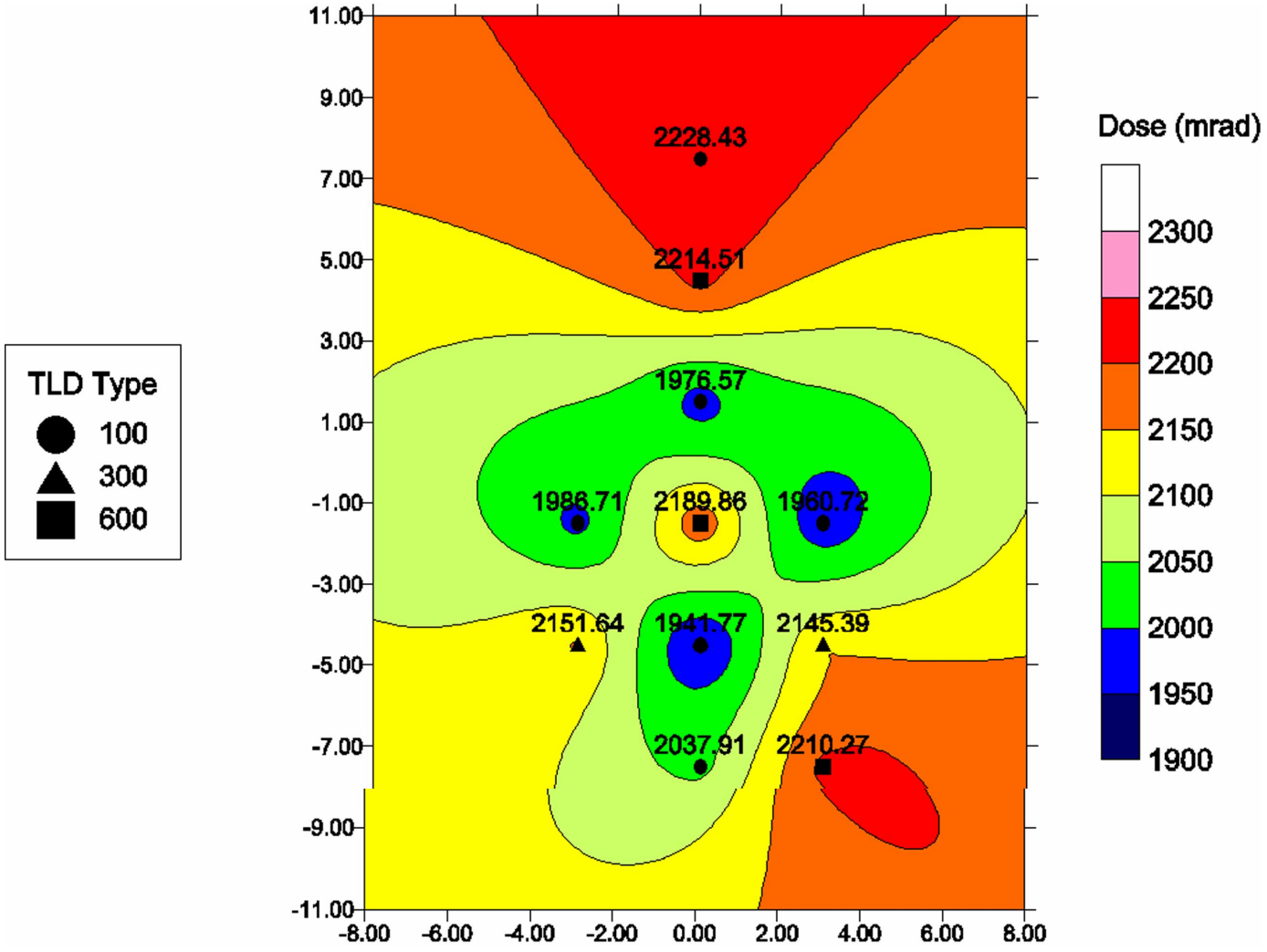



RSO,Inc.
Heart, Sec. 17


Brain, Sec. 3

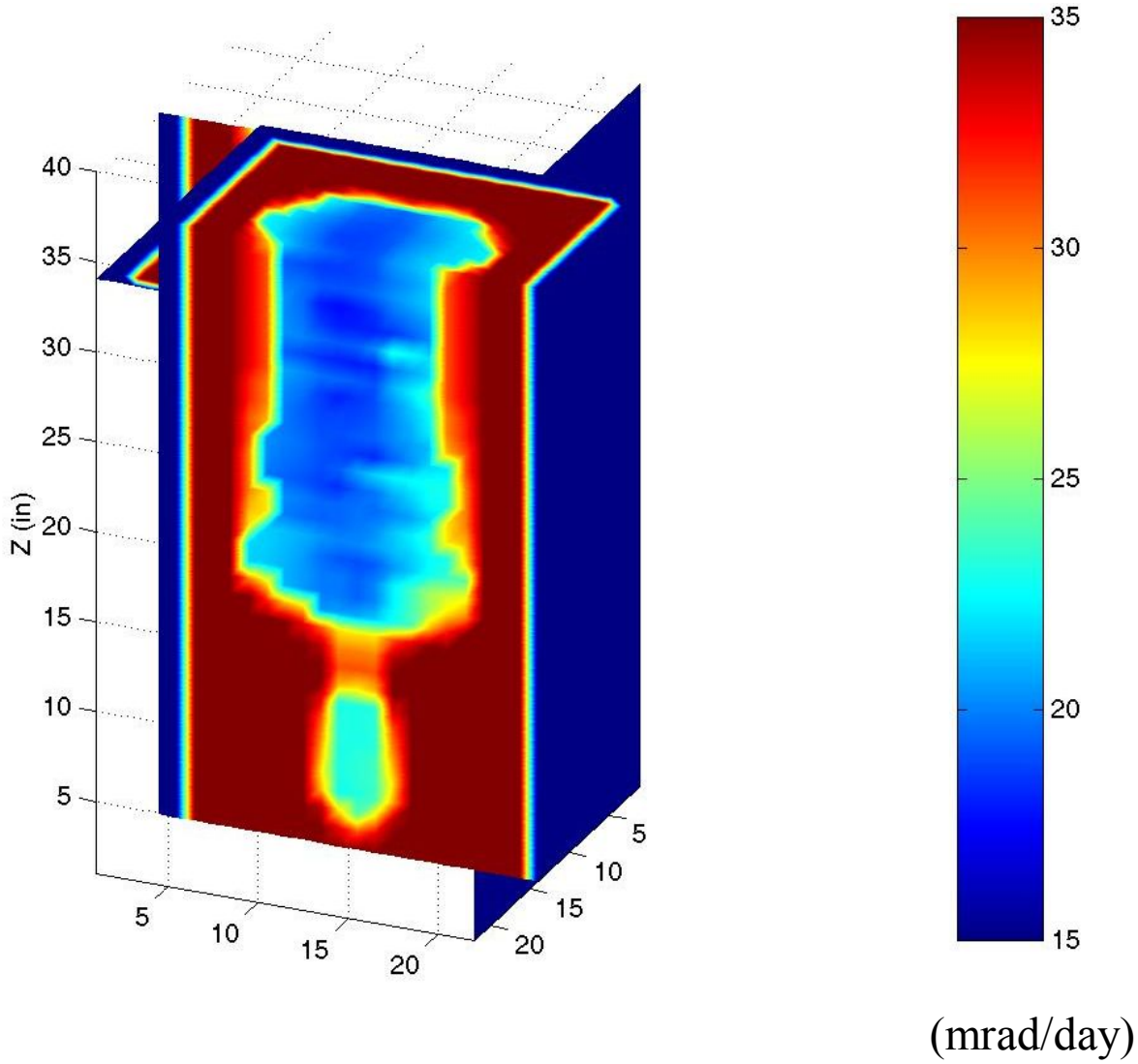

Thyroid, Sec. 8

PTE Brain Slice – TLD Dose Contours



Spatial Distributions of Absorbed Dose

(Visualization by P. Saganti)



PTE vs. HZETRN Model

Comparisons of TLD measurements inside a human phantom torso on STS-91 with predictions from HZETRN code for organ doses using the CAM model (by F. A. Cucinotta, E. Semones, F. Gibbons, J. Flanders, and G. Badhwar)

Phantom Data on STS-91 for Trapped + GCR (51.6 x 390 km)

Organ	Measured (mGy)	Theory (mGy)	Theory* (mGy)	% Difference	% Difference*
Brain	2.23	2.42	2.26	-8.5	-1.4
Bone Surface	2.16	2.36	2.21	-9.3	-2.1
Esophagus	1.71	1.79	1.67	-4.7	2.2
Lung	1.92	1.81	1.69	5.7	11.9
Stomach	2.05	2.08	1.94	-1.5	5.2
Liver	1.88	2.15	2.01	-14.4	-6.9
Spinal Column	1.65	1.98	1.85	-20.0	-12.1
Bone Marrow	1.75	1.98	1.85	-13.1	-5.7
Colon	1.71	1.9	1.78	-11.1	-3.8
Bladder	1.58	1.87	1.75	-18.4	-10.6
Gonad	1.75	1.85	1.73	-5.7	1.2
Skin/Breast	2.46	2.58	2.41	-4.9	2.0
Skin/Abdomen	2.35	2.58	2.41	-9.8	-2.6

*Includes a correction to TLD efficiency vs. LET.

Correction to TLD Efficiency vs. LET

χ^2 – fit to TLDs at Radiation Area Monitor Locations

$$a = \frac{\sum D_{TLD} D_p - \sum D_p D_{GCR}}{\sum D_p^{\,2}}$$

where D_{TLD} = TLD measurement at RAM

D_P = Trapped dose calculation

D_{GCR} = GCR dose calculation

Effective Dose (*E*)

$$E = \sum_{T} w_T H_T$$

Effective dose (*E*) expressed in Sv applies only to stochastic effects.

Tissue Weighting Factors
(ICRP, 1991)

Tissue or Organ	Tissue Weighting Factor, w_T
Gonads	0.2
Bone Marrow (red)	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Bladder	0.05
Breast	0.05
Liver	0.05
Esophagus	0.05
Thyroid	0.05
Skin	0.01
Bone Surface	0.01
Remainder*	0.05

* Additional tissues/organs: adrenals, brain, upper intestine, small intestine, kidney, muscle, pancreas, spleen, thymus, and uterus.

PTE vs. HZETRN Model

Comparisons of SMADOS measurements inside a human phantom torso during ISS Increment-2 with predictions from HZETRN code for organ doses using the CAM model (by W. Atwell, E. Semones, and F. A. Cucinotta)

SMADOS	Measurement time during July 26-August 1, 2001 and August 7-11, 2001 (day)	Trapped radiation (mGy/d)		GCR (mGy/d)		Total dose rate (mGy/d)		Difference
		Meas.	Calc.	Meas.	Calc.	Meas.	Calc.	
BRAIN	10.211	50.7	66.3	75.8	77.0	126.5	143.3	13.3%
THYROID	10.028	61.6	71.7	73.9	76.6	135.5	148.3	9.4%
HEART	11.149	53.5	61.4	75.3	76.0	128.8	137.4	6.7%
STOMACH	11.045	50.4	56.5	75.8	76.7	126.2	133.2	5.5%
COLON	10.349	55.4	55.5	72.8	75.9	128.2	131.4	2.5%

Results of PTE

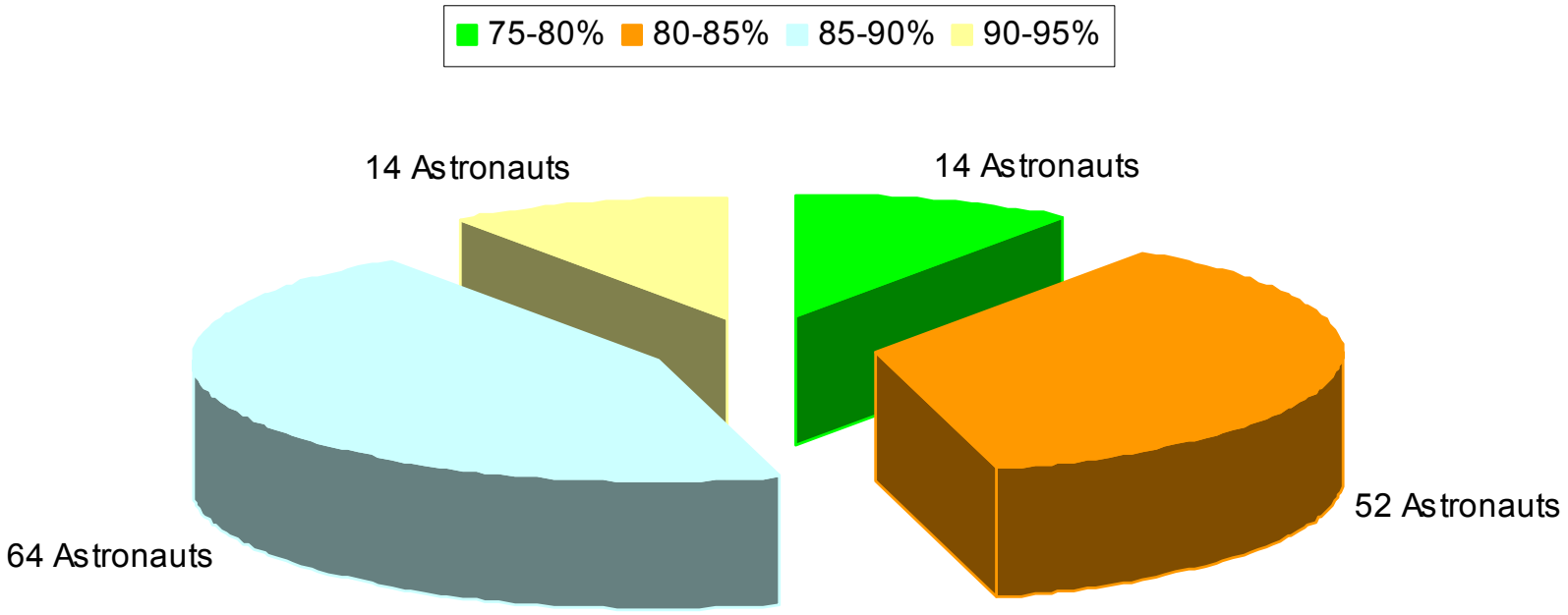
- PTE results are consistent with Crew Passive and Biodosimetry results for STS-91 and ISS-2
- PTE results are consistent with HZETRN model of space radiation organ doses
  - Trapped protons effectively absorbed by tissue and spacecraft
  - GCR makes up about 80% of organ doses < 400 km (51.6 deg)
  - Average quality factors < 400 km (51.6) are Q = 2.5

Radiation Quality and Models in LEO

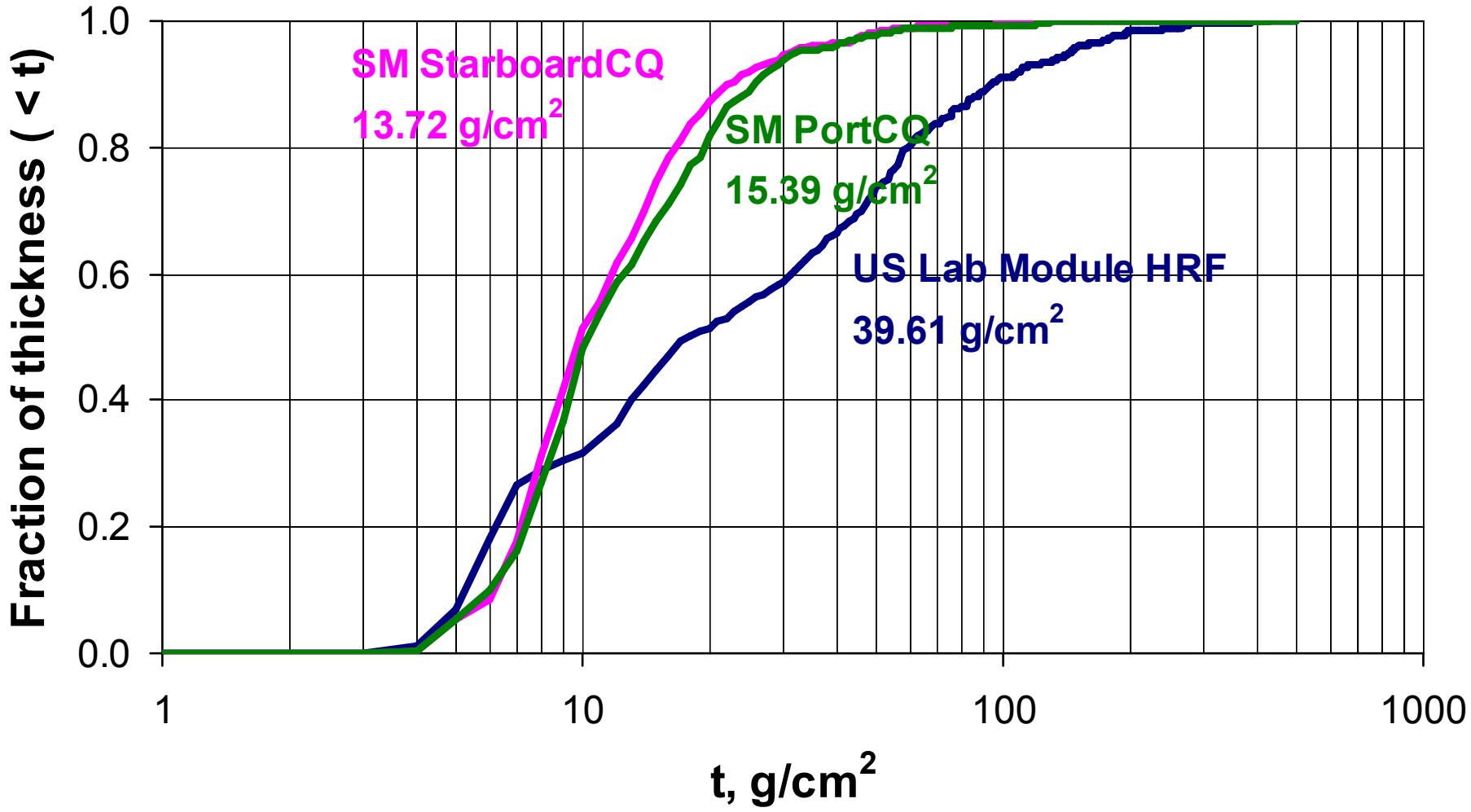
Comparisons of TEPC measurements for the GCR dose and dose equivalent
on several STS and Mir missions to HZETRN code with Badhwar and O'Neill GCR model
(by F. A. Cucinotta, E. Semones, F. Gibbons, J. Flanders, and G. Badhwar)

Mission	Date	Inclination	Altitude	Shielding	Dose, mGy/d			Dose Eq., mSv/d		
					Measured	Theory	%Difference	Measured	Theory	%Difference
STS-40	1991	39	293	DLOC2	0.052	0.048	7.7	0.13	0.16	-23.1
STS-49	1992	28.5	358	DLOC2	0.05	0.048	4.0	0.127	0.155	-22.0
STS-51	1993	28.5	296	Payload Bay	0.044	0.048	-9.1	0.144	0.154	-6.9
STS-57	1993	57	298	Payload Bay	0.113	0.109	3.5	0.422	0.434	-2.8
STS-57	1993	57	298	DLOC2	0.138	0.11	20.3	0.414	0.37	10.6
Mir-18	1995	51.6	390	P	0.142	0.141	0.7	0.461	0.526	-14.1
STS-81	1997	51.6	400	0-sphere	0.147	0.135	8.2	0.479	0.521	-8.8
STS-81	1997	51.6	400	Poly 3-in	0.138	0.138	0.0	0.441	0.400	9.3
STS-81	1997	51.6	400	Poly 5-in	0.129	0.118	8.5	0.316	0.368	-16.5
STS-81	1997	51.6	400	Poly 8-in	0.128	0.113	11.7	0.371	0.323	12.9
STS-81	1997	51.6	400	Poly 12-in	0.116	0.111	4.3	0.290	0.298	-2.8
STS-89	1998	51.6	393	0-sphere	0.176	0.148	15.8	0.561	0.614	-9.4
STS-89	1998	51.6	393	Al 3-in	0.167	0.159	4.8	0.445	0.488	-9.7
STS-89	1998	51.6	393	Al 7-in	0.149	0.161	-8.1	0.529	0.617	-16.6
STS-89	1998	51.6	393	Al 9-in	0.171	0.162	5.3	0.492	0.541	-10.0

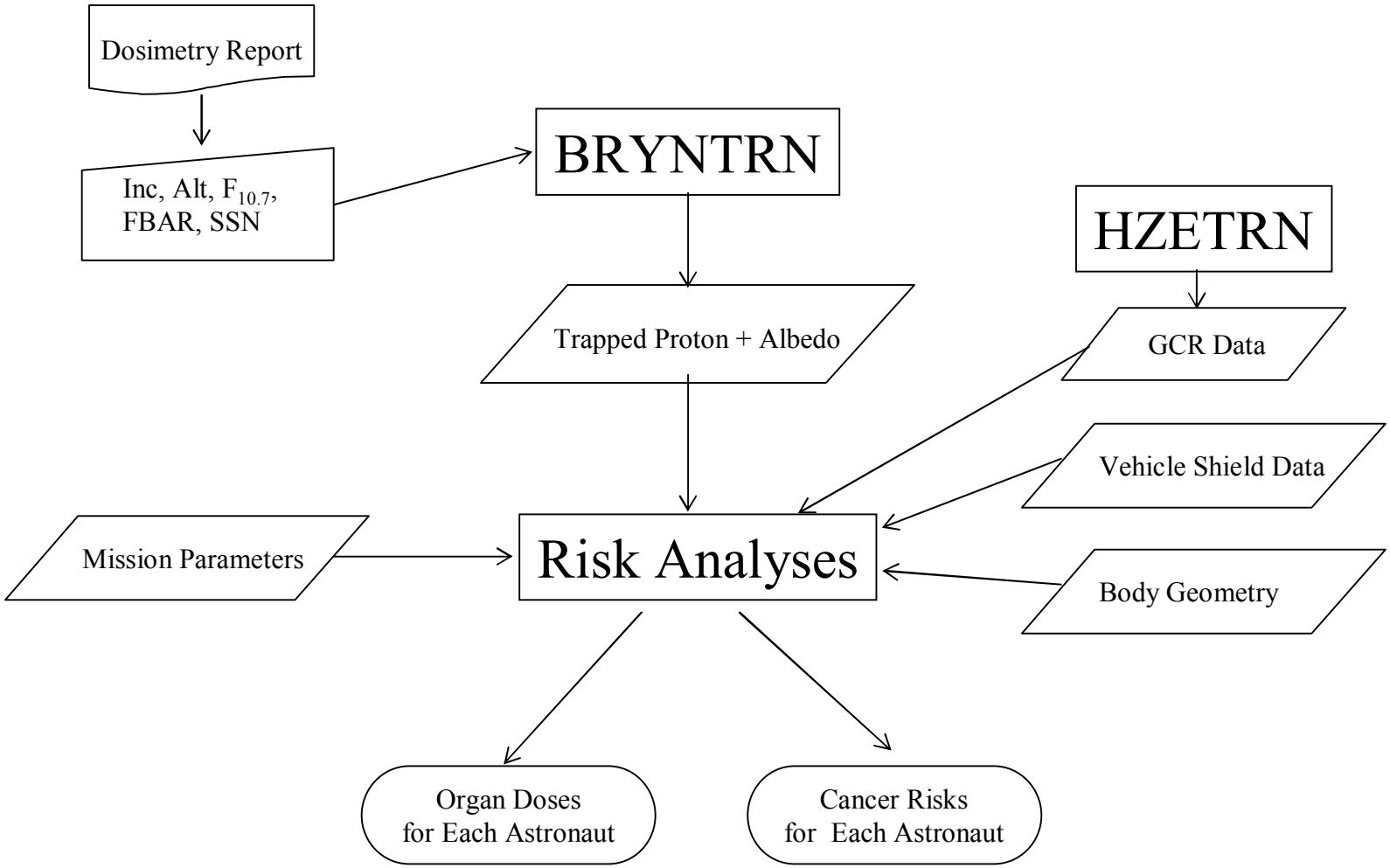
GCR Contribution on Space Missions at 51.6° Inclination



Cumulative Shield Thickness Distributions



Risk Assessment Procedure



Requirements for Improved Estimation of Effective Doses for Radiation Cancer Risks

- Accurate shielding distributions obtained by ray tracers: Phantom torso and vehicle geometry correctly aligned
- Detailed distribution of bone marrow sites:
  - Shoulders, hips, etc.
  - Age dependence of these sites
- Age- and gender-related tissue weighting factors
- Modified transport codes:
  - Vehicle-produced secondary neutrons
  - Improved environmental projection model for mission planning