Estimation of Organ Doses from Solar Particle Events for Future Space Exploration Missions

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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)

NASA Operational Radiation Protection Program

- Phantom Torso Experiment (PTE)
  - 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 the dose distribution inside the human phantom
  - Separate the contributions 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

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.

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%

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*)

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

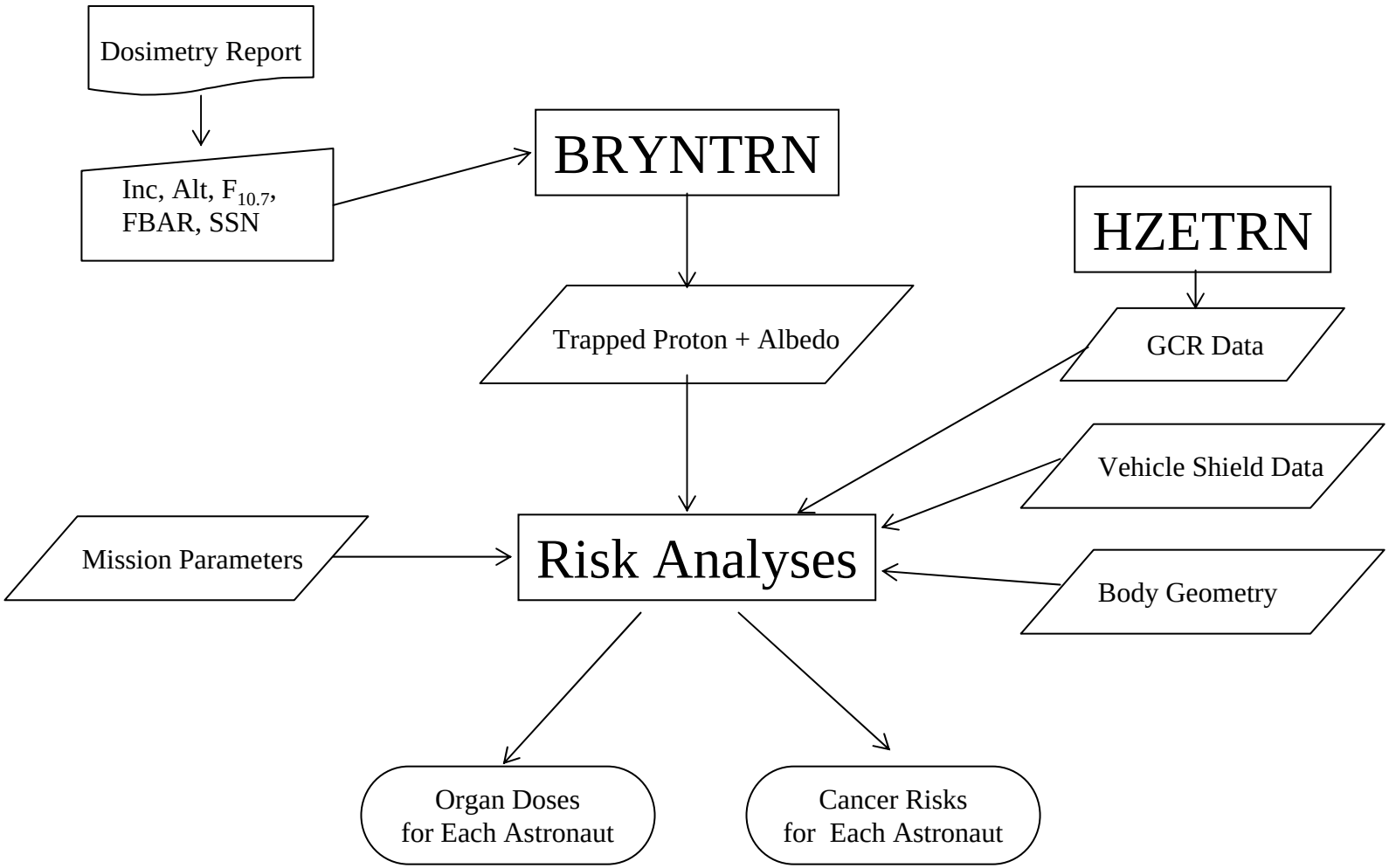
Tissue Weighting Factors (ICRP, 1991)

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.

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

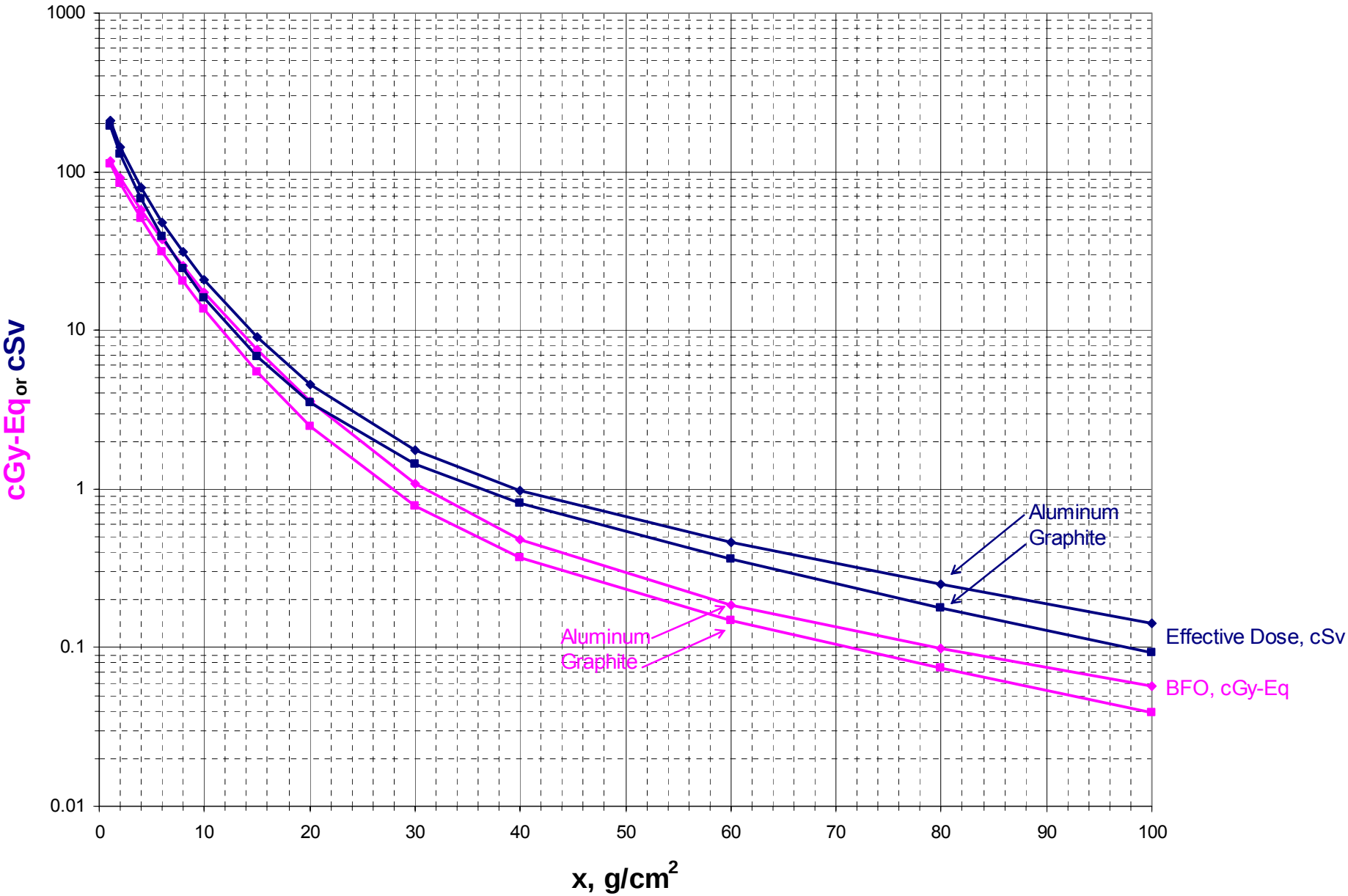
Risk Assessment Procedure



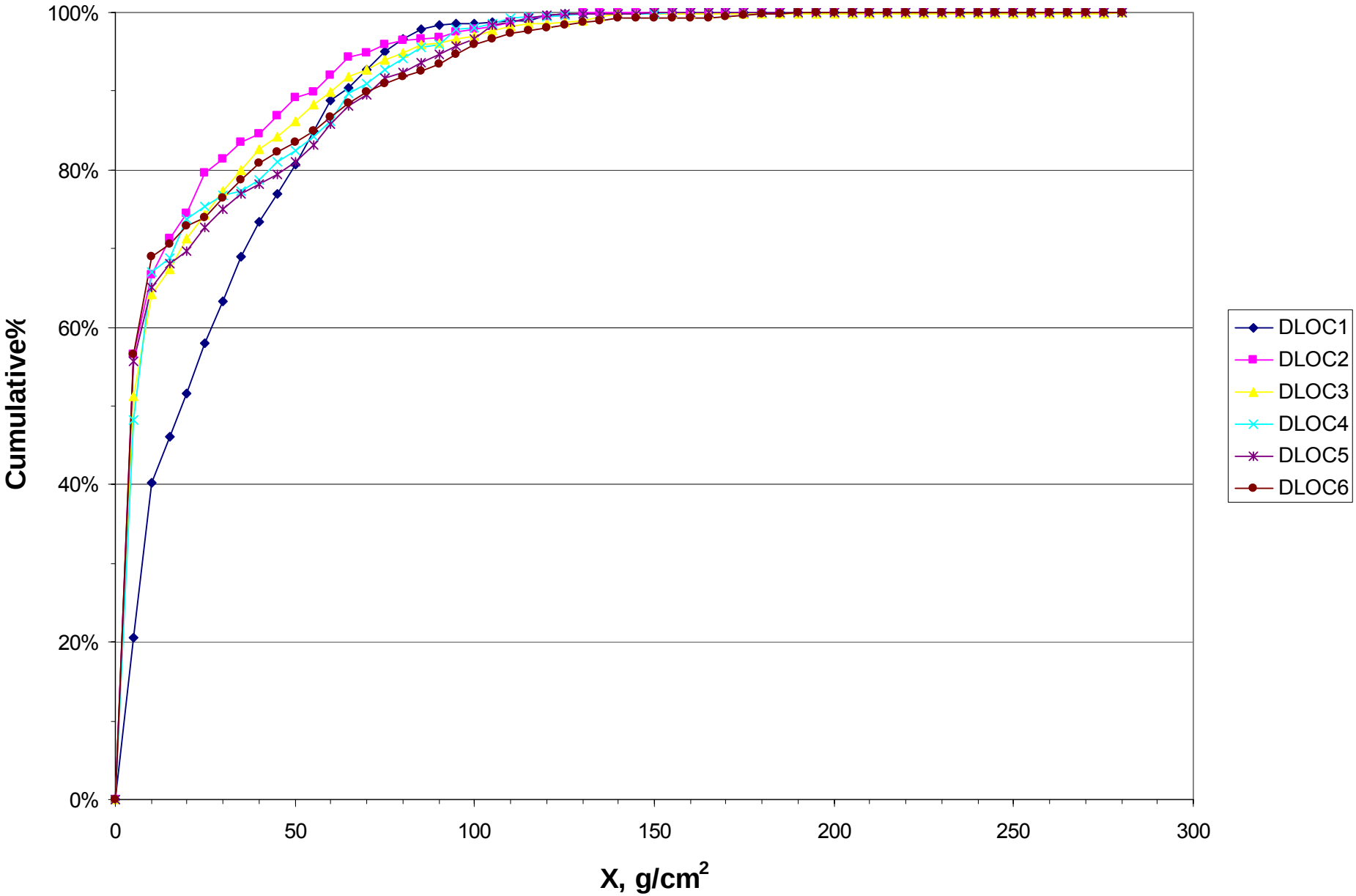
Current Considerations Concerning the Improvement of Estimation of Effective Doses for Radiation Cancer Risks

- Detailed distribution of bone marrow sites
  - ✓ Head and neck, chest, abdomen, pelvis, and thighs
  - ✓ Age dependence of the sites
- Accurate shielding distributions obtained by ray tracers: Correctly aligned geometries between human and vehicle

1972 Solar Particle Event



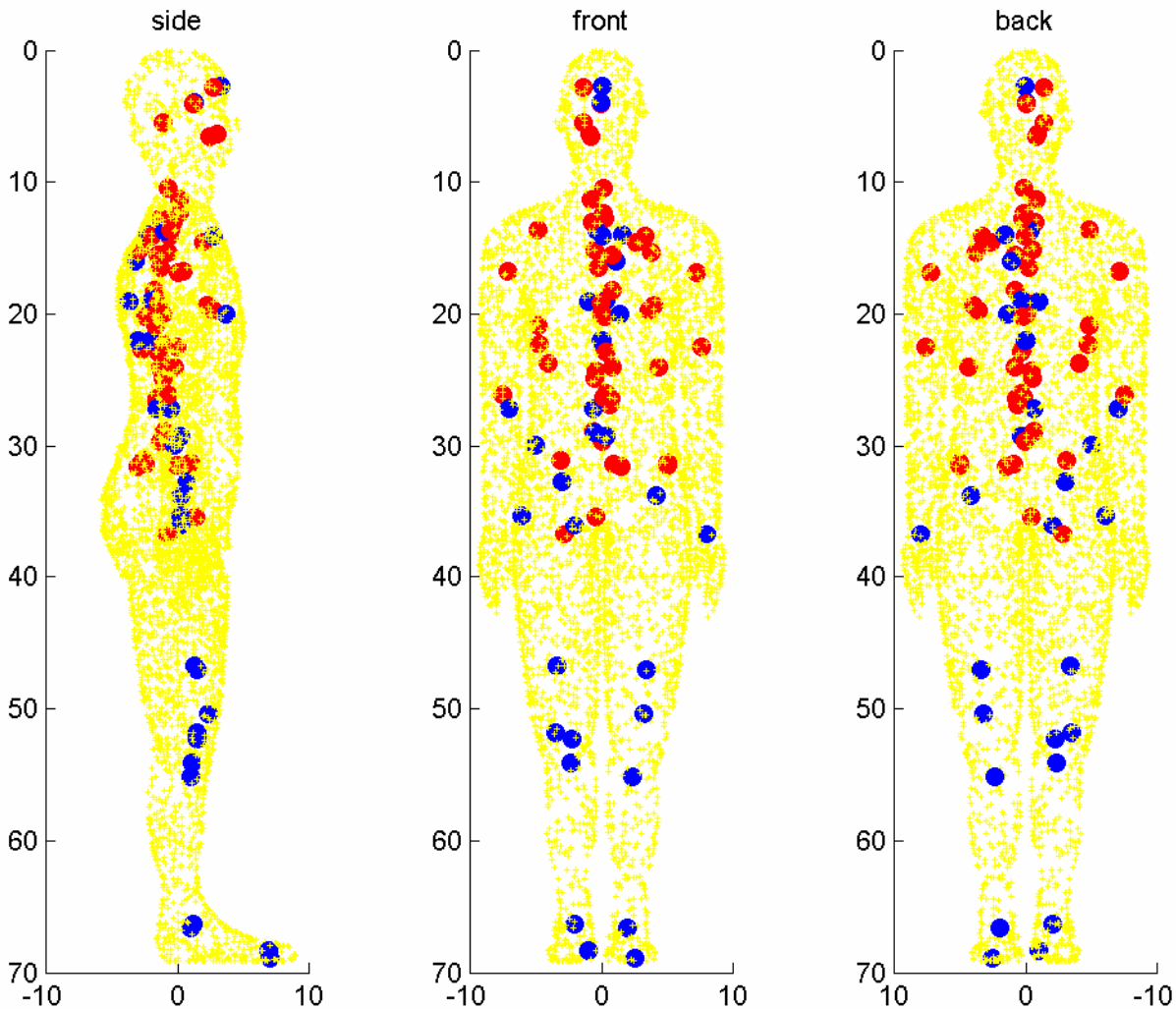
Shuttle Shielding Distributions at 6 DLOCs



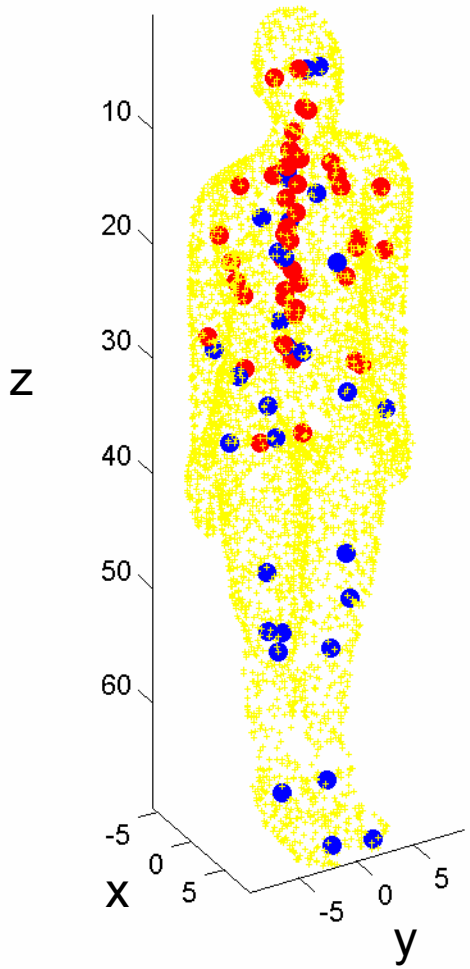
Shuttle Average Thickness at 6 Locations, and Effective Dose and BFO Dose at the Average BFO site with/without Shuttle Ray Tracing

	$\overline{X} = \frac{1}{N}\sum X_i$	$\overline{E} = \frac{1}{N}\sum E(X_i)$	$\overline{E}(\overline{X})$	$\overline{B} = \frac{1}{N}\sum B(X_i)$	$\overline{B}(\overline{X})$
Shuttle	g/cm^2	Ray tracing, cSv	No ray tracing, cSv,	Ray tracing, cGy-Eq	No ray tracing, cGy-Eq
DLOC1	26.67	36.41	2.8	24.28	1.8
DLOC2	16.46	76.05	8.0	49.62	7.0
DLOC3	19.44	72.60	4.5	47.13	3.5
DLOC4	20.01	60.11	4.4	41.77	3.4
DLOC5	21.08	73.44	3.9	48.10	3.0
DLOC6	20.92	74.09	3.9	48.96	3.0

82 BFO Locations

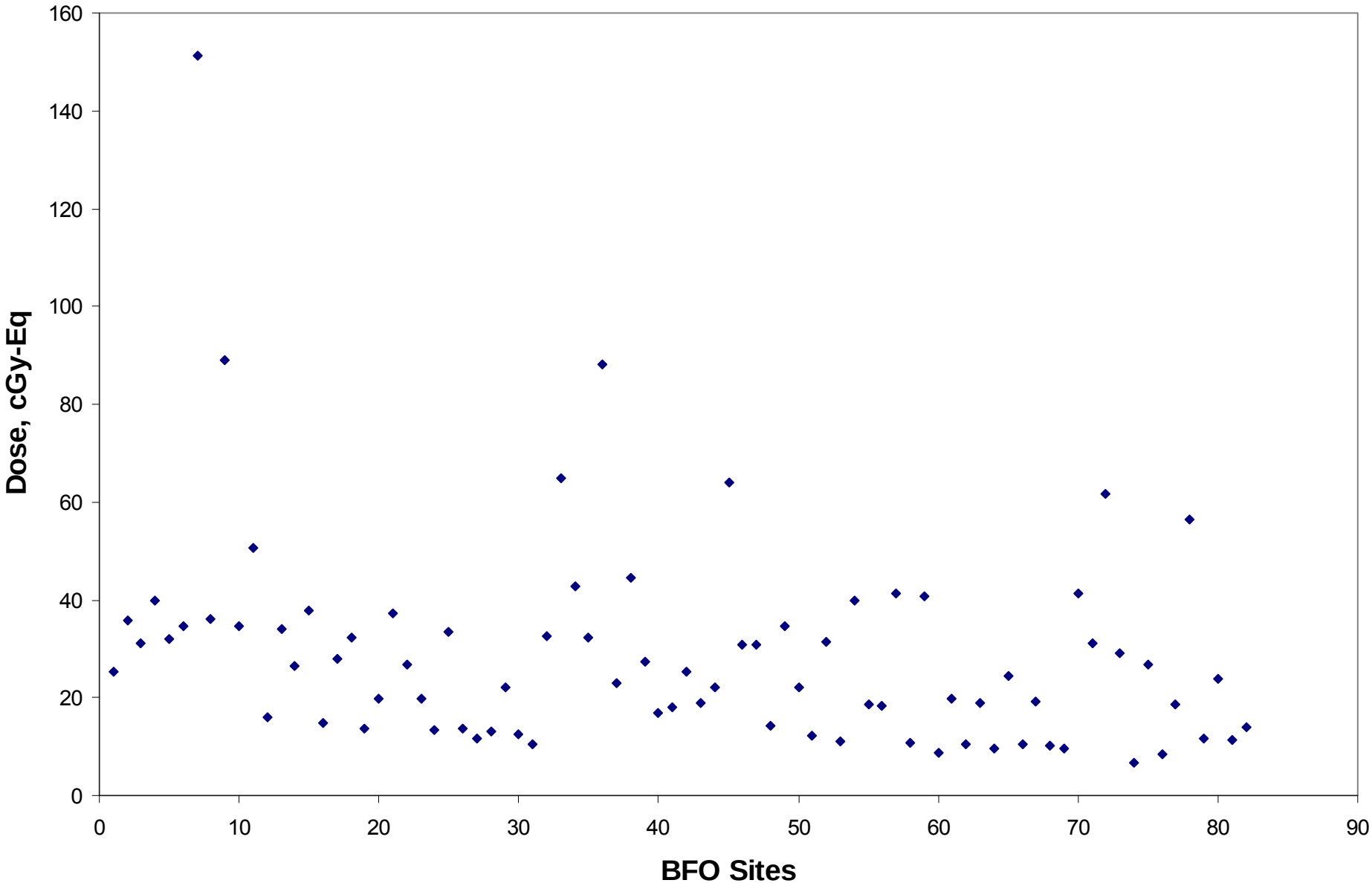


82 BFO Locations

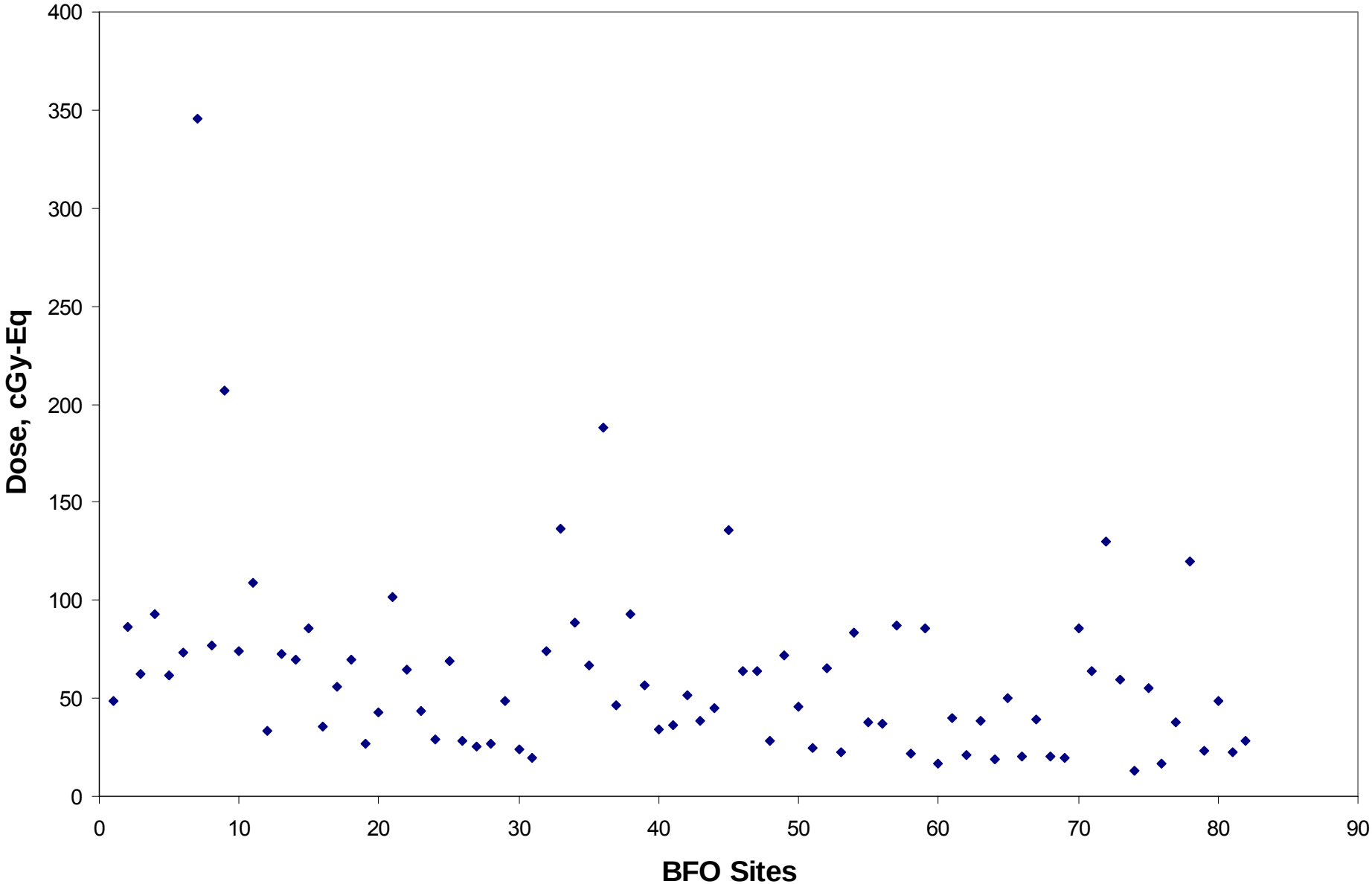


- 32-location set
- 50-location set

BFO Dose at DLOC1 from 1972 SPE



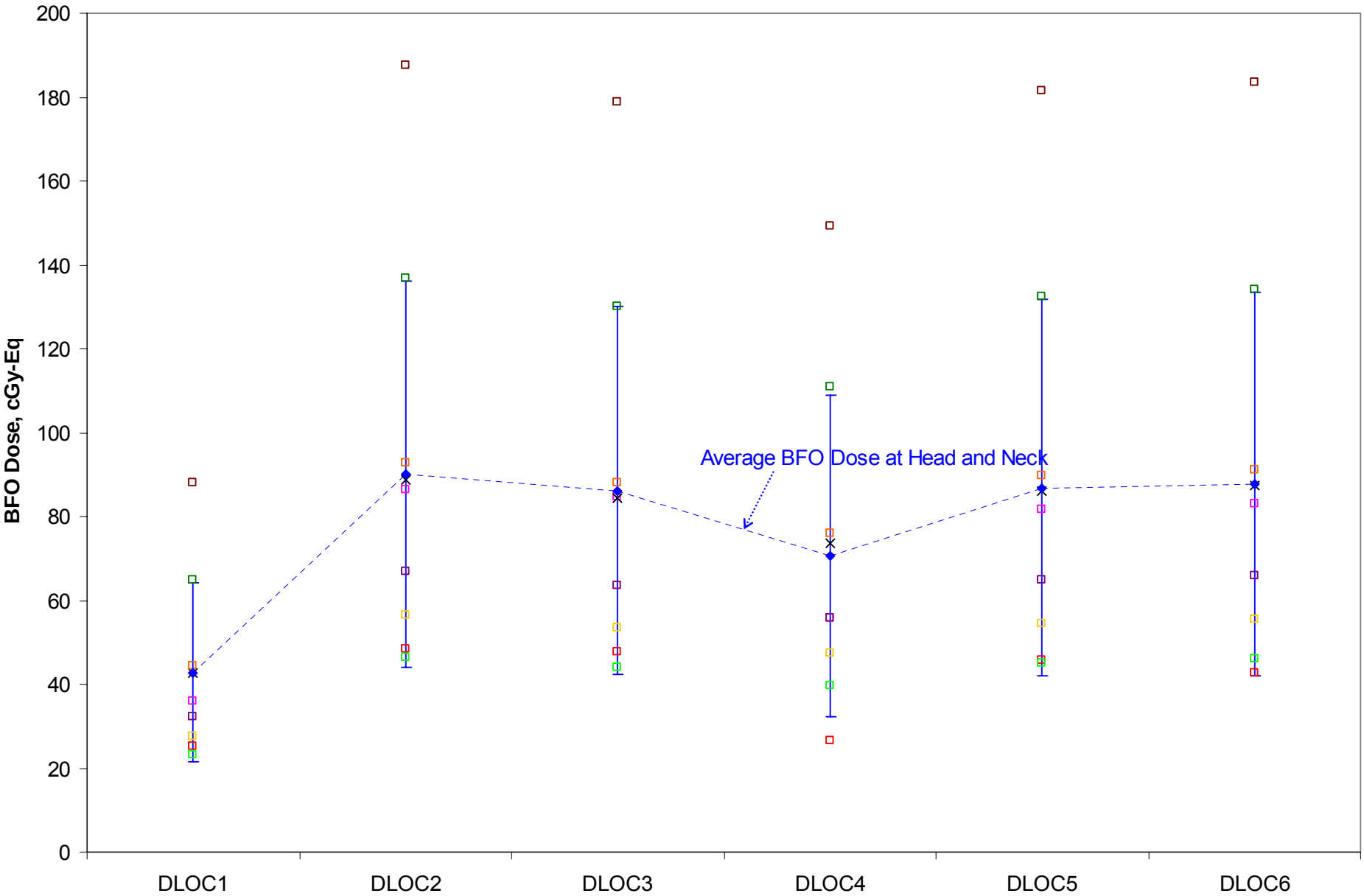
BFO Dose at DLOC2 from 1972 SPE



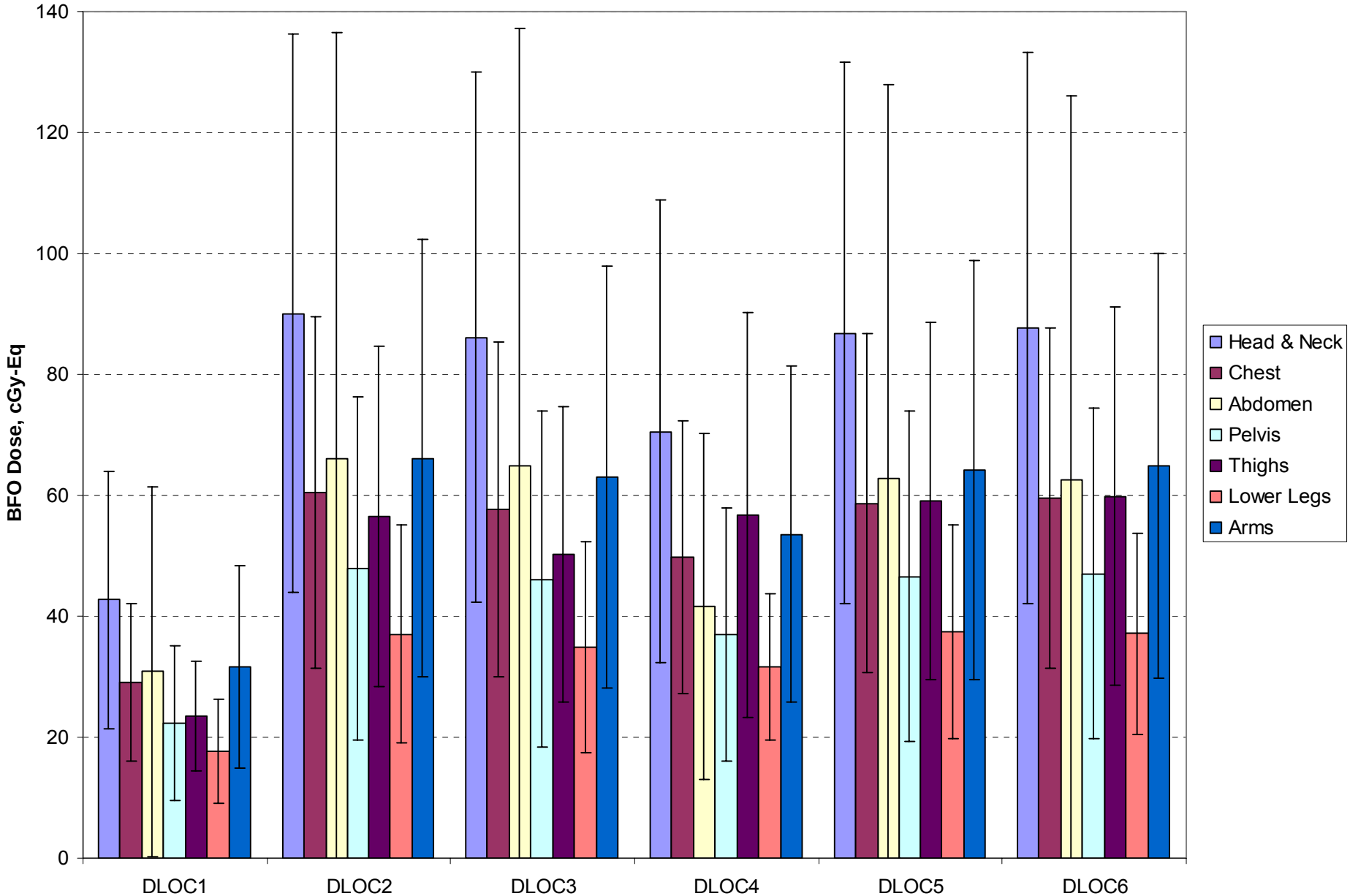
Body Regions for BFO Locations and Active Marrow Distributions in Adult (Cristy, 1981)

Region Number	Body Region	Location	Marrow Distribution
1	Head and Neck	Z= up to 11.34"	12.2%
2	Chest (Upper Torso)	Z=11.34" to 15.6"	26.1%
3	Abdomen (Mid Torso)	Z=15.6" to 27.0"	24.9%
4	Pelvis (Lower Torso)	Z=27.0" to 36.7"	33.4%
5	Thighs (Upper Legs)	Z=36.7" to 52.3"	3.4%
6	Lower Legs	Z=52.3" to 70"	n/a
7	Arms	Y<-6.9" for right arm; Y>6.9" for left arm	n/a

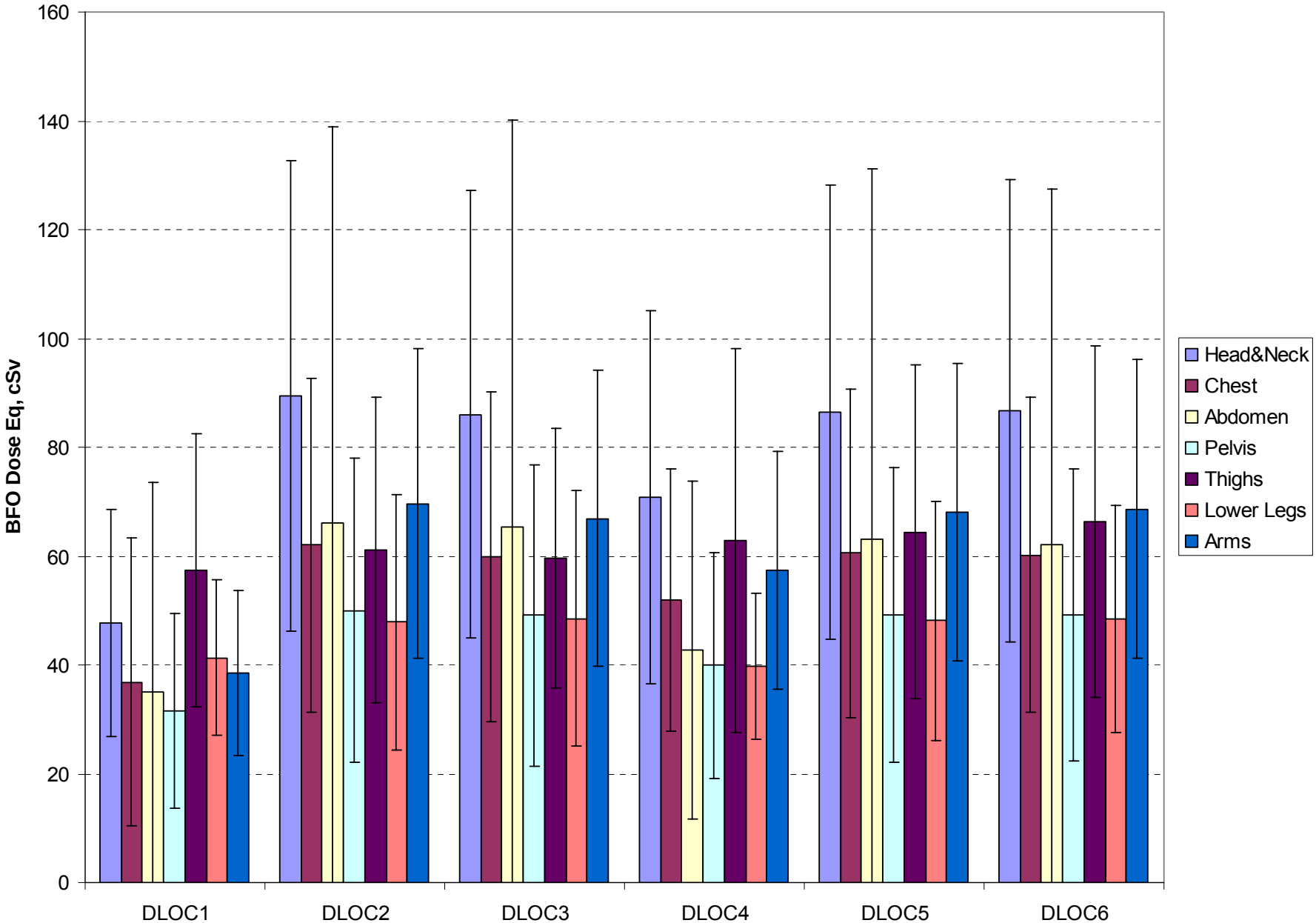
BFO Doses at Head and Neck Sites from 1972 SPE



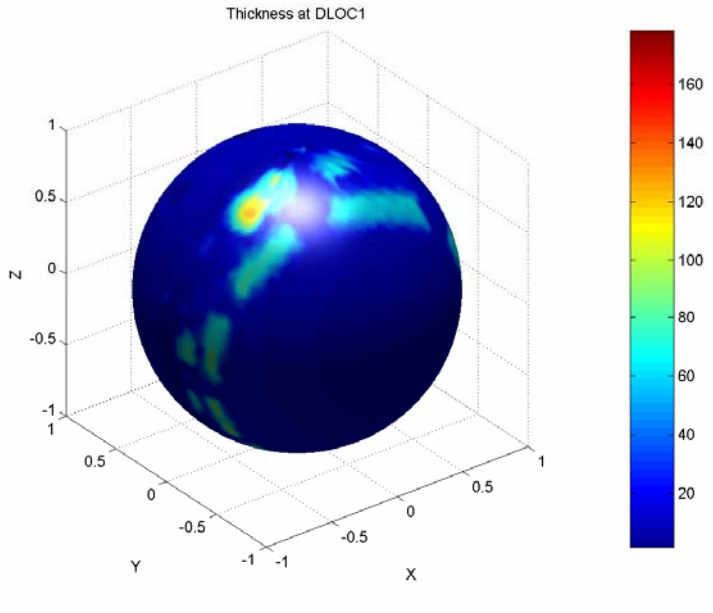
Average BFO Doses of All Regions at 6 DLOCs

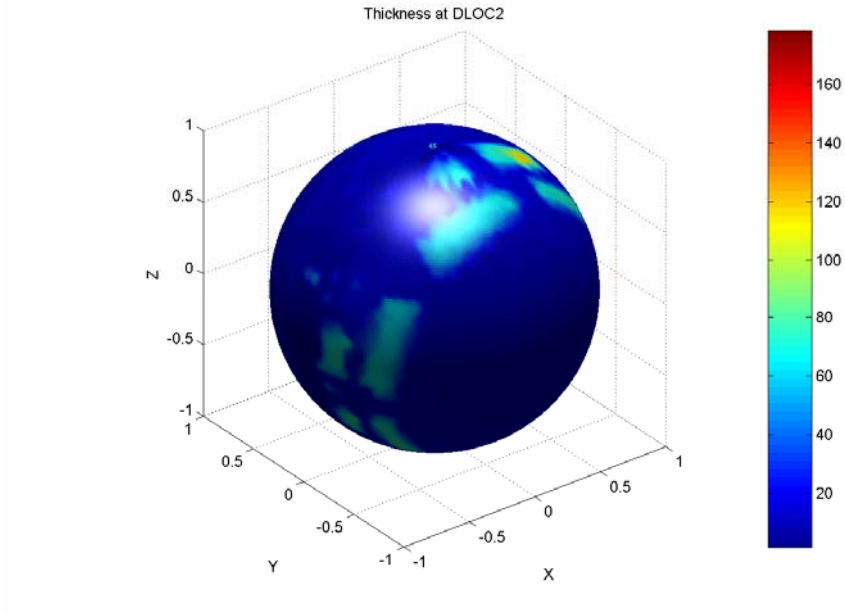


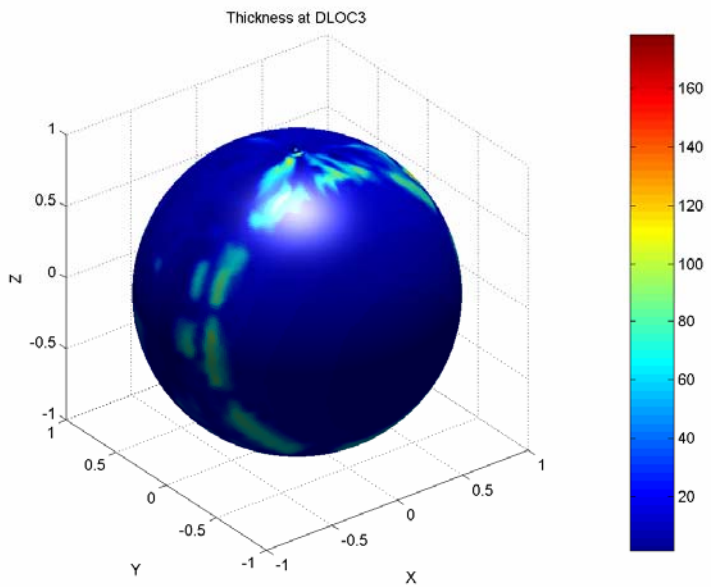
Average BFO Dose Eq of All Regions at 6 DLOCs

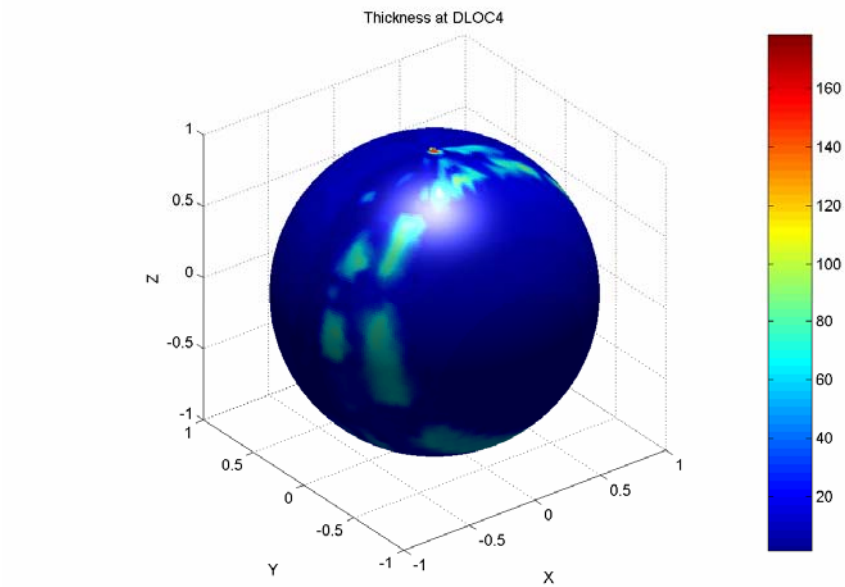


Shielding Distributions at 4 Locations of Spacecraft

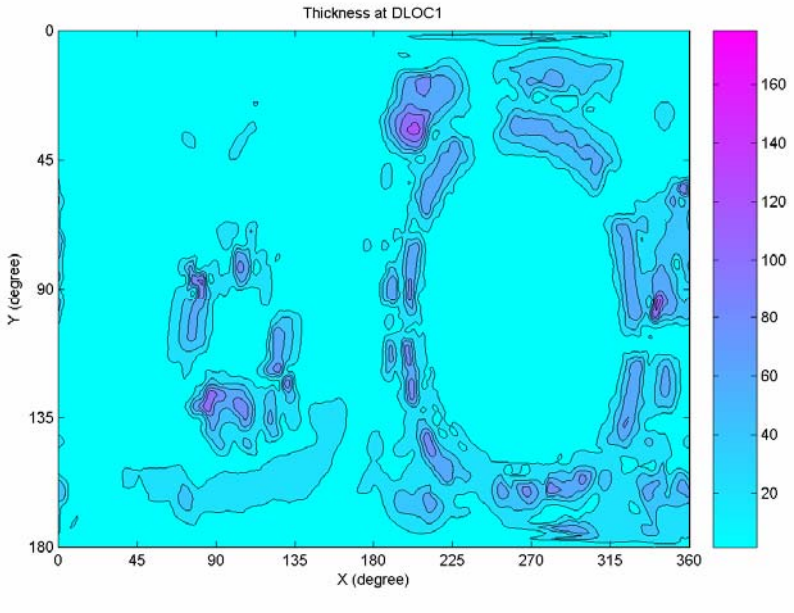


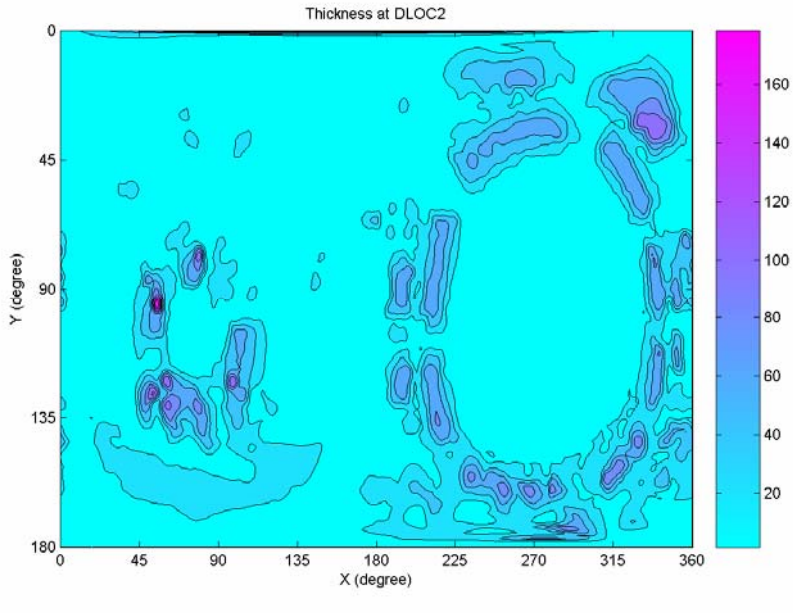


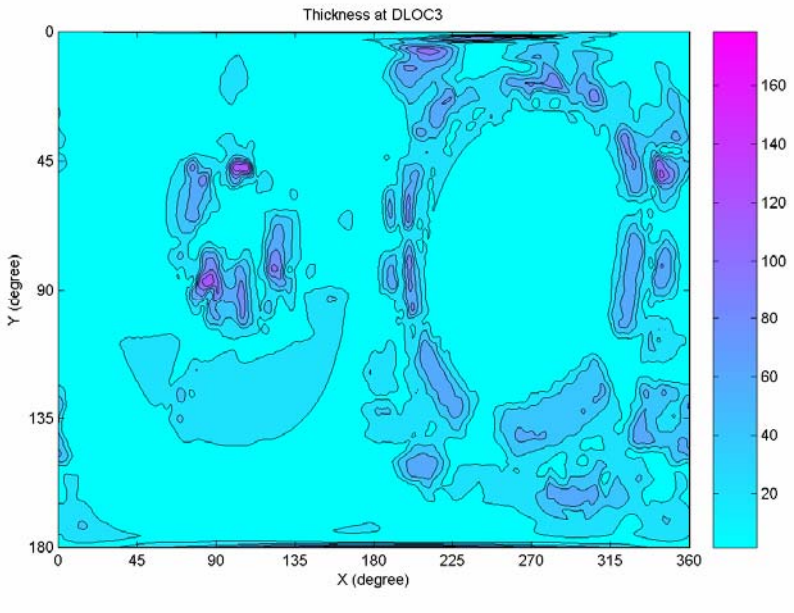


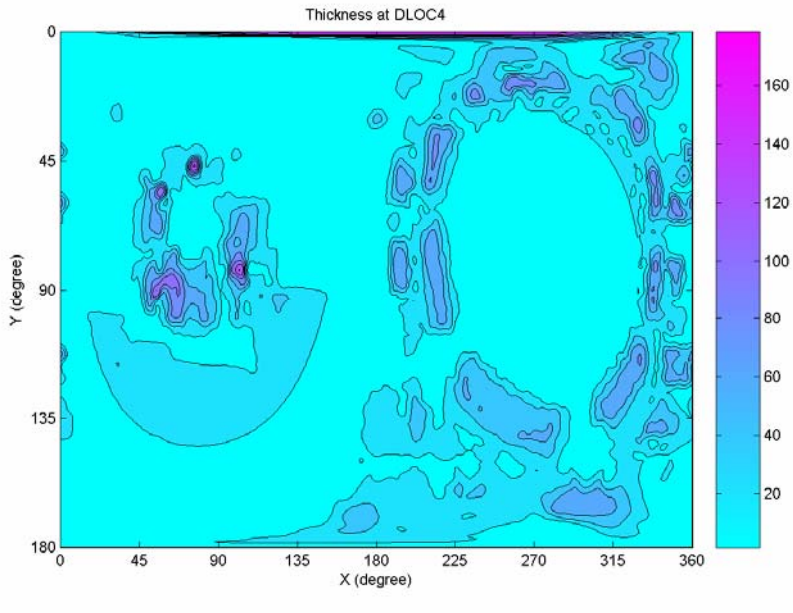


Shielding Distributions at 4 Locations of Spacecraft







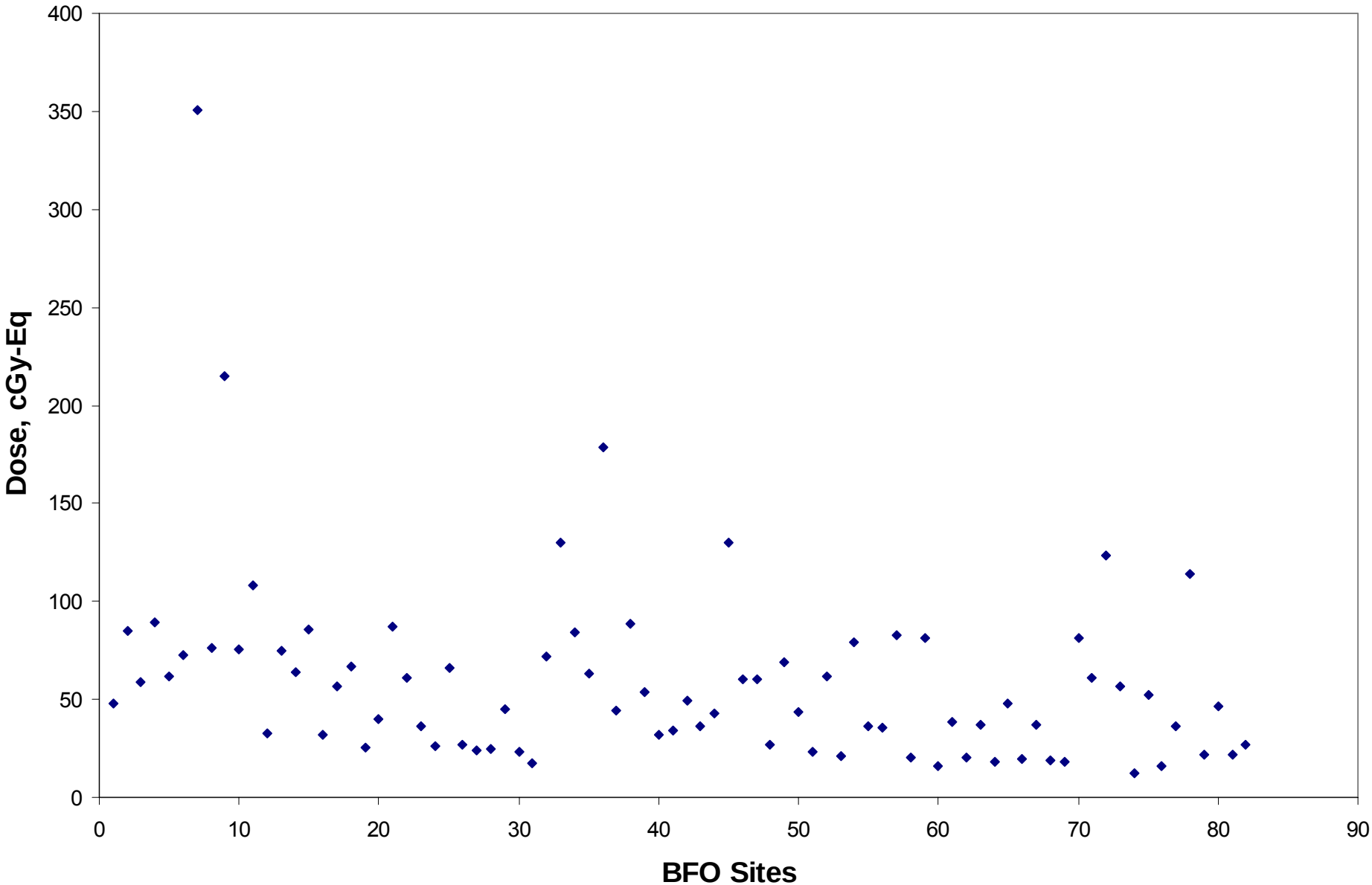


Requirements for Improved Estimation of Effective Doses for Radiation Cancer Risks

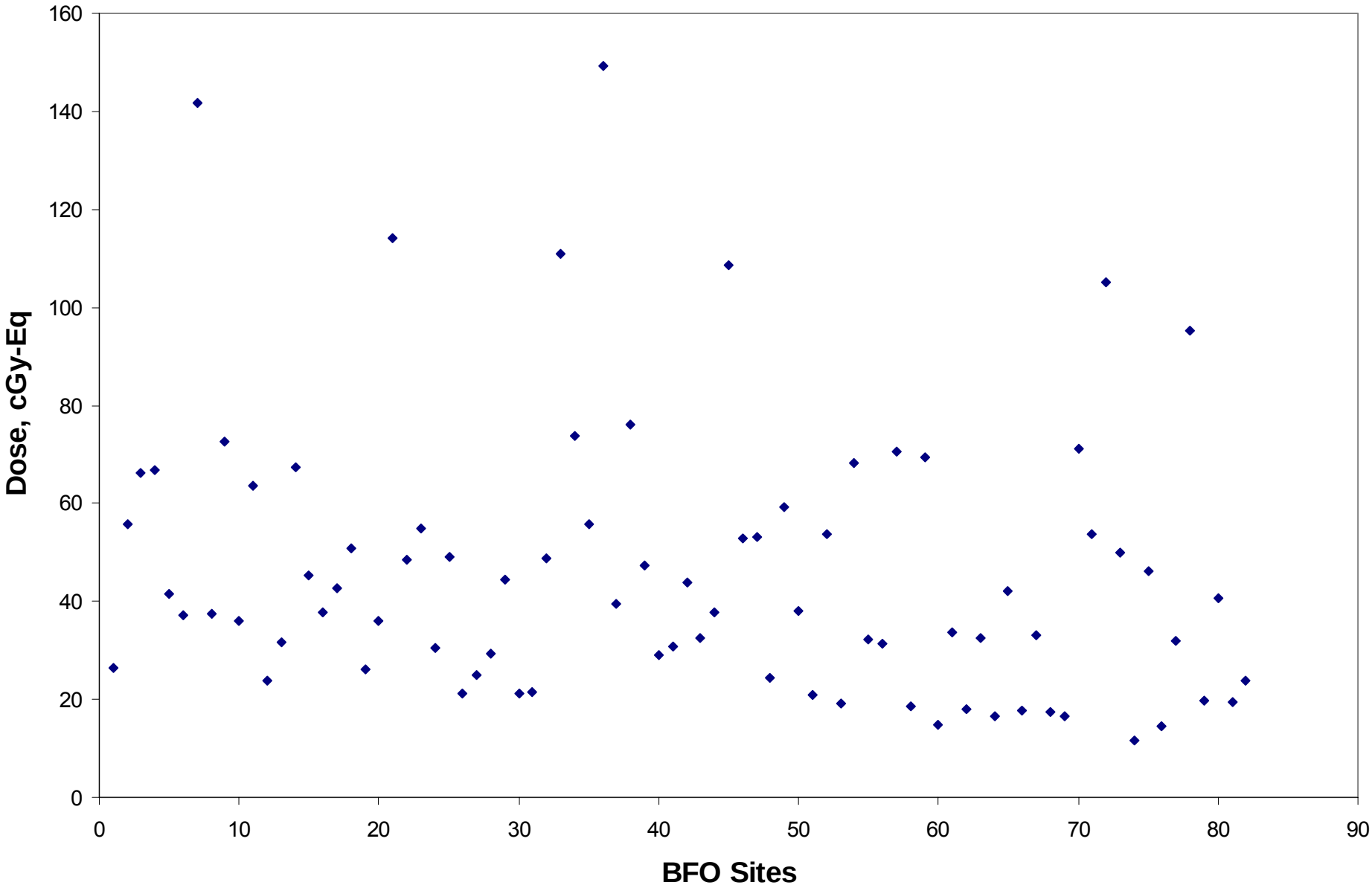
- Accurate shielding distributions obtained by ray tracers: Human and vehicle geometry correctly aligned
- Detailed distribution of bone marrow sites:
  - Head and neck, chest, abdomen, pelvis, and thighs
  - Age dependence of these sites
- Age- and gender-related tissue weighting factors
- Modified transport codes:
  - Vehicle-produced secondary neutrons
  - Improved environmental projection model for mission planning

Detailed Extra

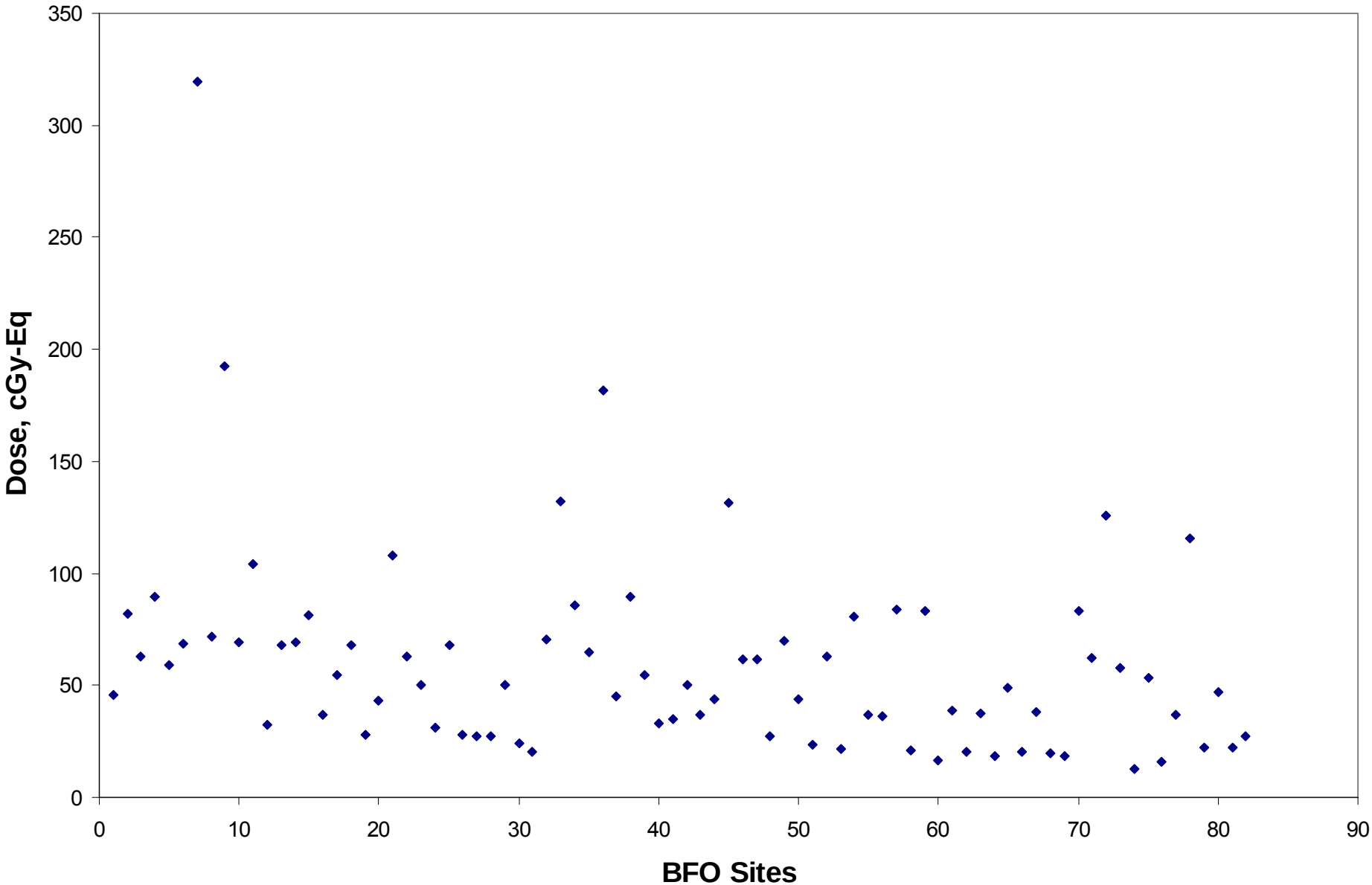
BFO Dose at DLOC3 from 1972 SPE



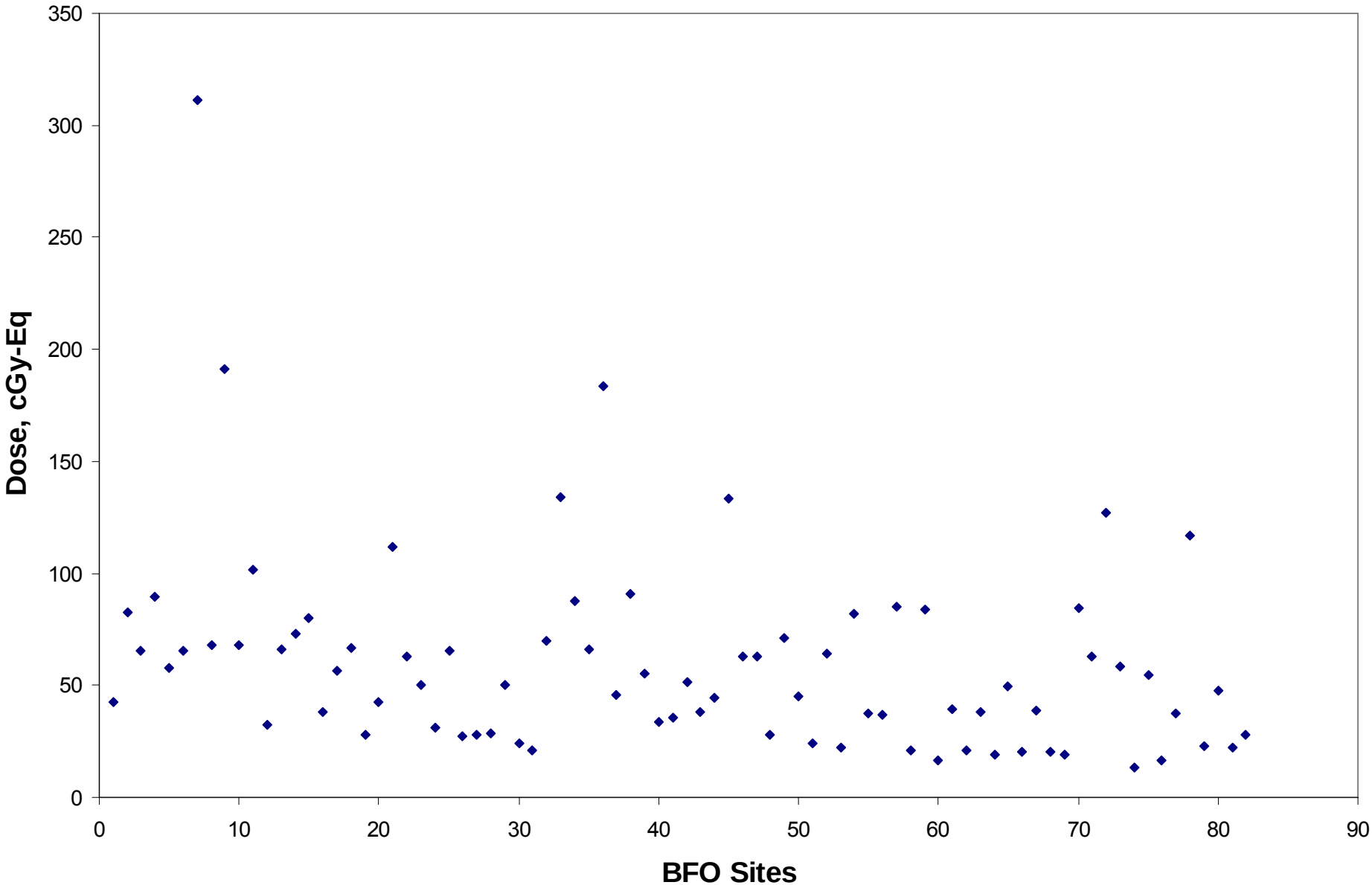
BFO Dose at DLOC4 from 1972 SPE



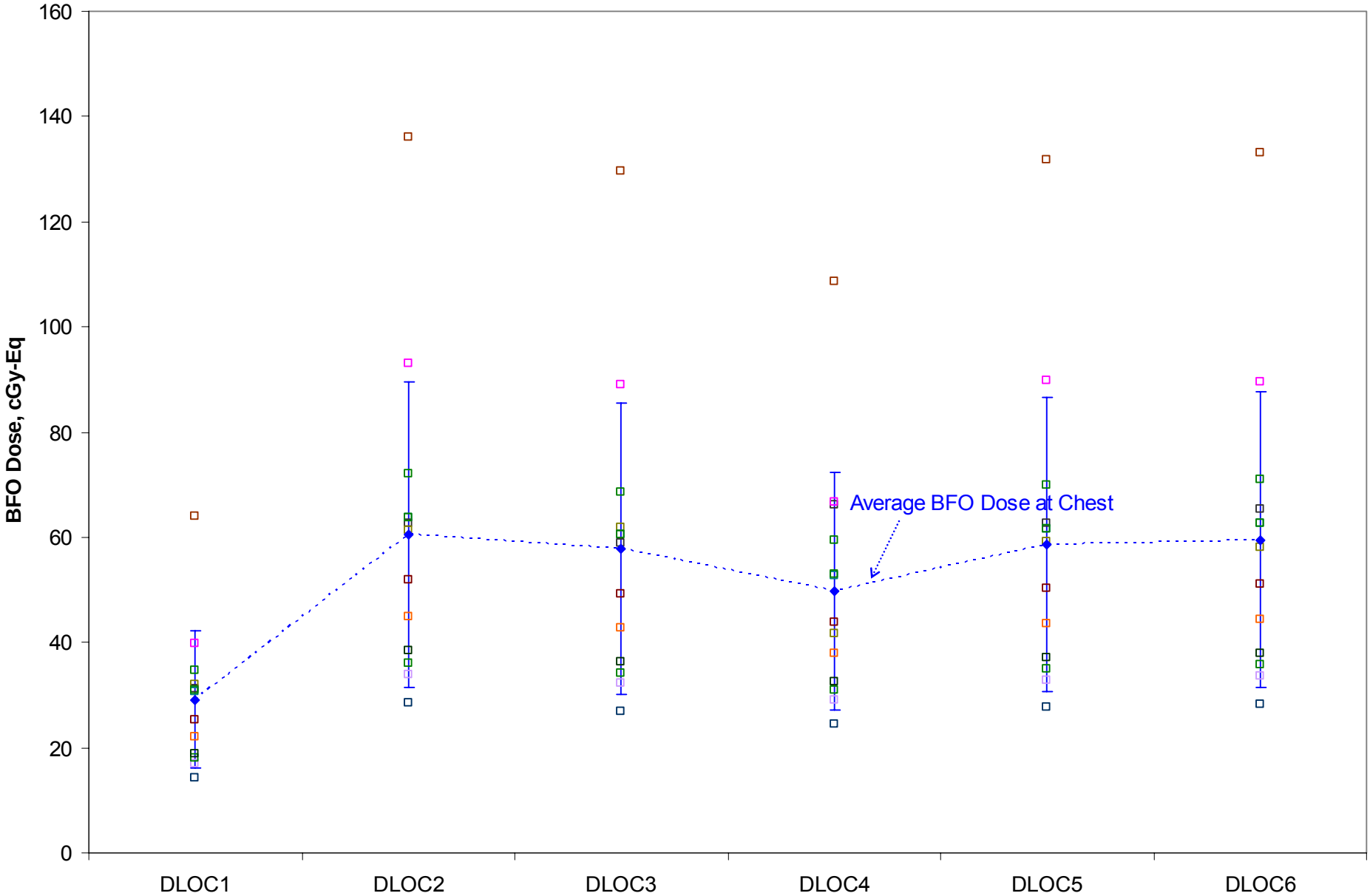
BFO Dose at DLOC5 from 1972 SPE



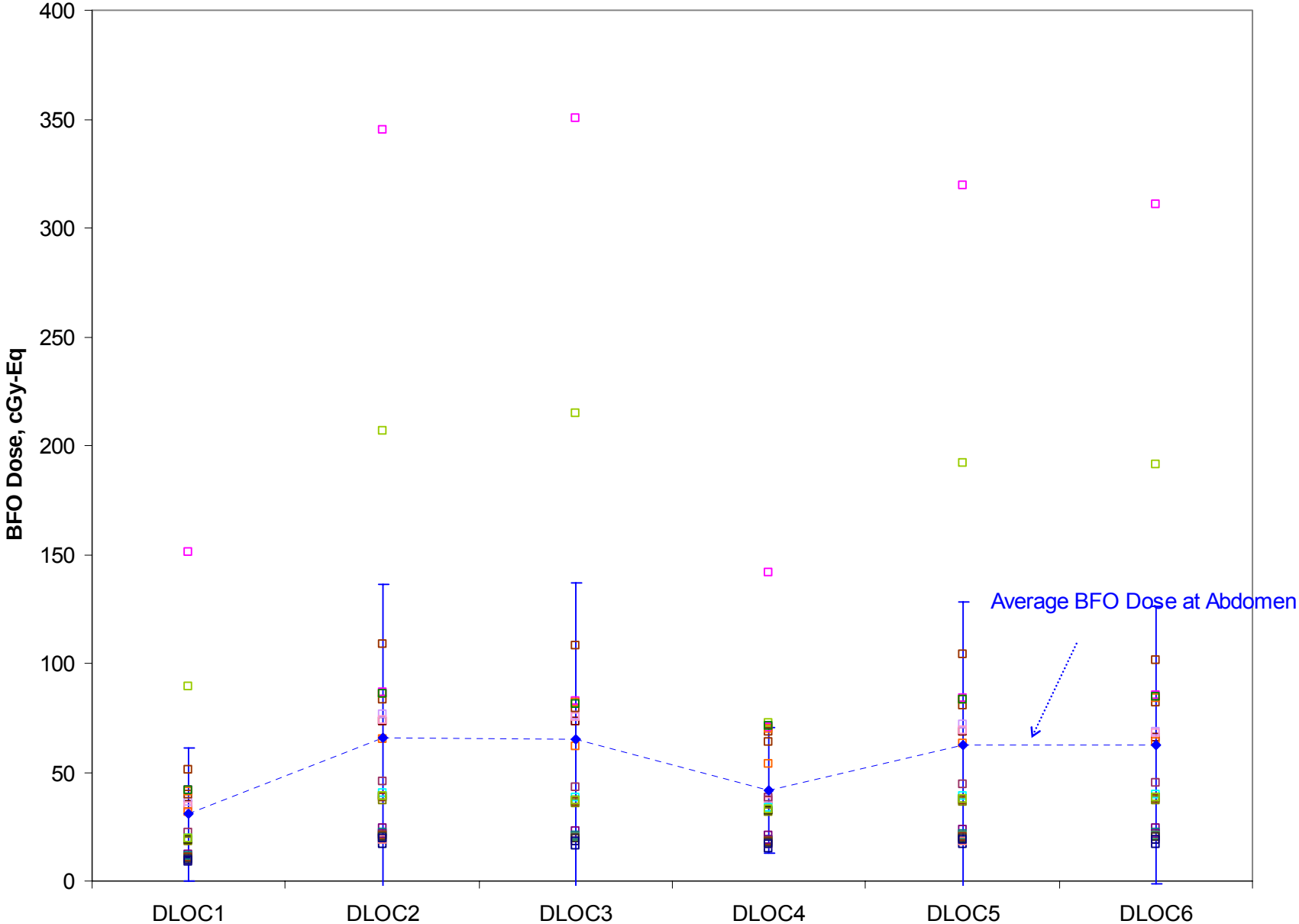
BFO Dose at DLOC6 from 1972 SPE



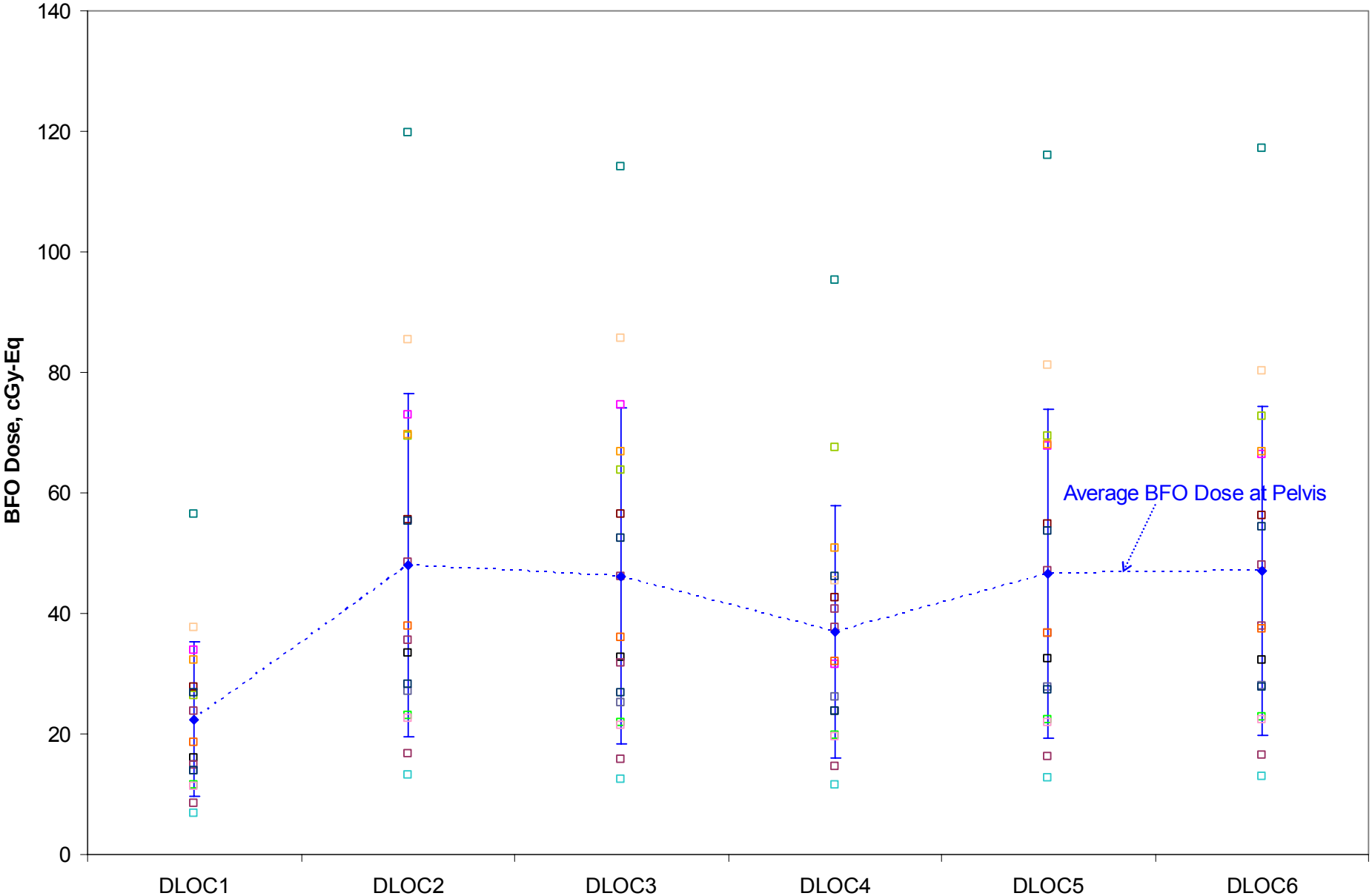
BFO Doses at Chest Sites from 1972 SPE



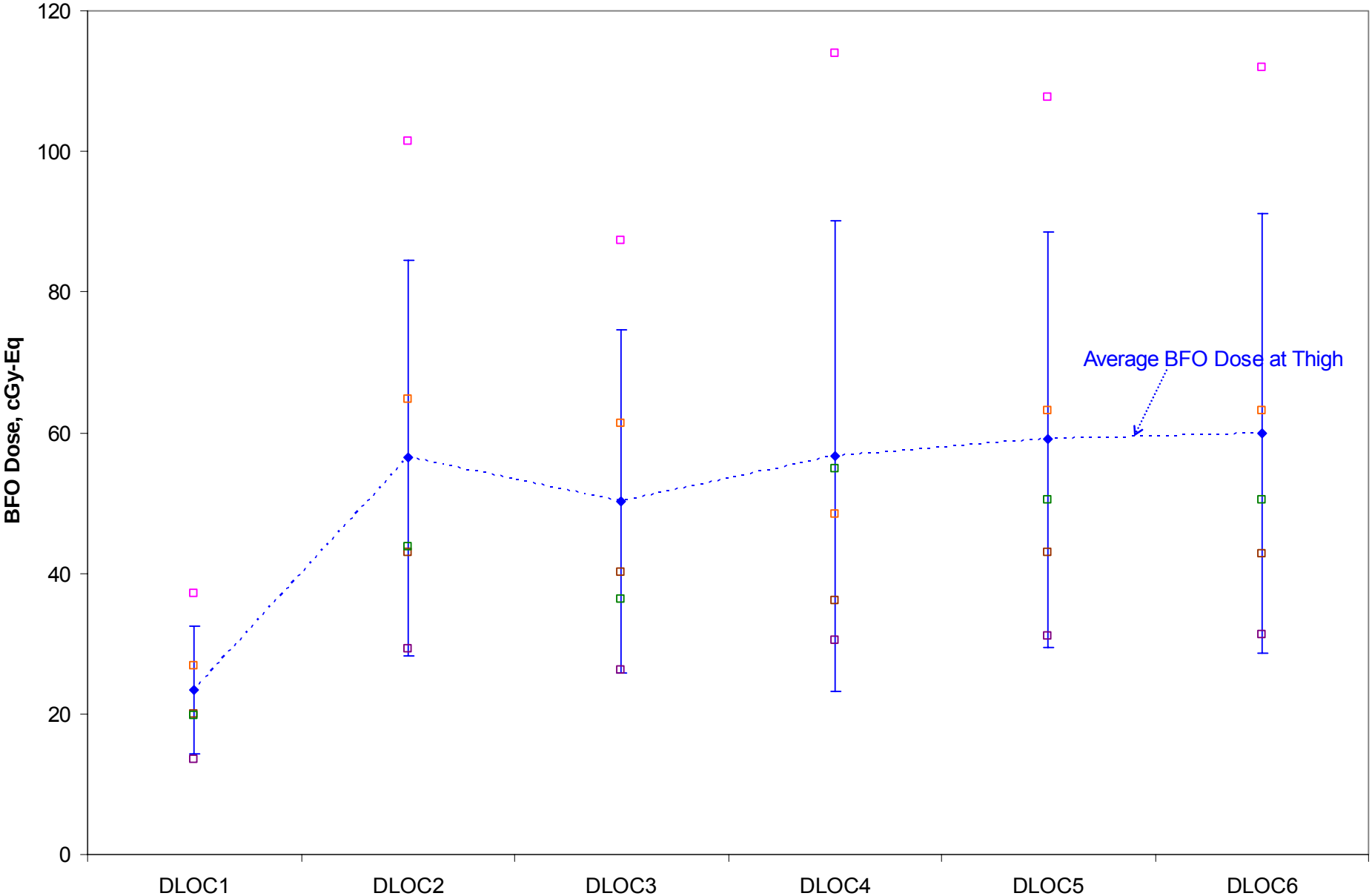
BFO Doses at Abdomen Sites from 1972 SPE



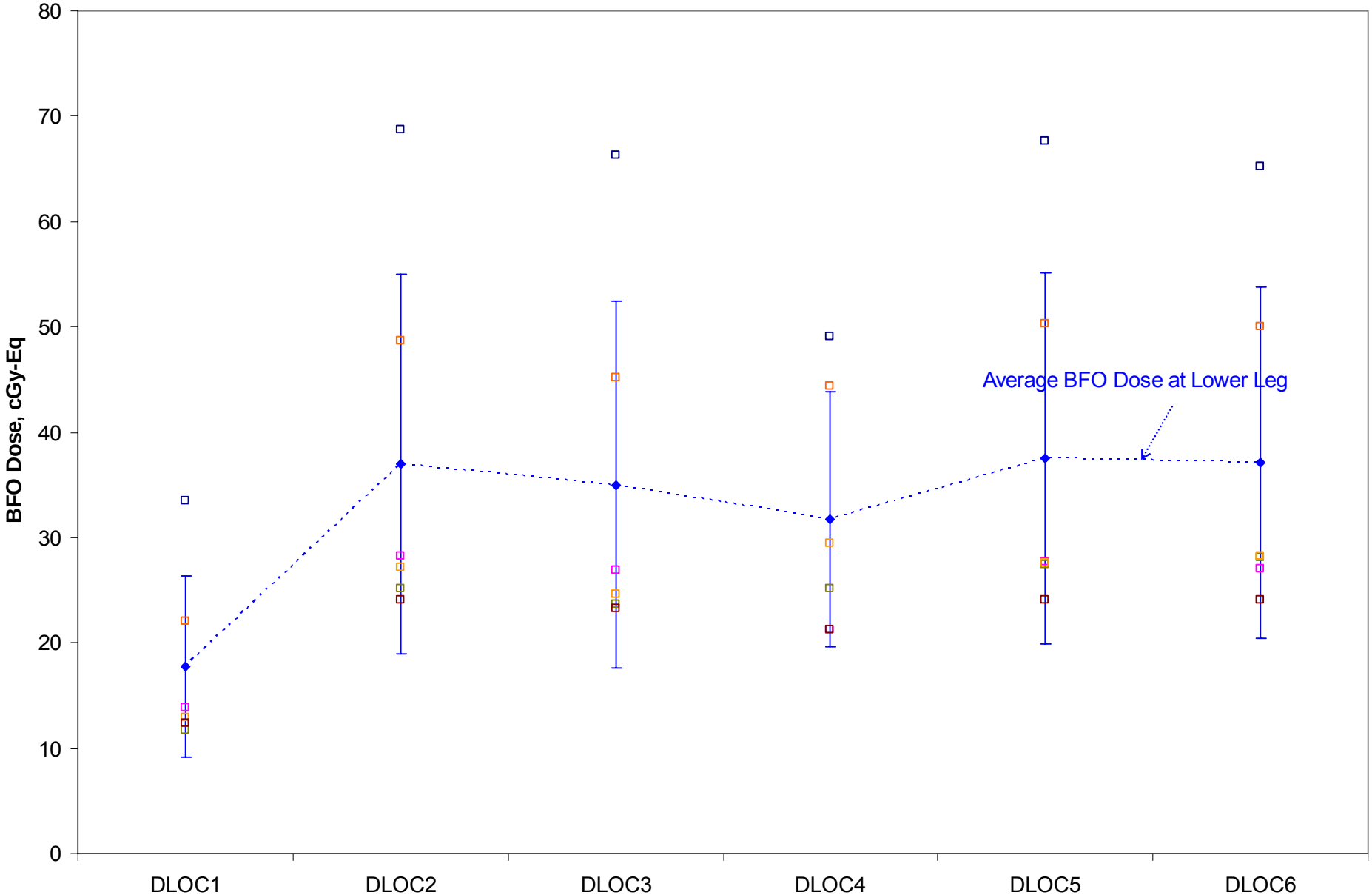
BFO Doses at Pelvis Sites from 1972 SPE



BFO Doses at Thigh Sites from 1972 SPE



BFO Doses at Lower Leg Sites from 1972 SPE



BFO Doses at Arm Sites from 1972 SPE