Comparisons of Carrington-Class Solar Particle Event Radiation Exposure Estimates utilizing the CAM, CAF, MAX, and FAX Human Body Models

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Young Professional Prize Nominee

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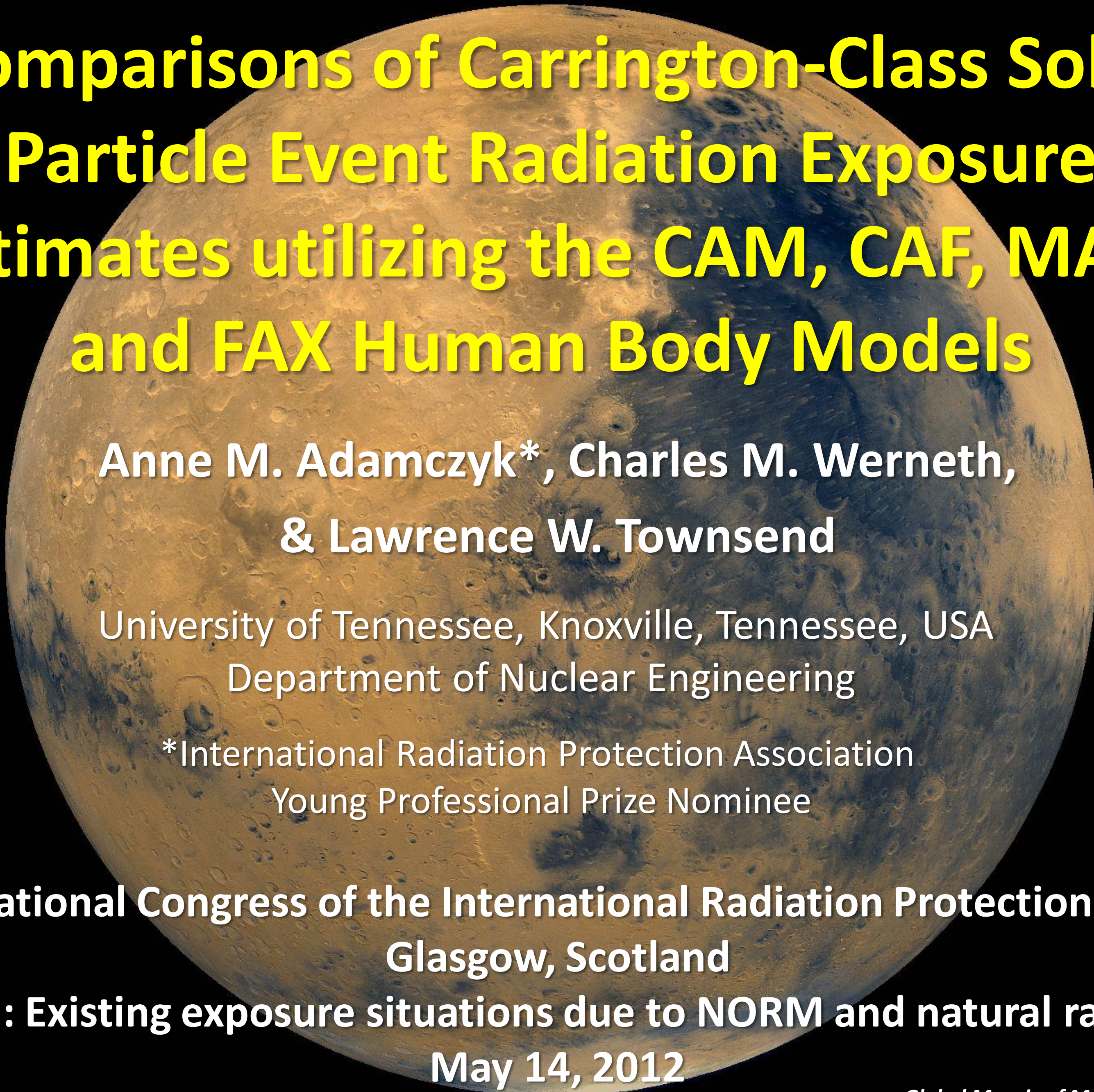

Global Mosaic of Mars – Syrtis Major Region
NASA / GSFC

Introduction

- Solar Particle Event (SPE) radiation estimates are made for male and female astronauts on the surface of Mars, comparable to the Carrington event of 1859.

- Exposures are estimated for aluminum shield areal densities similar to a spacesuit, surface lander, and permanent habitat at various altitudes.

- Exposure related quantities relevant for comparisons to NASA permissible exposure limits (PELs) are calculated using NASA's On-Line Tool for the Assessment of Radiation in Space (OLTARIS), https://oltaris.larc.nasa.gov/ .

- Comparisons of organ dose and effective dose are made between two types of human body models, since differences in the mass and location of various organs will affect radiation exposure quantities.

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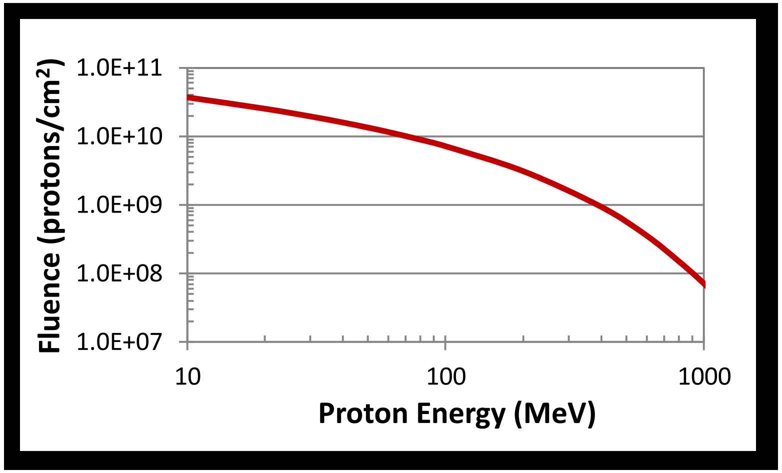
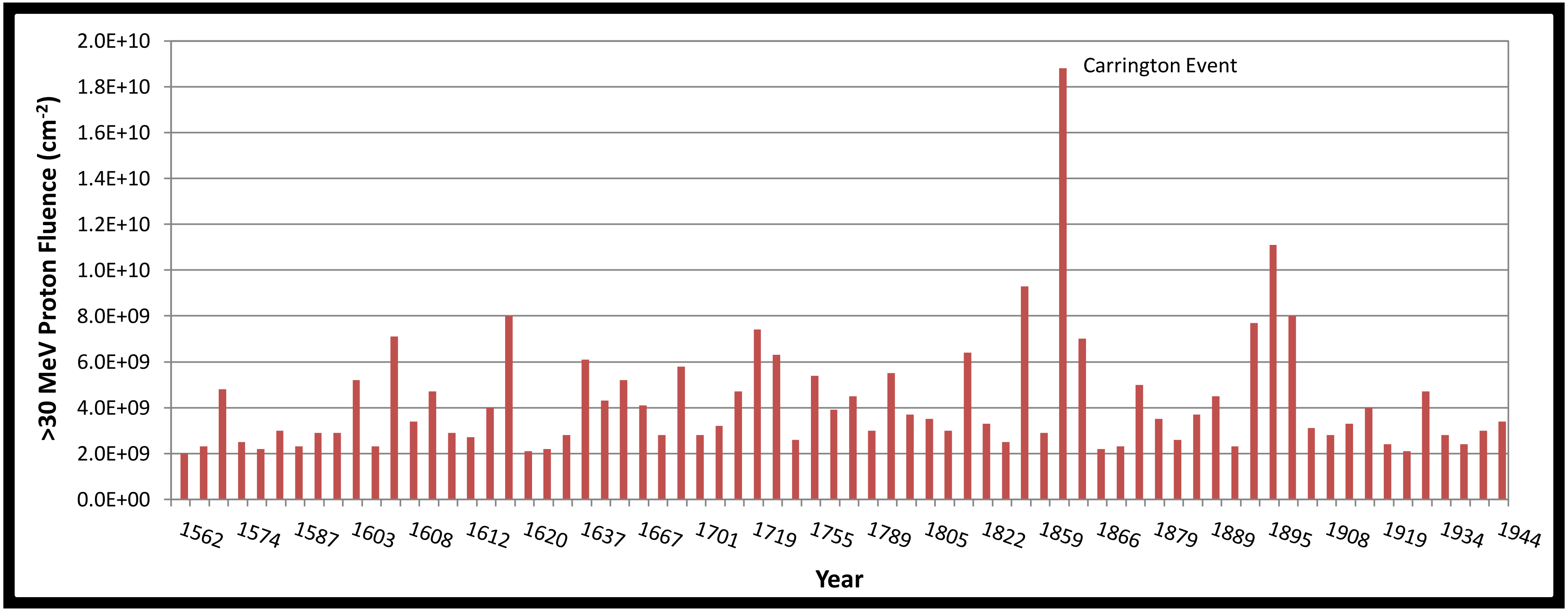
Environment

- The Carrington event of 1859 produced the largest estimated omni-directional integral fluence of protons >30 MeV (1.88×10^{10} cm^{-2}).
- The spectral character of the large, very hard, space age February 1956 SPE was used in combination with the fluence historical record of the Carrington event.



Proton fluence spectrum for the Band function parameterization of the February 1956 event normalized to the Carrington event.

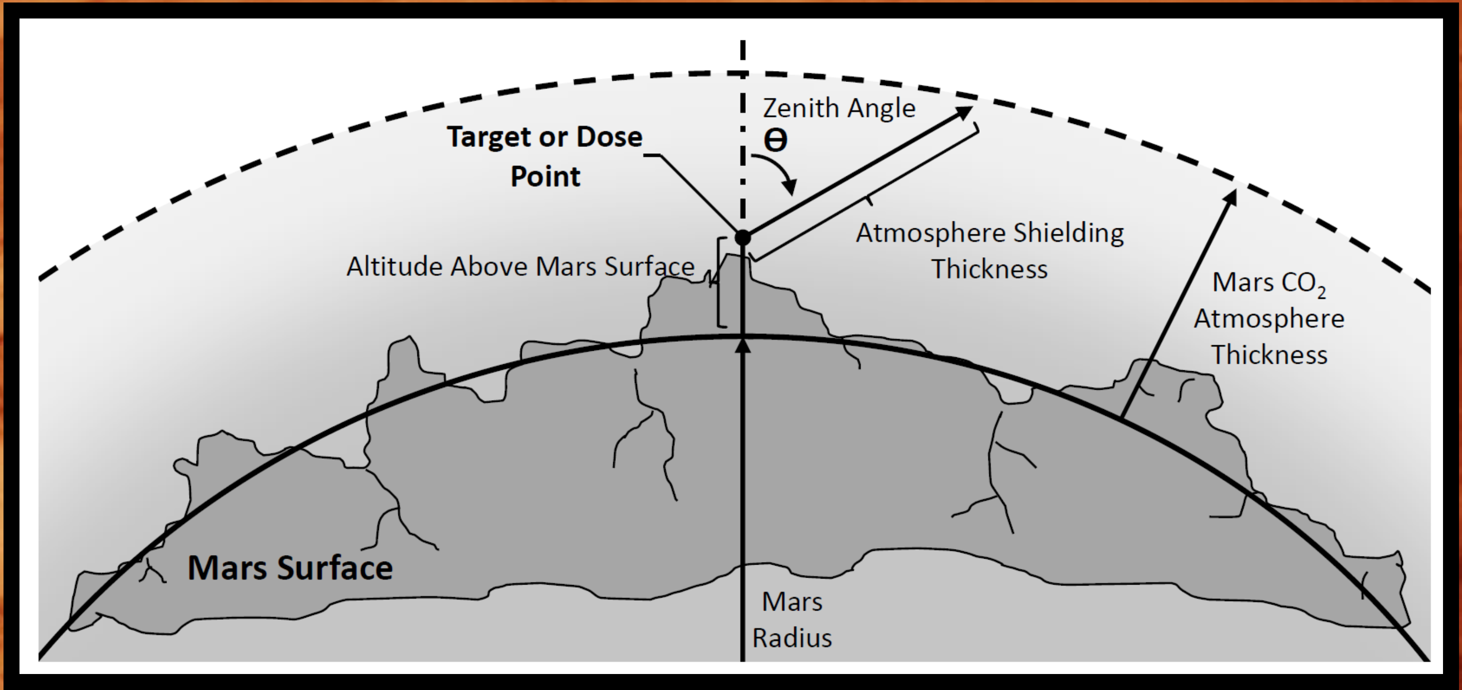
Greater than 30 MeV proton fluence events in the interval 1561-1950. Data from McCracken et al., J. Geophys. Res. 106 (2001) 21585.



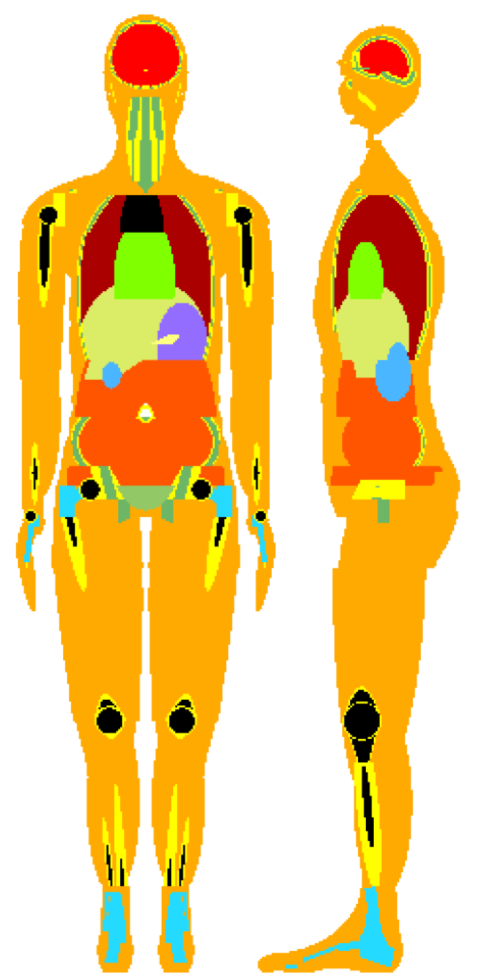
Particle Transport

The incident SPE proton spectrum is transported through:

1. The Mars pure CO_2 atmosphere (up to 300 g cm^{-2}).
   A spherically symmetric model is assumed using three areal densities:
   - Low density (16 g cm^{-2}) at the mean surface elevation, 0 km.
   - High density (22 g cm^{-2}) at the mean surface elevation, 0 km.
   - Low density (7 g cm^{-2}) at an altitude of 8 km.
2. The appropriate hemispherical aluminum shielding thickness (0.3, 5, or 40 g cm^{-2}).
3. The body thickness distribution of the organ/tissue of interest, using the space radiation transport code HZETRN (High charge (Z) and Energy TRaNsport).



Human Body Models

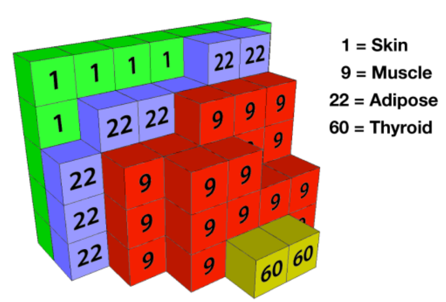

Cutaway view of CAM

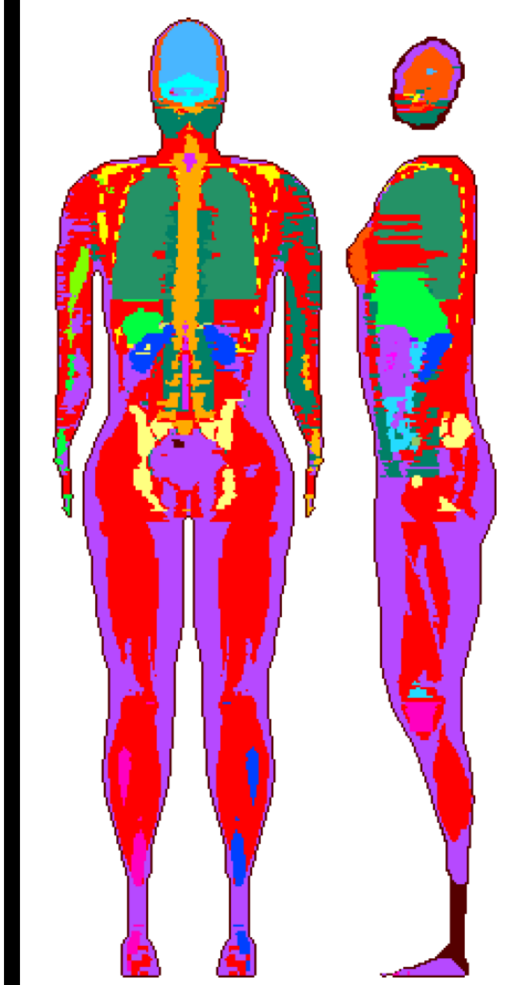
CAM / CAF

- Mathematical models based on quadric surfaces.
- Developed in 1973 (1992).
- Matched to USAF personnel.

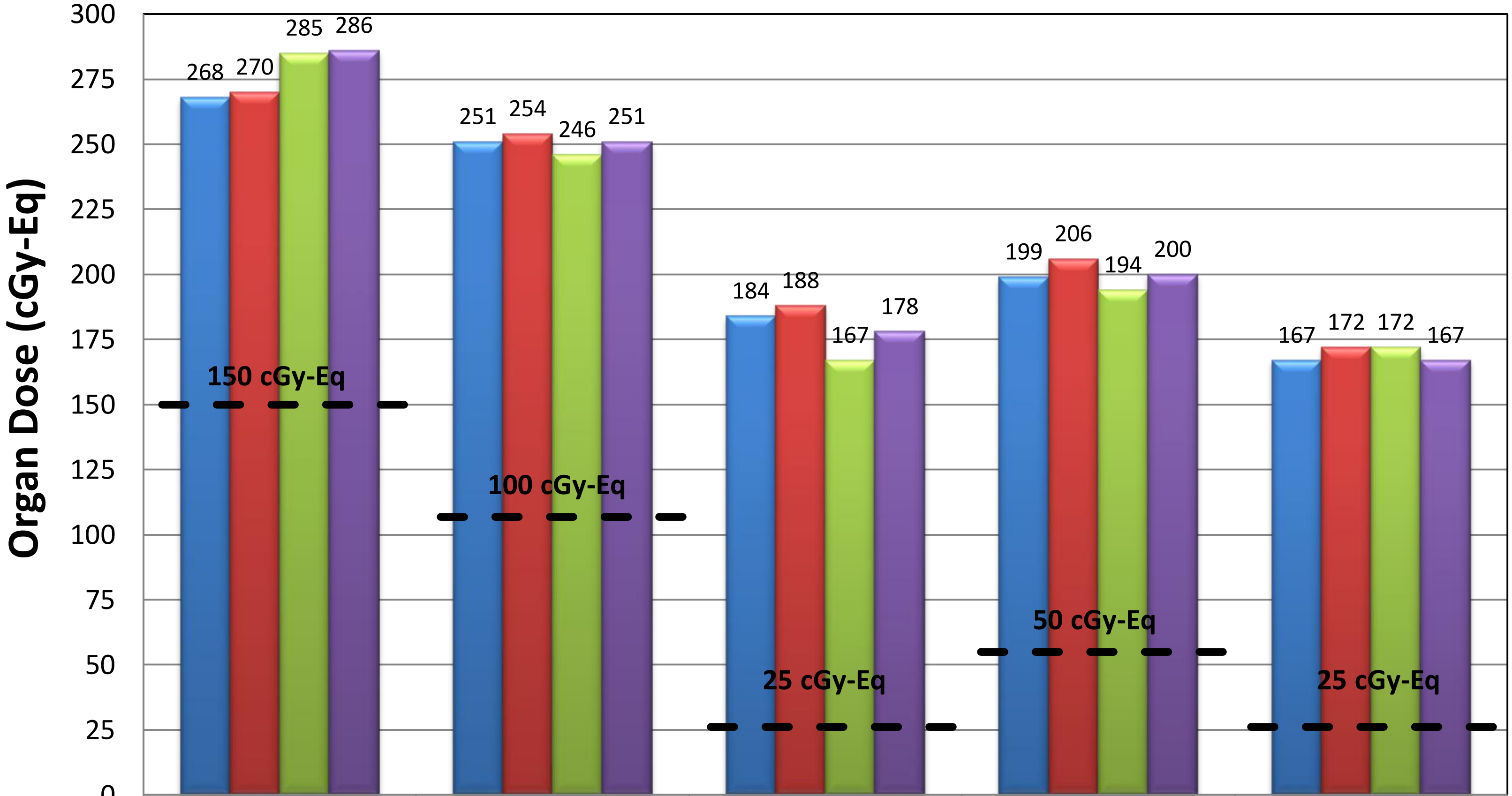
MAX / FAX

- Voxel models based on CT scans of human cadavers.
- Developed in 2003 (2004).
- Matched to ICRP reference male and female.




Cutaway view of FAX

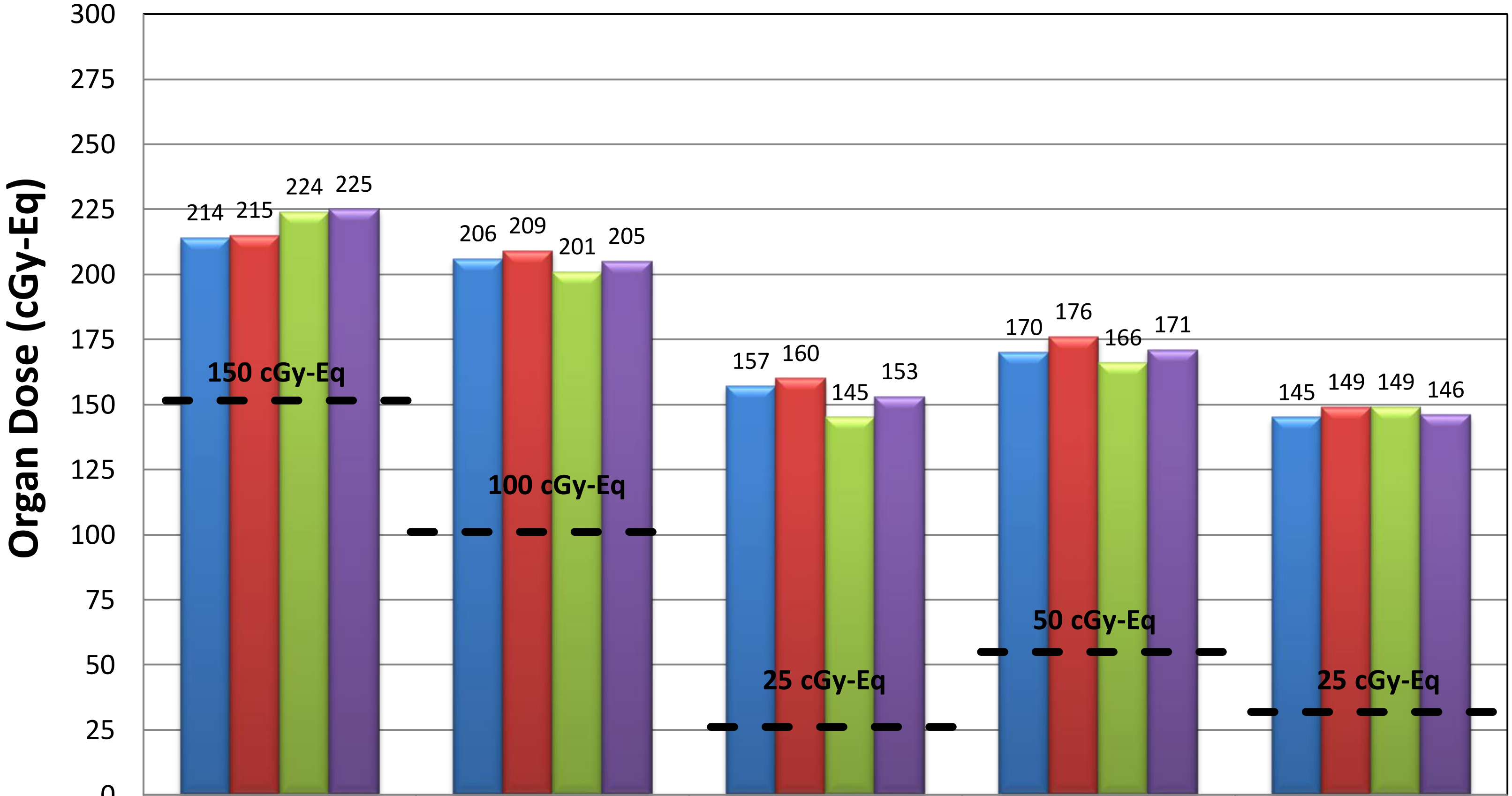
0.3 g cm^{-2} Aluminum Shield (Spacesuit)
Low density atmosphere at 8 km



	Skin	Lens	BFO	CNS	Heart
CAM	268	251	184	199	167
CAF	270	254	188	206	172
MAX	285	246	167	194	172
FAX	286	251	178	200	167

Note: 1 cGy = 0.01 Gy = 1 rad

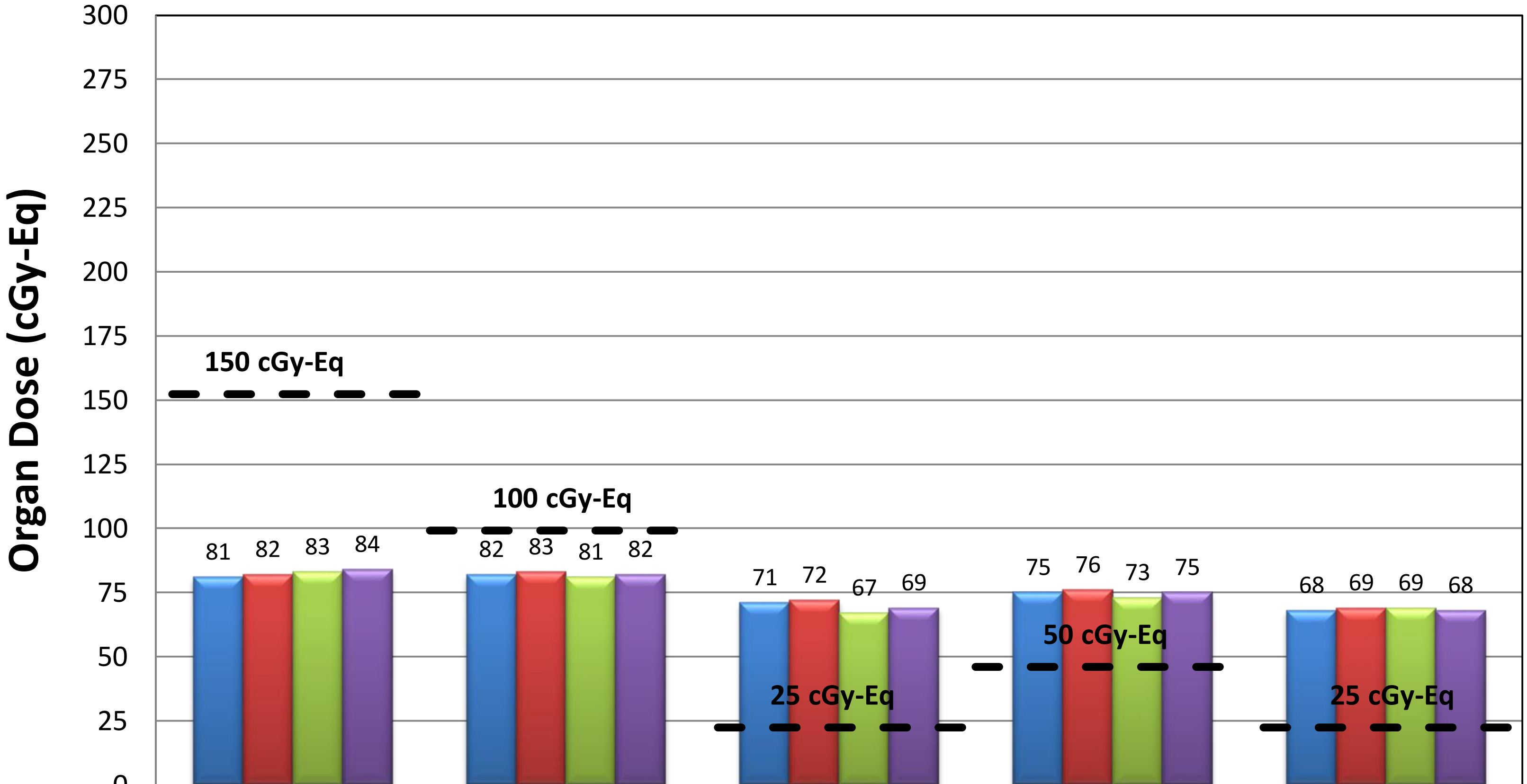
5 g cm^{-2} Aluminum Shield (Surface Lander)
Low density atmosphere at 8 km



	Skin	Lens	BFO	CNS	Heart
CAM	214	206	157	170	145
CAF	215	209	160	176	149
MAX	224	201	145	166	149
FAX	225	205	153	171	146

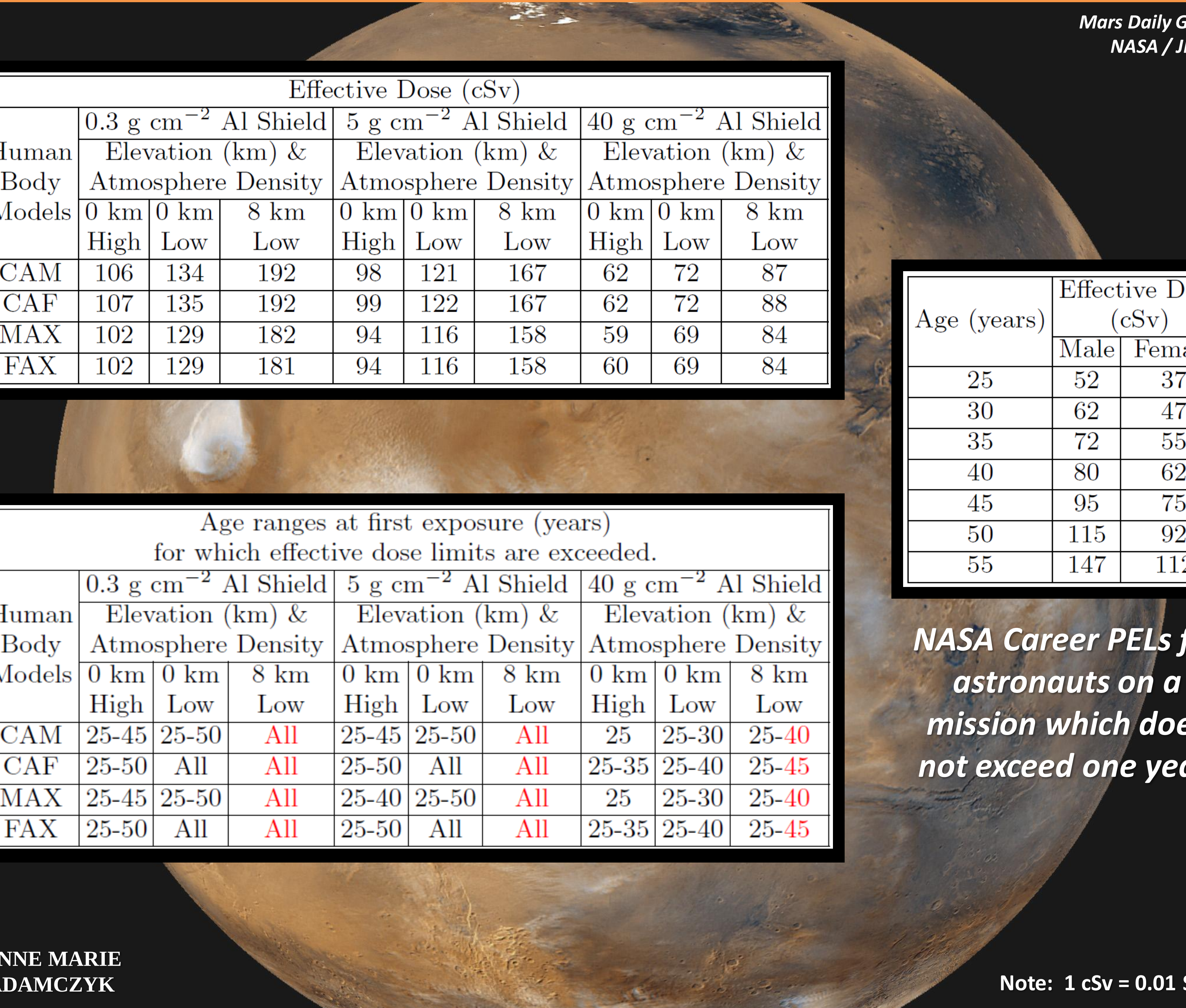
Note: 1 cGy = 0.01 Gy = 1 rad

40 g cm^{-2} Aluminum Shield (Permanent Habitat)
Low density atmosphere at 8 km



	Skin	Lens	BFO	CNS	Heart
CAM	81	82	71	75	68
CAF	82	83	72	76	69
MAX	83	81	67	73	69
FAX	84	82	69	75	68

Note: 1 cGy = 0.01 Gy = 1 rad



Mars Daily Global Image
NASA / JPL 1999

Effective Dose (cSv)									
Human Body Models	0.3 g cm^{-2} Al Shield			5 g cm^{-2} Al Shield			40 g cm^{-2} Al Shield		
	Elevation (km) & Atmosphere Density			Elevation (km) & Atmosphere Density			Elevation (km) & Atmosphere Density		
	0 km High	0 km Low	8 km Low	0 km High	0 km Low	8 km Low	0 km High	0 km Low	8 km Low
CAM	106	134	192	98	121	167	62	72	87
CAF	107	135	192	99	122	167	62	72	88
MAX	102	129	182	94	116	158	59	69	84
FAX	102	129	181	94	116	158	60	69	84

Age (years)	Effective Dose (cSv)	
	Male	Female
25	52	37
30	62	47
35	72	55
40	80	62
45	95	75
50	115	92
55	147	112

NASA Career PELs for astronauts on a mission which does not exceed one year.

Age ranges at first exposure (years) for which effective dose limits are exceeded.									
Human Body Models	0.3 g cm^{-2} Al Shield			5 g cm^{-2} Al Shield			40 g cm^{-2} Al Shield		
	Elevation (km) & Atmosphere Density			Elevation (km) & Atmosphere Density			Elevation (km) & Atmosphere Density		
	0 km High	0 km Low	8 km Low	0 km High	0 km Low	8 km Low	0 km High	0 km Low	8 km Low
CAM	25-45	25-50	All	25-45	25-50	All	25	25-30	25-40
CAF	25-50	All	All	25-50	All	All	25-35	25-40	25-45
MAX	25-45	25-50	All	25-40	25-50	All	25	25-30	25-40
FAX	25-50	All	All	25-50	All	All	25-35	25-40	25-45

Note: 1 cSv = 0.01 Sy = 1 rem

Conclusions

- The Mars atmosphere offers enough additional shielding to skew the differences between the two sets of human body models and the two types of phantoms for each gender.
- The resulting organ doses were found to generally exceed NASA 30 day PELs. More specifically, the BFO and heart doses substantially exceed the NASA 30 day PELs.
- Male and female astronauts older than 40 and 45 years, respectively, will not exceed effective dose NASA PELs when located in a permanent habitat.
- The conventional amount of shielding materials used in the construction of spacesuits and surface landers will not provide the radiation protection needed for an SPE comparable to the Carrington event of 1859. Radiation mitigation strategies will need to be employed to reduce the exposures to more acceptable levels.

Victoria Crater
NASA / JPL 2006

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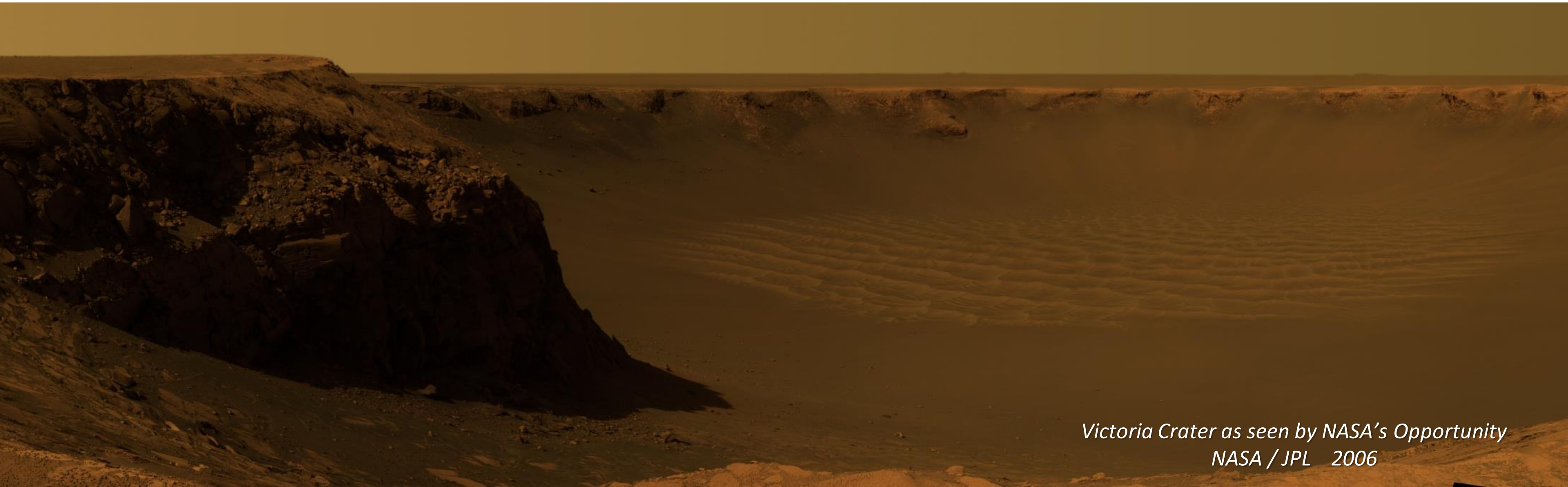

Victoria Crater as seen by NASA's Opportunity
NASA / JPL 2006

Galactic Cosmic Ray (GCR)

- Made up of heavy and light charged ions.
- Modulated by solar wind.
- Omni-present low intensity background radiation.
- The high energy particles have great penetrating power through shield materials, which makes GCRs difficult to shield.
- The 2004 Badhwar-O'Neill model is used to define the 1977 solar minimum GCR environment at 1 AU.

Solar Particle Event (SPE)

- SPEs are isolated events and consist of primarily protons.
- Large SPEs are rare, but can be lethal if not enough shielding is provided.
- Shielding mass is effective at reducing the intensity of the SPE environment.
- The King model of the August 1972 SPE is used, since it is the DSNE reference environment.
- SPEs vary in intensity and spectral shape, and are time dependent.

Environment

The Band function parameterization:

- A double power law in proton rigidity.
- Yields more reliable dose estimates than other commonly used proton spectral fitting methodologies.
- Based on actual solar proton data over the entire proton energy spectrum.
- More specifically, it is based on low and medium energy satellite data, as well as high energy ground level enhancement (GLE) data, out to ~10 GeV, measured from neutron monitors on Earth's surface.

Environment

The Band function parameterization is given by

$$\Phi(>R) = \begin{cases} \Lambda R^{-\gamma_1} \exp\left(-\dfrac{R}{R_0}\right), \\ \qquad\qquad \mathit{for}\ R \le (\gamma_2 - \gamma_1) R_0 \\ \Lambda R^{-\gamma_2} \left[(\gamma_2 - \gamma_1) R_0\right]^{(\gamma_2 - \gamma_1)} \exp(\gamma_1 - \gamma_2), \\ \qquad\qquad \mathit{for}\ R \ge (\gamma_2 - \gamma_1) R_0 \end{cases}$$

where Φ is the proton fluence.

R is the particle rigidity (momentum per unit charge).

Λ is the total integral fluence.

γ_1, γ_2 are spectral indices.

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OLTARIS

- OLTARIS is a World Wide Web based tool that can be used to assess the effects of space radiation on humans and electronics in space mission architectural elements, such as spacecraft, habitats, rovers, and spacesuits.
- Users can input their own complicated geometry models into OLTARIS for analysis.
- In order to calculate the radiation environment at a particular location in a habitat using OLTARIS, the habitat shielding model must be ray-traced.
- Ray-tracing is performed by dividing the volume surrounding the dose point into a number of equal solid angle elements and calculating the thickness of each type of shielding along a ray through a solid angle element.

OLTARIS
On-Line Tool for the Assessment of Radiation In Space

Computations performed with OLTARIS utilize the following modules:

ENVIRONMENTAL MODULE

- Where the external radiation environment is defined.
- User can choose from six different types of environments – free space GCR, free space SPE, lunar surface GCR, lunar surface SPE, Earth orbit, or Jupiter's icy moon Europa.
- Albedo neutrons are not included in the current OLTARIS lunar environment modules.

TRANSPORT MODULE

- Used to propagate particles of an ambient space radiation environment, chosen by the user, through a combination of a vehicle, shielding, and/or tissue.
- Uses the deterministic space radiation transport code HZETRN, which has been used extensively for both GCR and SPE dosimetric calculations in complex geometries.

REPSONSE MODULE

- Allows users to calculate dose, dose equivalent, linear energy transfer, and/or whole body effective dose.
- If the effective dose response function is chosen, organ averaged dose equivalent values are also produced for the organs and tissue types utilized in the effective dose calculation.
- For effective and organ averaged dose equivalent calculations, the user can select from four human body models – CAM, CAF, MAX, or FAX.

OLTARIS
On-Line Tool for the Assessment of Radiation In Space

Transport Methods

- Transport methods are based on the latest version of the deterministic space radiation transport code HZETRN (High change (Z) and Energy TRaNsport), namely HZETRN2010.

- HZETRN was developed at NASA Langley Research Center and accurately models the transport of all incident charged ions and their nuclear reaction products.

- For this application, only incident protons are transported, as well as their nuclear reaction products, namely, protons, neutrons, deuterons, tritons, helions, and alpha particles.

- The transport algorithms of HZETRN provide approximate solutions to the time independent linear Boltzmann transport equation and utilize the straight ahead approximation and the continuous slowing down approximation.

- An advantage of the HZETRN transport algorithm is its computational speed. Consequently, it has been utilized extensively for both GCR and SPE dosimetric calculations using complex geometries.

Organ Dose

- Organ Dose (*D*) is calculated by

$$D[cGy - Eq] = D[cGy] \times RBE$$

where $D[cGy]$ is the organ dose given in units of cGy.

RBE is the Relative Biological Effectiveness value, which accounts for the ability of some types of radiations to produce more short term and non-cancer damage than others for the same dose.

- An RBE value of 1.5 was assumed, as recommended by NCRP Report 132.

Exposure Limits

- NASA Standard 3001, "NASA Space Flight Human Standard, Volume 1: Crew Health " defines career cancer risk limits for space radiation exposure and dose limits for non–cancer effects.
- The permissible exposure limit for cancer risk is defined such that an astronaut's Risk of Exposure Induced Death (REID) must not exceed three percent. NASA must assure that this risk is not exceeded at a ninety-five percent confidence level.
- NASA is required to insure that the principle of ALARA (As Low As Reasonably Achievable) is followed. This requirement ensures that these limits are not treated as "tolerance values". CxP 70024 states that, "the protection from radiation exposure is ALARA when the expenditure of further resources would be unwarranted by the reduction in exposure that would be achieved".

Skin Dose (cGy-Eq)

Organ	30 day limit (cGy-Eq)	1 Year Limit (cGy-Eq)	Career (cGy-Eq)
Skin	**150**	300	400

Skin Dose (cGy-Eq)									
Human Body Models	$0.3\ g\ cm^{-2}$ Al Shield			$5\ g\ cm^{-2}$ Al Shield			$40\ g\ cm^{-2}$ Al Shield		
	Elevation (km) & Atmosphere Density			Elevation (km) & Atmosphere Density			Elevation (km) & Atmosphere Density		
	0 km High	0 km Low	8 km Low	0 km High	0 km Low	8 km Low	0 km High	0 km Low	8 km Low
CAM	118	**161**	**268**	102	137	**214**	50	62	81
CAF	119	**162**	**270**	103	138	**215**	51	62	82
MAX	122	**169**	**285**	105	142	**224**	51	63	83
FAX	123	**169**	**286**	106	143	**225**	51	63	84

Lens Dose (cGy-Eq)

Organ	30 day limit (cGy-Eq)	1 Year Limit (cGy-Eq)	Career (cGy-Eq)
Lens	**100**	200	400

Lens Dose (cGy-Eq)									
Human Body Models	$0.3\ g\ cm^{-2}$ Al Shield			$5\ g\ cm^{-2}$ Al Shield			$40\ g\ cm^{-2}$ Al Shield		
	Elevation (km) & Atmosphere Density			Elevation (km) & Atmosphere Density			Elevation (km) & Atmosphere Density		
	0 km High	0 km Low	8 km Low	0 km High	0 km Low	8 km Low	0 km High	0 km Low	8 km Low
CAM	**116**	**158**	**251**	**102**	**135**	**206**	52	63	82
CAF	**117**	**158**	**254**	**103**	**137**	**209**	52	64	83
MAX	**114**	**154**	**246**	100	**132**	**201**	51	62	81
FAX	**116**	**157**	**251**	**101**	**135**	**205**	51	63	82

BFO Dose (cGy-Eq)

Organ	30 day limit (cGy-Eq)	1 Year Limit (cGy-Eq)	Career (cGy-Eq)
BFO	25	50	N/A

BFO Dose (cGy-Eq)									
Human Body Models	$0.3\ g\ cm^{-2}$ Al Shield			$5\ g\ cm^{-2}$ Al Shield			$40\ g\ cm^{-2}$ Al Shield		
	Elevation (km) & Atmosphere Density			Elevation (km) & Atmosphere Density			Elevation (km) & Atmosphere Density		
	0 km High	0 km Low	8 km Low	0 km High	0 km Low	8 km Low	0 km High	0 km Low	8 km Low
CAM	94	123	184	84	108	157	45	54	71
CAF	96	126	188	86	111	160	46	55	72
MAX	88	114	167	79	101	145	43	52	67
FAX	92	120	178	83	106	153	44	53	69

CNS Dose (cGy-Eq)

Organ	30 day limit (cGy-Eq)	1 Year Limit (cGy-Eq)	Career (cGy-Eq)
CNS	50	100	150

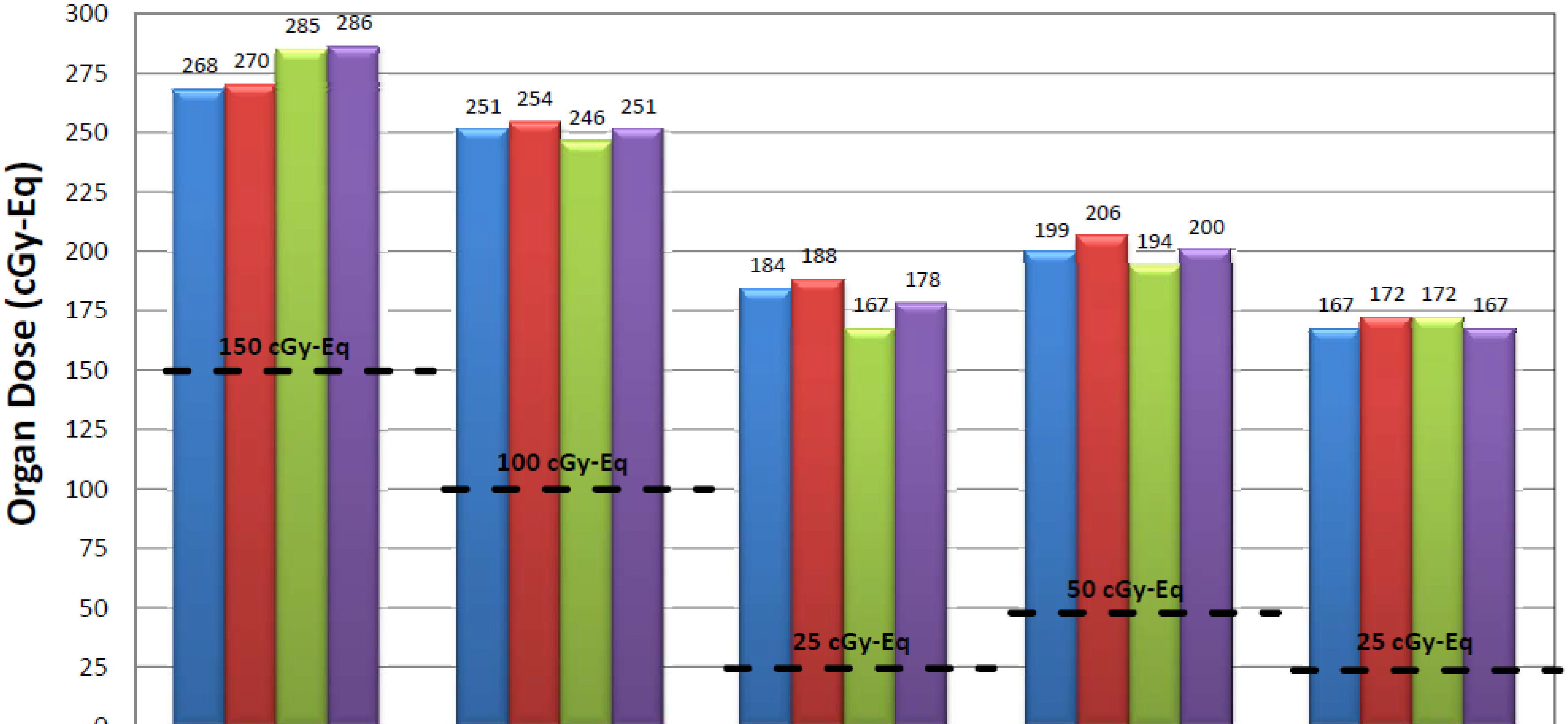
CNS Dose (cGy-Eq)									
Human Body Models	$0.3\ g\ cm^{-2}$ Al Shield			$5\ g\ cm^{-2}$ Al Shield			$40\ g\ cm^{-2}$ Al Shield		
	Elevation (km) & Atmosphere Density			Elevation (km) & Atmosphere Density			Elevation (km) & Atmosphere Density		
	0 km High	0 km Low	8 km Low	0 km High	0 km Low	8 km Low	0 km High	0 km Low	8 km Low
CAM	101	133	199	91	117	170	48	58	75
CAF	103	137	206	93	121	176	49	59	76
MAX	100	130	194	89	115	166	47	57	73
FAX	101	133	200	91	118	171	48	58	75

Heart Dose (cGy-Eq)

Organ	30 day limit (cGy-Eq)	1 Year Limit (cGy-Eq)	Career (cGy-Eq)
Heart	25	50	100

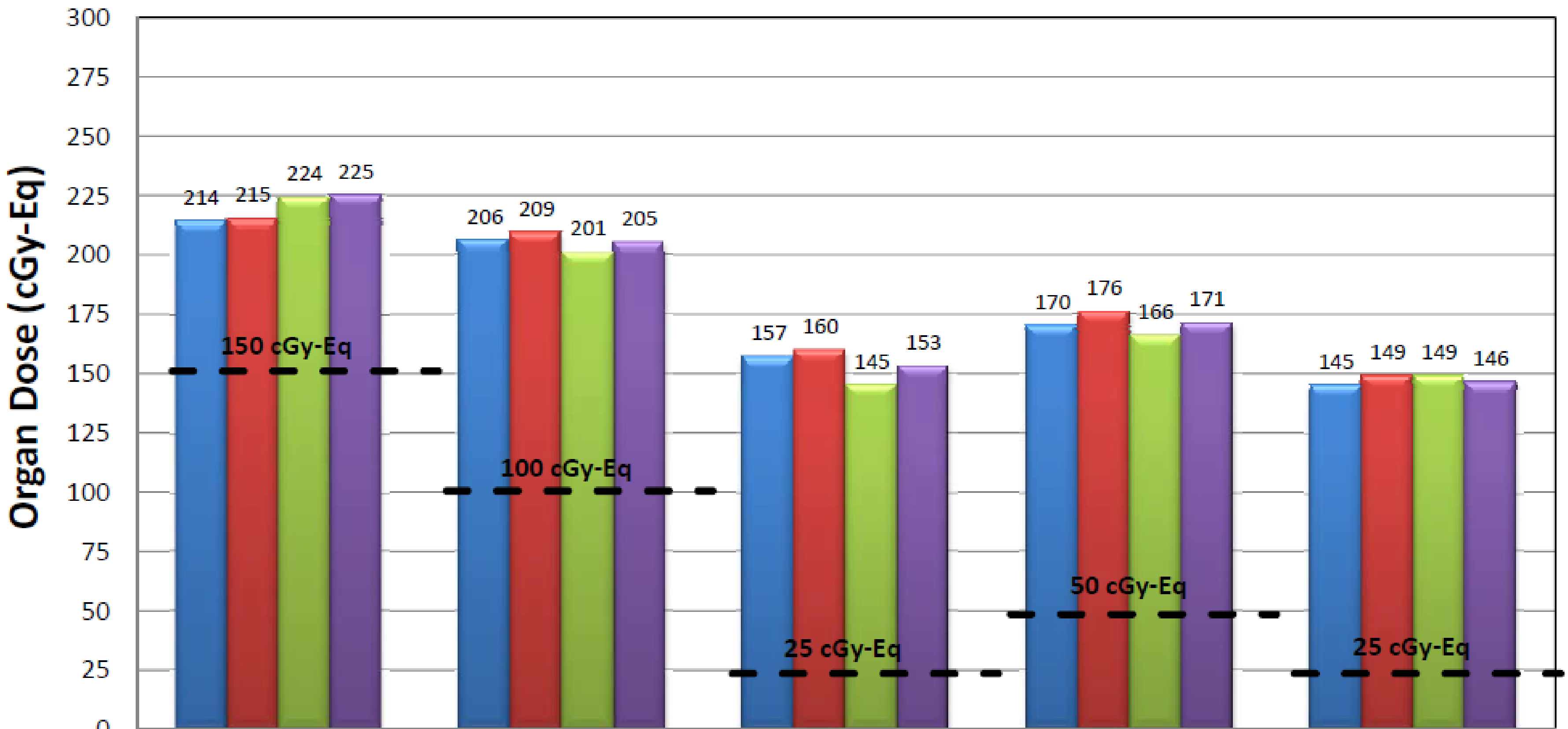
Heart Dose (cGy-Eq)									
Human Body Models	0.3 g cm^{-2} Al Shield			5 g cm^{-2} Al Shield			40 g cm^{-2} Al Shield		
	Elevation (km) & Atmosphere Density			Elevation (km) & Atmosphere Density			Elevation (km) & Atmosphere Density		
	0 km High	0 km Low	8 km Low	0 km High	0 km Low	8 km Low	0 km High	0 km Low	8 km Low
CAM	**89**	**115**	**167**	**80**	**102**	**145**	**43**	**52**	**68**
CAF	**91**	**118**	**172**	**82**	**104**	**149**	**44**	**53**	**69**
MAX	**91**	**118**	**172**	**81**	**104**	**149**	**44**	**53**	**69**
FAX	**89**	**115**	**167**	**80**	**102**	**146**	**43**	**52**	**68**

0.3 g cm⁻² Aluminum Shield (Spacesuit)
Low density atmosphere at 8 km



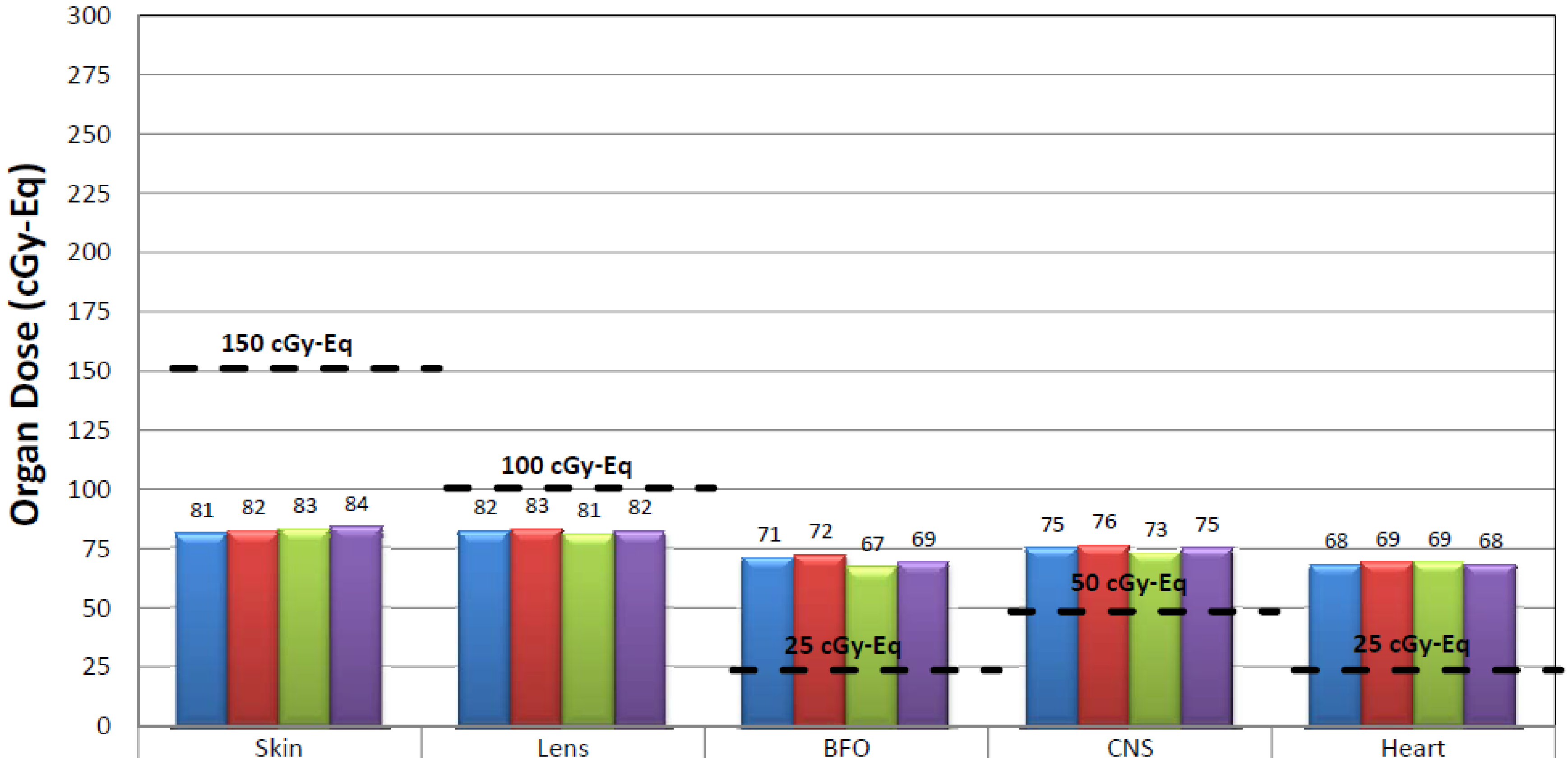
	Skin	Lens	BFO	CNS	Heart
CAM	268	251	184	199	167
CAF	270	254	188	206	172
MAX	285	246	167	194	172
FAX	286	251	178	200	167

5 g cm^{-2} Aluminum Shield (Surface Lander)
Low density atmosphere at 8 km



	Skin	Lens	BFO	CNS	Heart
CAM	214	206	157	170	145
CAF	215	209	160	176	149
MAX	224	201	145	166	149
FAX	225	205	153	171	146

40 g cm^{-2} Aluminum Shield (Permanent Habitat)
Low density atmosphere at 8 km



	Skin	Lens	BFO	CNS	Heart
CAM	81	82	71	75	68
CAF	82	83	72	76	69
MAX	83	81	67	73	69
FAX	84	82	69	75	68