National Aeronautics and Space Administration

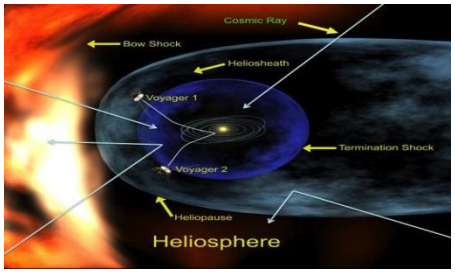
Space Radiation Issues for Manned Spaceflight

AMS-02 Workshop October 23, 2015

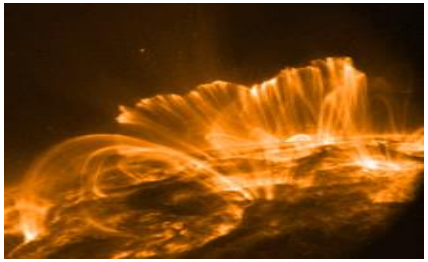
Eddie Semones • HEOMD • NASA JSC
Space Radiation Analysis Group

Human Space Radiation Challenge

Galactic cosmic rays (GCR) – penetrating protons and heavy nuclei



Solar Particle Events (SPE) – low to medium energy protons



What are the levels of radiation in deep space and how does it change with time? → **How much radiation is inside the spacecraft, on Mars surface and in the human body?** → **What are the health risks associated with radiation exposure?** → **How do we mitigate these health risks?**

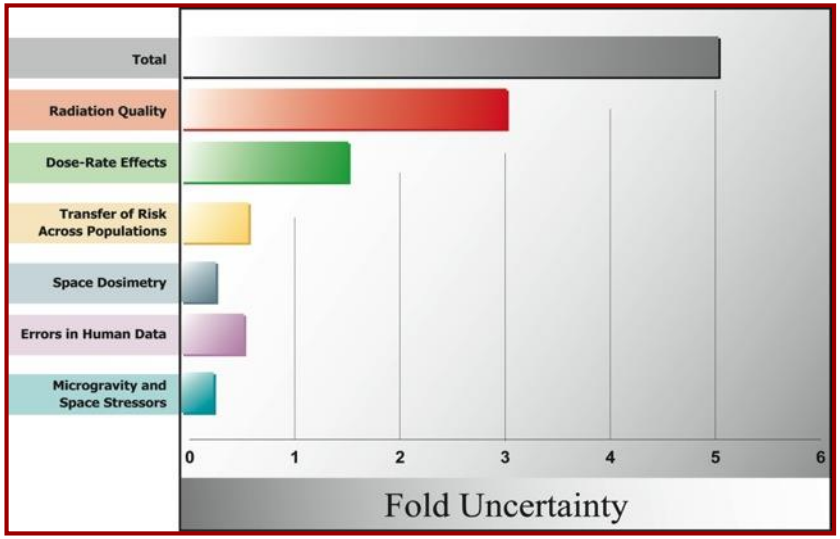
SMD R&D *Helio-& Astrophysics Characterization/ measurement* *Modeling/Prediction & Measurements*	*HEOMD R&D* *Radiation Transport Code Development* *Transport of radiation into body* ***Tissue/Organ doses***	*Cancer risks* *Acute radiation* *Non-cancer risks*	*NSRL research* *Spacecraft Shielding* *Bio-Countermeasures* *Medical Standards*

Space Radiation Health Risks

Health Risk Areas	Status
Carcinogenesis Space radiation exposure may cause increased cancer morbidity or mortality risk in astronauts	➢ Cancer risk model developed for mission risk assessment ➢ Model is being refined through research at NASA Space Radiation Laboratory (NSRL) ➢ Health standard established
Acute Radiation Syndromes from SPEs Acute (in-flight) radiation syndromes, which may be clinically severe, may occur due to occupational radiation exposure	➢ Acute radiation health model has been developed and is mature ➢ Health standards established ➢ Operational & shielding mitigations are understood & risk area is controlled
Degenerative Tissue Effects Radiation exposure may result in effects to cardiovascular system, as well as cataracts **Central Nervous System Risks (CNS)** Acute and late radiation damage to the central CNS may lead to changes in cognition or neurological disorders	➢ Non-cancer risks (**Cardiovascular and CNS**) are currently being defined ➢ Research is underway at NSRL and on ISS to address these areas ➢ May need appropriate animal models to assess clinical significance

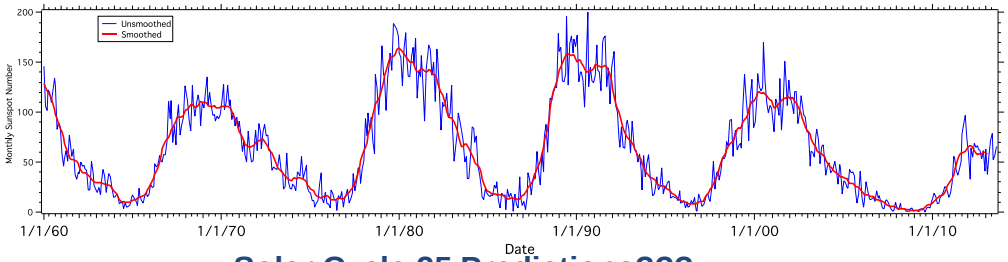
Major Sources of Uncertainty in Estimating Risks from Space Radiation for Exploration Missions

- **Radiation quality effects on biological damage**
  - Qualitative and quantitative differences between space radiation compared with x-rays or gamma rays
- **Dependence of risk on dose rates in space**
  - Biology of repair, cell, and tissue regulation
- **Extrapolation from experimental animal data to humans**
- **Individual radiation sensitivity**
  - Genetic, dietary and healthy worker effects



Major Uncertainties in Cancer Risk Model
Durante and Cucinotta, Nature Rev. Cancer, 2008

- **Predicting galactic cosmic ray solar min/max conditions at future time points**
- **Predicting solar events**
  - Temporal and size predictions



Solar Cycle 25 Predictions???

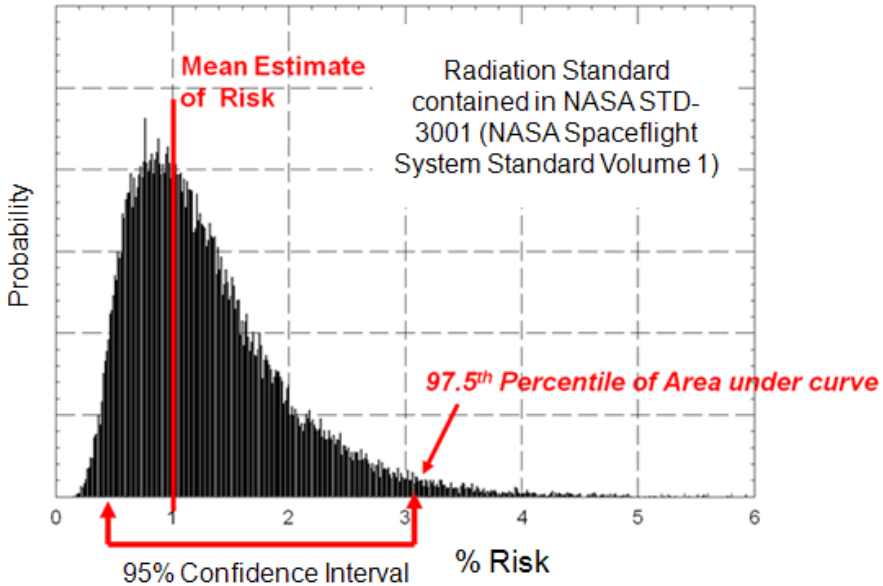
NASA Permissible Exposure Limits (PELs)

Cancer

- NASA Standard is 95% Confidence level for Risk of Exposure Induced Death (REID) less than 3%.
  - Less than 1 in 33 chance of early death
  - Best estimate is multi year life loss for space radiation attributable cancer

- Limit of 3% fatal cancer risk based on 1989 comparison of risks in “less-safe” industries

- NCRP-132 carried this forward with comparison to ground based standards.
  - –Current PELs are set to limit Central Nervous System (CNS) and circulatory disease risks from space radiation
    - *–Protection further provided by cancer REID PEL*



95% confidence is conservative and is intended to account for uncertainties inherent in risk projection model – vary from 50% - <300%

Epidemiology data (statistics, bias, transfer to US population)
Dose-rate reduction factors
Biological response to space radiation, Q
Organ dose equivalent assessment
measurement dosimetry, space environment, radiation transport models

NASA Radiation Risk Prediction Model

- **The NASA Space Cancer Risk (NSCR)* model was reviewed by the National Research Council in 2012 (last NASA model update was 2005).**
  - **Basis for estimating crew risks for ISS missions and trade studies of future Exploration Class missions**
  - **Only considers the risk of carcinogenesis**
  - **Includes up to date GCR environment (Badhwar-O'Neill 2011/2014), AP8/E8 trapped radiation environment, and radiation transport (HZETRN), for comprehensive dosimetry evaluation**
  - **Provides estimate of cancer incidence and mortality**
    - **Age and Gender Specific Risks**
  - Slope for age modification 1.3:1 from age 35 to 55
  - Risk model utilizes astronaut healthy population characteristics (lifetime never-smokers), lowers space radiation risk compared to U.S. Avg. population of about 20%
  - New Quality Factors and improved Uncertainty estimates

Model utilizes data/information from:

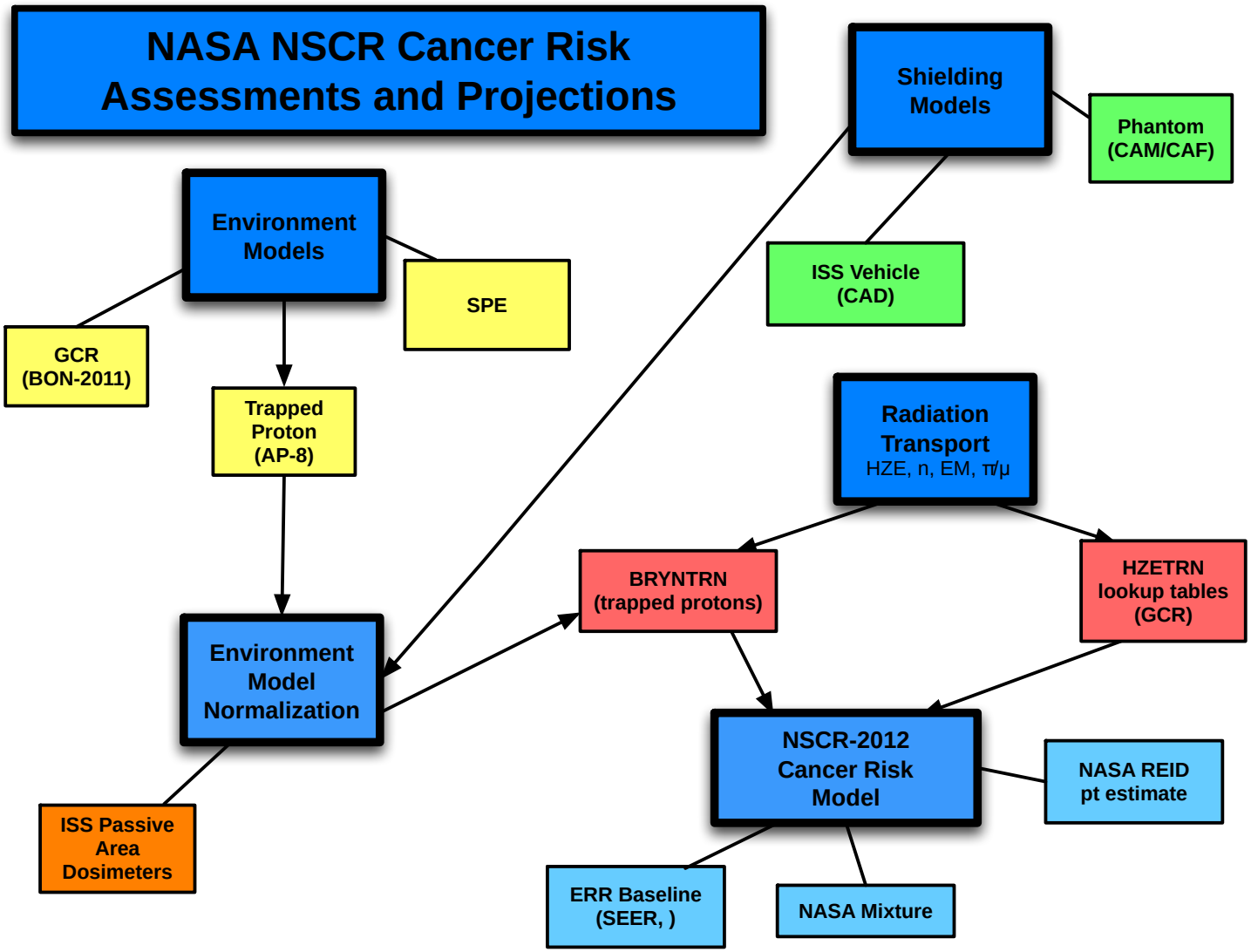
Epidemiological
-BEIR - Biological Effects of Ionizing Radiation
-UNSCEAR - United Nations Scientific Committee on the effects of Atomic Radiation
-RERF – Radiation Effects Research Foundation

Terrestrial Research
-NIH/NCI – Terrestrial Cancer Research
-DOE/DOD/DARPA – Radiation Effects Research
-International Research Activities

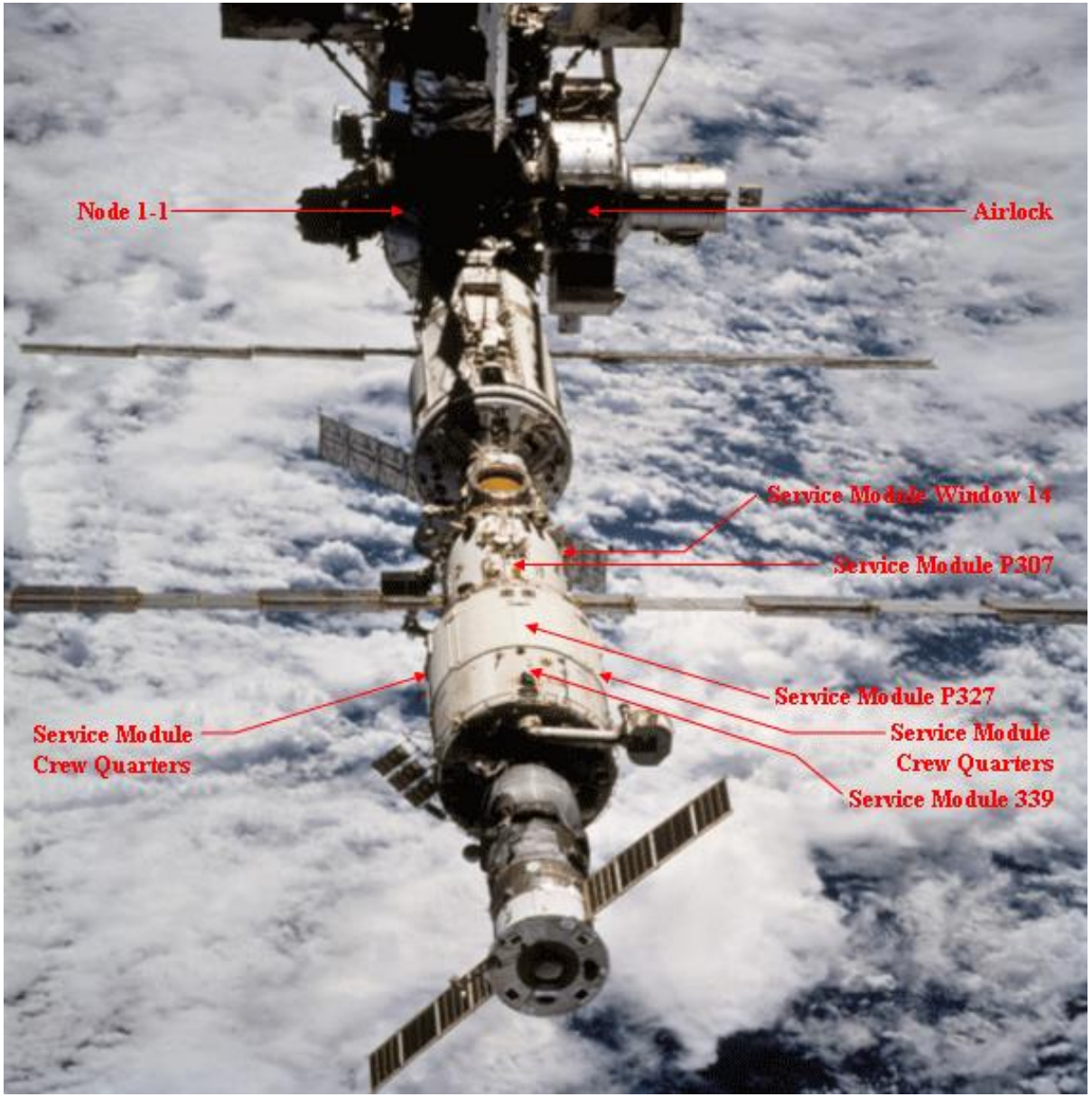
Space Radiation Research
-Human Research Program
-Space Radiation focused research
-Utilizes animal models with simulated space environment **(NSRL)**

*F. A. Cucinotta, L. Chappell, M. Y. Kim, "Space radiation cancer risk projections and uncertainties – 2012, NASA/TP-2013-217375 (2013).

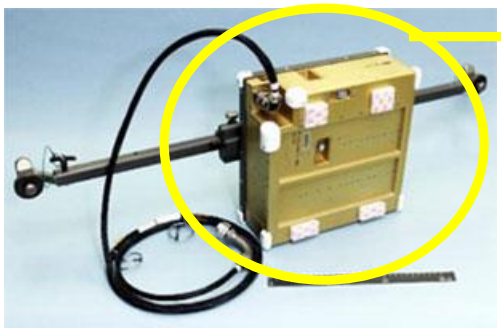
Astronaut Cancer Risk Analyses
Risk Assessment Flow

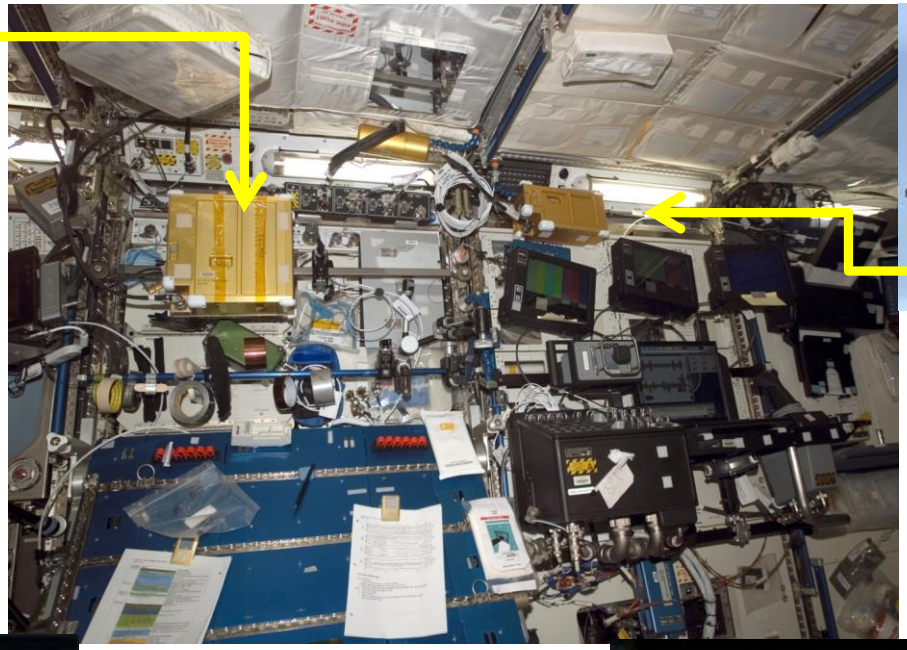


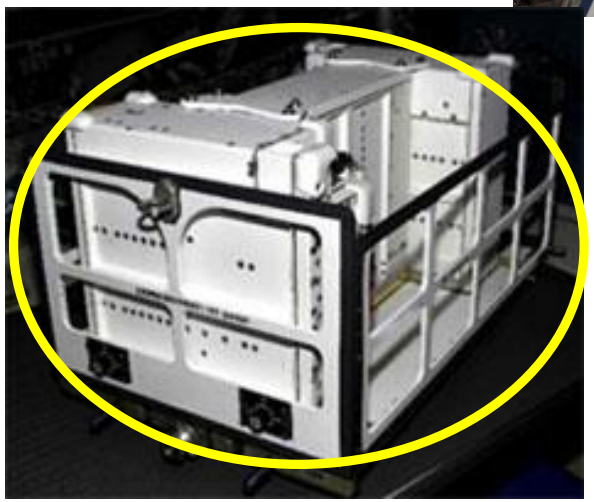
Passive Monitoring Locations - Example

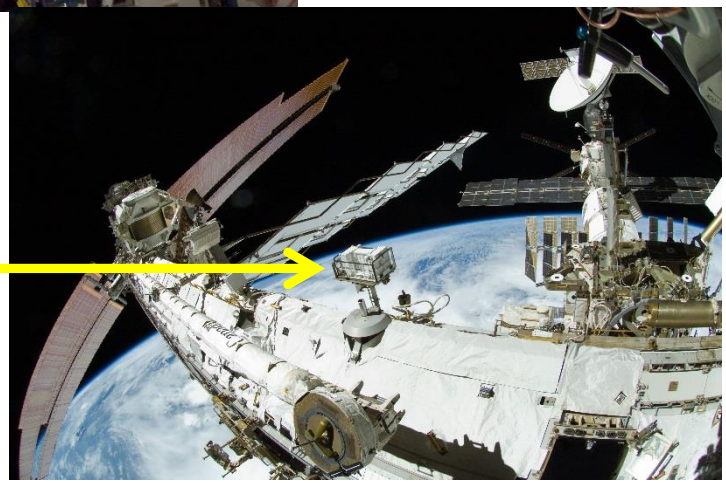


Original ISS Operational Instruments Provide Real-time Dosimetry and Alarming









EV/IV detailed radiation survey information

ISS Dosimetry – low dose/dose rates

- Current estimate of NASA Effective Dose Rate in 2017:
  0.6 mSv/day

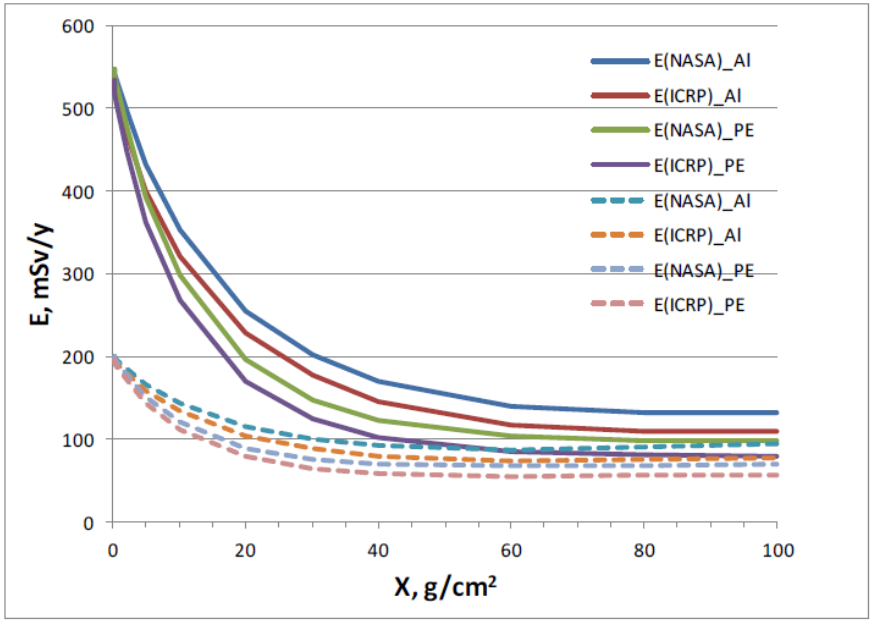
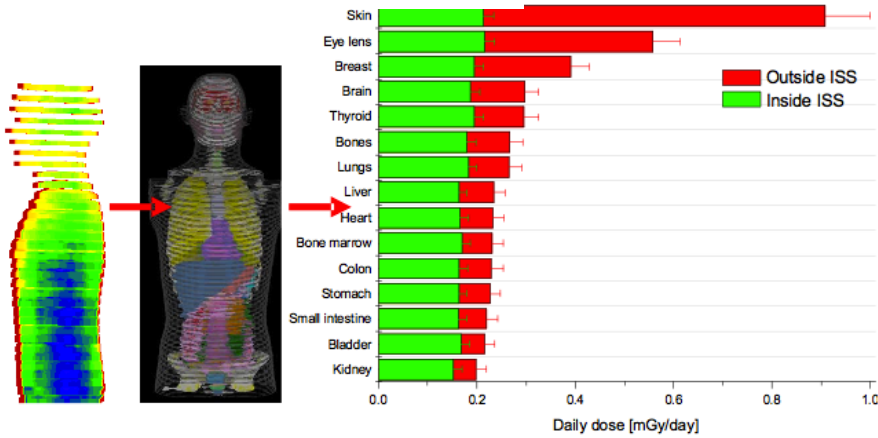


Figure 6.5. Comparison of annual Effective dose or NASA Effective for males in ISS orbit (51.6 deg × 400 km) vs. depth of shielding. Values for solar minimum and maximum are shown.

Table 2.7.b. Comparison of small active dosimetry data from ISS Increment 2 phantom torso (for July-August 2001) to predictions from the HZETRN/QMSFRG model.[73]

Organ	*Trapped, mGy/d*		*GCR, mGy/d*		*Total Dose, mGy/d*		*Difference*
	Expt.	Model	Expt.	Model	Expt.	Model	*(%)*
Brain	0.051	0.066	0.076	0.077	0.127	0.143	13.3
Thyroid	0.062	0.072	0.074	0.077	0.136	0.148	9.4
Heart	0.054	0.061	0.075	0.076	0.129	0.137	6.7
Stomach	0.050	0.057	0.076	0.077	0.126	0.133	5.5
Colon	0.055	0.056	0.073	0.076	0.128	0.131	2.5



NSCR-2012 Model Inputs

	Purpose	Example Value
Crewmember Parameter		
Sex	Sex-based risk parameters	male
Smoking status	organ-risk dependence	NS
Birthdate	Age at exposure	1-Jan-75
Mission Parameters		
Launch date	Calculate mid-mission date	10-Sep-14
Land date	Calculate mid-mission date	10-Nov-14
Altitude & orbit inclination	Trapped proton env.	405km, 51.6
Space Weather		
Avg sunspot number	GCR modulation	64
Avg F10.7 radio flux	Trapped proton env.	calc
Avg GCR - Phi	Modulation parameter	817
Shield Models		
Vehicle CAD	Shielding	SMP-327
Phantom (male/female)	Self-shielding	CAM
ISS Area Dosimeters		
RAMs (x4)	Normalize trapped protons	SMP-327 TLD-100

Example Results for ISS Mission

Solar Minimum Activity, altitude 400 km, Male, age 57, never-smoker

Input Parameter	Purpose
Crewmember Parameter	
Sex	Sex-based risk parameters
Smoking status	organ-risk dependence
Birthdate	Age at exposure
Mission Parameters	
Launch date	Calculate mid-mission date
Land date	Calculate mid-mission date
Altitude & orbit inclination	Trapped proton env.
Space Weather	
Avg sunspot number	GCR modulation
Avg F10.7 radio flux	Trapped proton env.
Avg GCR - Phi	Modulation parameter
Shield Models	
Vehicle CAD	Shielding
Phantom (male/female)	Self-shielding
ISS Area Dosimeters	
RAMs (x4)	Normalize trapped protons

Organ	D(mGy)	H(mSv)
Stomach	88.77	210.15
Colon	101.98	237.98
Liver	93.02	219.11
Lung	98.47	230.77
Breast	0.00	0.00
Prostate	109.08	252.14
Uterus	0.00	0.00
Ovary	0.00	0.00
Bladder	87.09	206.55
Esophagus	96.98	227.67
Brain-CNS	118.11	272.04
Thyroid	107.78	250.35
OralCavity	107.78	250.35
Remainder	103.57	241.40
EffectiveSolid	97.72	229.03
BoneMarrow	103.57	137.53
NASA_Eff_Dose	97.72	229.03
Heart	108.61	266.79
Skin	142.90	320.97
Heff= 290 mSv		

Organ	REIC [%]	REID[%]
Leukemia	0.13594	0.07175
Stomach	0.11448	0.06597
Colon	0.14064	0.0659
Liver	0.05378	0.04606
Bladder	0.27221	0.06726
Lung	0.16625	0.14858
Esophagus	0.01618	0.01523
OralCav	0.02057	0.00624
Brain-CNS	0.01243	0.01078
Thyroid	0.00073	0.00011
Skin	0.0011	0.00087
Remainder	0.05429	0.02514
Prostate	0.17103	0.03627
TotalSolid	1.0237	0.48843
Total(sol+leuk)	1.16944	0.56017

NSCR-2012 Dosimetry Results – Free Space

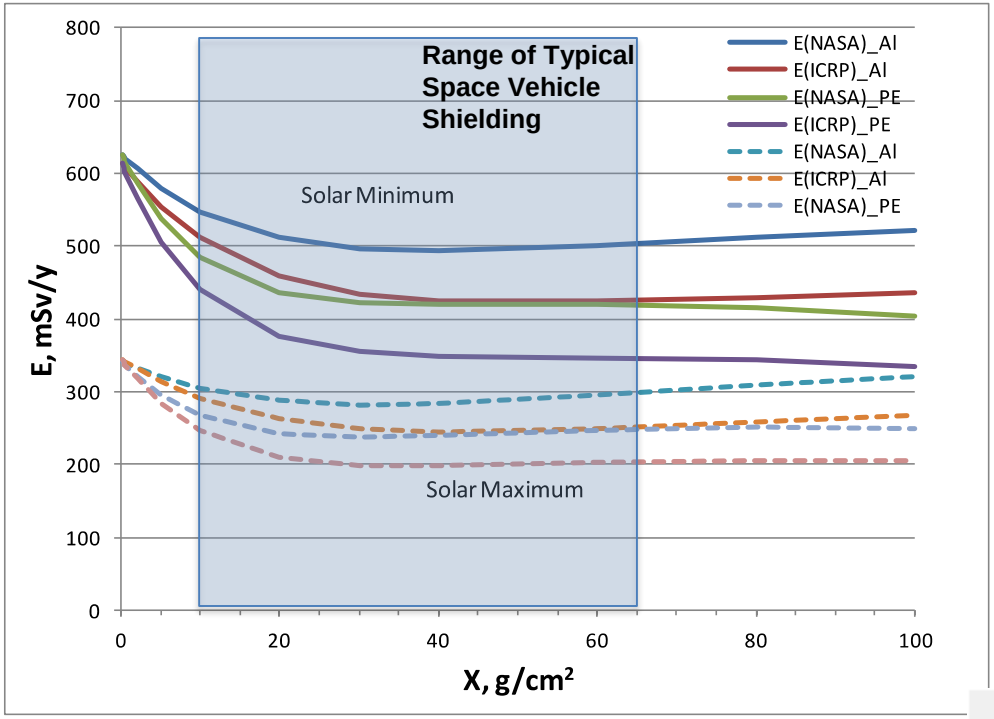
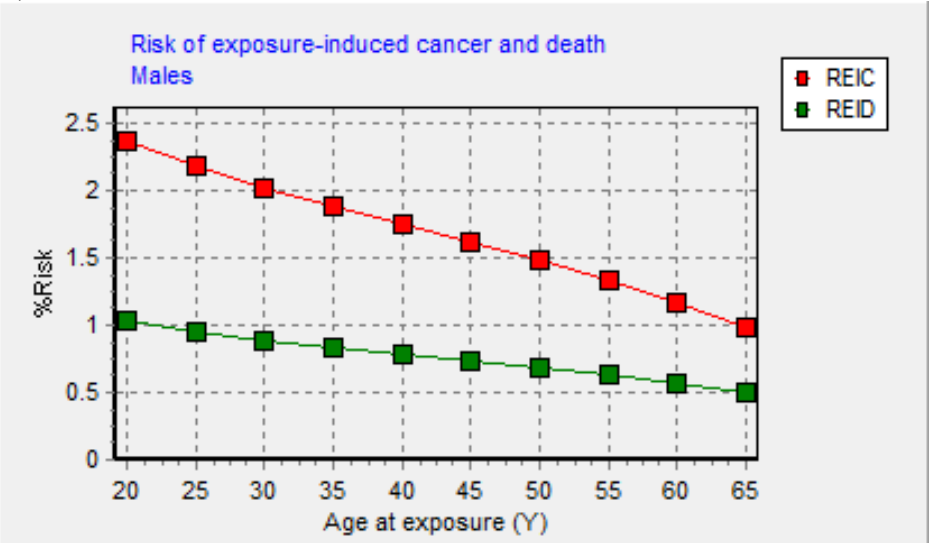


Figure 6.6. Annual GCR Effective doses or NASA Effective dose in deep space vs. depth c shielding for males. Values for solar minimum and maximum are shown.

GCR Dose Rates in Free Space

- NASA Effective Dose are ~500 mSv/year in Solar min
  - **1.36 mSv/day**
- Influence of body shielding
- # Safe Days are based on these calculated doses



*F. A. Cucinotta, L. Chappell, M. Y. Kim, "Space radiation cancer risk projections and uncertainties – 2012, NASA/TP-2013-217375 (2013).

NASA Radiation Risk Prediction Model

Solar Minimum Safe Days

in Deep Space Maximum Days in Deep Space to have 95% Confidence Level to be below the NASA Limit of 3%. Calculations are for average solar minimum with 20g/cm^2 of aluminum shielding. Values in parenthesis is deep solar minimum of 2009.

a_E, y	NASA 2012 Never-smokers
Males	
35	271 (256)
45	308 (291)
55	351 (335)
Females	
35	187 (180)
45	227 (212)
55	277 (246)

Higher GCR
Lower SPE

Solar Maximum Safe Days

in Deep Space to have 95% Confidence Level to be below the NASA Limit of 3%. Calculations are for average solar maximum assuming large August of 1972 SPE with 20g/cm^2 aluminum shielding. Values in parenthesis without the 1972 SPE event and ideal storm shelters/monitoring which would reduce SPE doses to negligible amounts

a_E, y	NASA 2012 Never-smokers
Males	
35	395 (458)
45	456 (526)
55	500 (615)
Females	
35	276 (325)
45	319 (394)
55	383 (472)

Lower GCR
Higher SPE

Data in Tables from Space Radiation Cancer Risk Projections and Uncertainties – 2012
Cucinotta et al.

Post Mission Cancer Risk For A 900-day Mars Mission

Mars Mission Timing	Mission Shielding Configuration	Calculated REID, 95% C.I. (Age=45, Male-Female)	Amount Above 3% Standard
Solar Max	Good shielding like ISS (20 g/cm2) w/no exposure from SPEs	4% - 6%	1% - 3%
Solar Max	Good shielding like ISS (20 g/cm2) w/large SPE	5% - 7%	2% - 4%
Solar Min	Good shielding like ISS (20 g/cm2)	7% - 10%	4% - 7%

NASA Standards Limit The Additional Risk Of Cancer Death By Radiation Exposure, Not The Total Lifetime Risk Of Dying From Cancer

- Baseline lifetime risk of death from cancer (non-smokers): 16% males, 12% females
- After Mars Mission (solar max), Astronauts lifetime risk of death from cancer ~20%

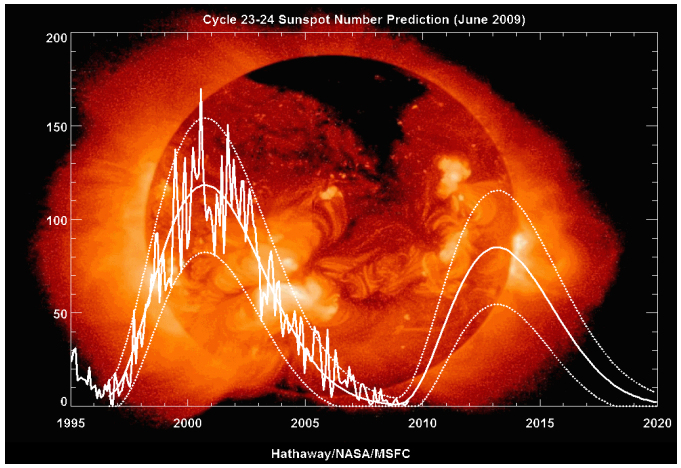
Mars Space Radiation Risk For Solar Max Can Be Explained As Follows

- If 100 astronauts were exposed to the Mars mission space radiation, in a worst case (95% confidence) 5 to 7 would die of cancer, later in life, attributable to their radiation exposure and their life expectancy would be reduced by an average on the order of 15 years
- Challenging to use a population-based risk model to estimate individual risk for the few individuals that would undertake a Mars Mission

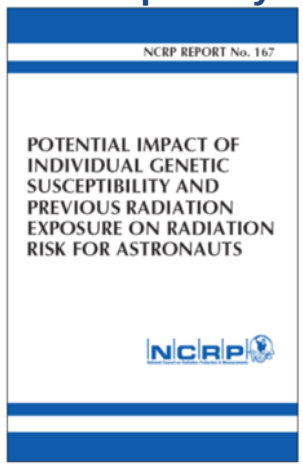
Mitigation Approaches

- **Crew Selection**
  - Age, gender, lifestyle factors, etc.
  - Individual Sensitivity (genetic factors
- **Mission date-time in the Solar Cycle**
- **Ability to minimize exposure to SPE's**
  - **Real time spectral measurements**
  - **Radiation Shielding**
  - Amounts and material types
  - Design Optimization
- **Biological Countermeasures (BCMs)**
  - Radioprotectors / Mitigators
- **Biomarkers predictive of radiation induced diseases**
  - Future individualized risk assessment
  - Early detection and prognostic monitoring

Variation of Solar Activity

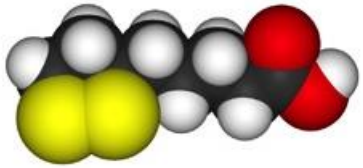


Individual Susceptibility

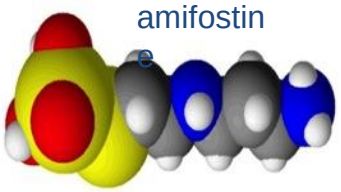


(NCRP 2011)

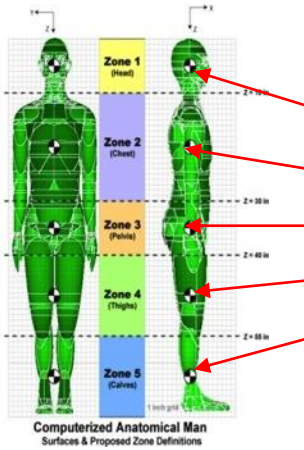
α-lipoic acid

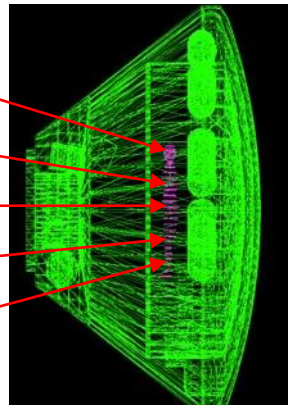


amifostin



BCM: Pharmaceuticals

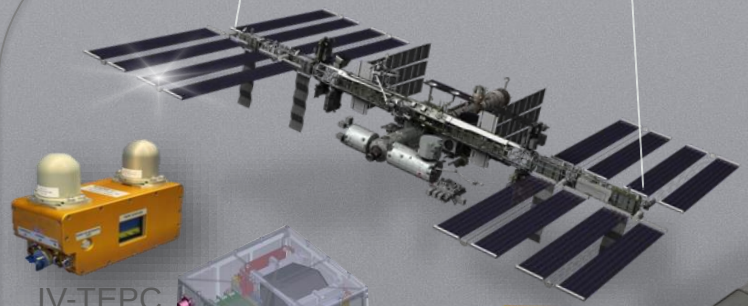




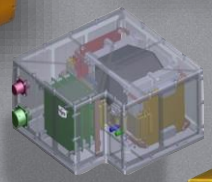
Shield Design and Optimization

D O S I M E T R Y T E C H N O L O G Y

Long Duration/Habitats/Large Mass Vehicles



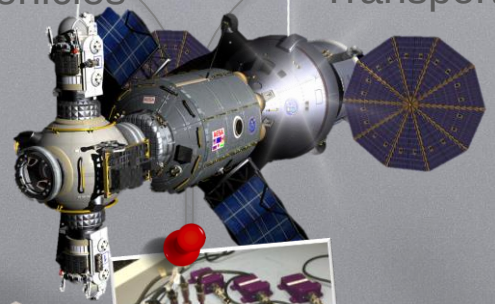
IV-TEPC

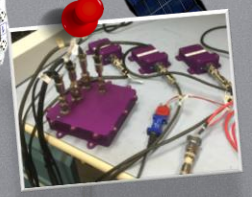


FNS

RAD

REM



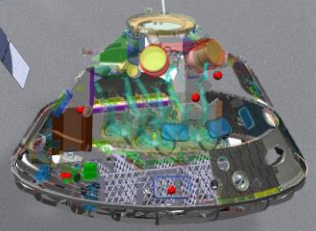


HERA

RAM/CPD

Transportation/Low Mass Vehicles

PRD



Active Radiation Area Monitoring:

REM: Radiation Event Monitor
limited particle + dose
HERA: Hybrid Electronic Radiation Assessor
limited particle + dose; will be tech-demoed on ISS
IV-TEPC: Intra-Vehicle Tissue Equivalent Proportional Counter
broad sensitivity dosimeter
Charged Particle Spectrometer (CPS):
Current technology is ISS-Radiation Assessment Detector (RAD)
Neutron Spectrometers:
ISS-RAD, Fast Neutron Spectrometer (FNS)

Passive Radiation Area Monitoring:

RAM: Radiation Area Monitor
CPD: Crew Passive Dosimeter
Uses same technology as RAM; may be replaced with PRD (right)

Active Radiation Area Monitoring:

HERA: Hybrid Electronic Radiation Assessor
limited particle + dose; planned for EM-1,EM-2
Charged Particle Spectrometer (CPS): TBD
Neutron Spectrometers: TBD

Active Personal Radiation Dosimeter (PRD):

Currently looking at options; market survey, dose only, not real time; planned for EM-2 and potentially ISS

Passive Radiation Area Monitoring:

RAM: Radiation Area Monitor
Planned for EM-1; will not fly EM-2
Crew Passive Dosimeter(CPD);
If PRD (above) is successful, will not be required

Acute Radiation Effects from a Solar Particle Event

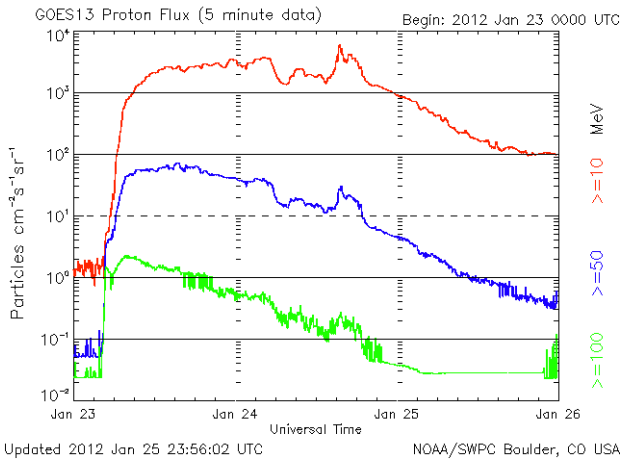
- 30-day and yearly limits to the blood forming organs (BFO) and skin are intended to protect astronauts from acute radiation syndromes (ARS) including the prodromal risks (i.e., nausea, vomiting, anorexia, and fatigue), alterations to the hematopoietic system, and skin injury resulting from exposure to a large solar particle event (SPE)
  - Symptoms appear 4 to 48 hours post-exposure for sub-lethal doses with a latency time inversely correlated with dose
  - Clinical course of ARS are well defined in human populations accidently exposed to acute, high doses of gamma- and X-rays
  - Uncertainty exists about the magnitude of acute health effects from whole-body exposures to protons from an SPE, which are characterized by a high degree of variability in dose distribution in the body as well as by dynamic changes in dose-rates and energy spectra

- Majority of SPE's are harmless; however, prodromal effects could occur during the occurrence of an historically large event if crew fails to seek shelter in a timely manner
  - Radiation sickness possible if unprotected >2 hours
  - Occurrence and magnitude of SPE's are difficult to predict
  - **Optimized event alert, dosimetry, and operational responses must be assured**
  - **Adequate shielding must be provided**

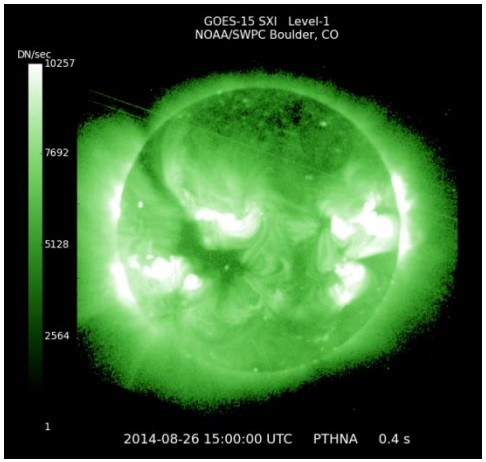
- Minimizing cancer risk is a priority for both EVA and IVA even if ARS are avoided

Protecting ISS Crew: Solar Particle Event (SPE) Action Summary

- Radiation flight controller returns to console during contingency operations such as SPEs
  - Alert/Warning messages to management and flight control team
  - Ensure radiation monitoring system availability
- If SPE dose projection is determined to be negligible, then no action will be taken
- If energetic solar particle event has increased above threshold or radiation detector alarm activation is confirmed, inform crew to remain in higher shielded areas during intervals of high risk orbital alignments (geomagnetic cut-offs).
- ISS higher shielded locations used to protect crew
  - Service module aft of treadmill (panel 339), Node 2 crew quarters, and U.S. Lab

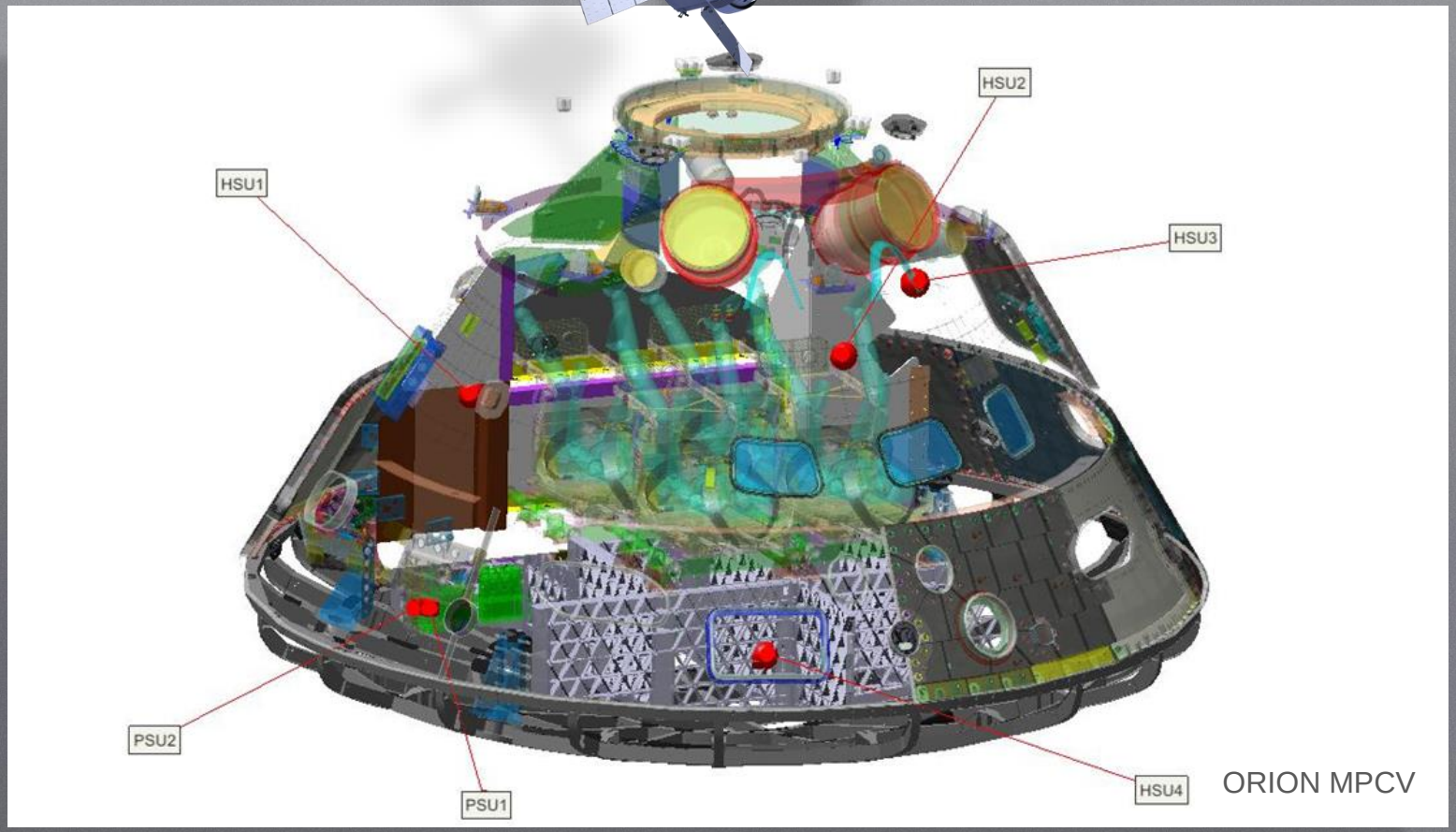


Geostationary Operational Environmental Satellite (GOES) Proton Flux Monitor used to monitor SPEs



GOES Solar X-ray Image for the early detection of solar flares and coronal mass ejections

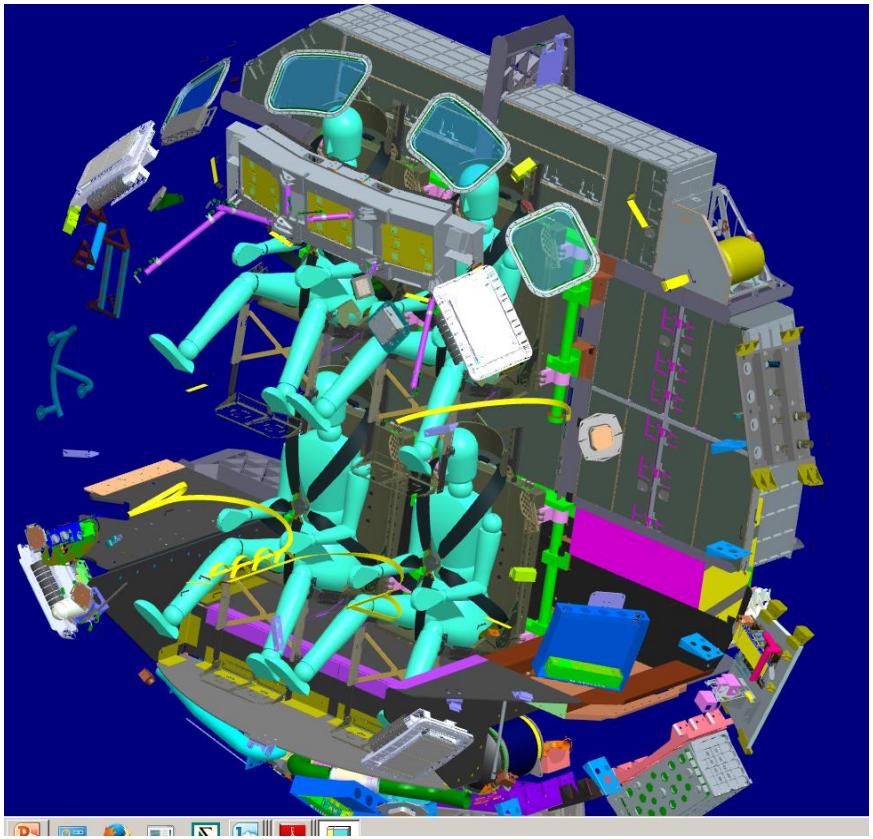
INSIDE ORION MPCV



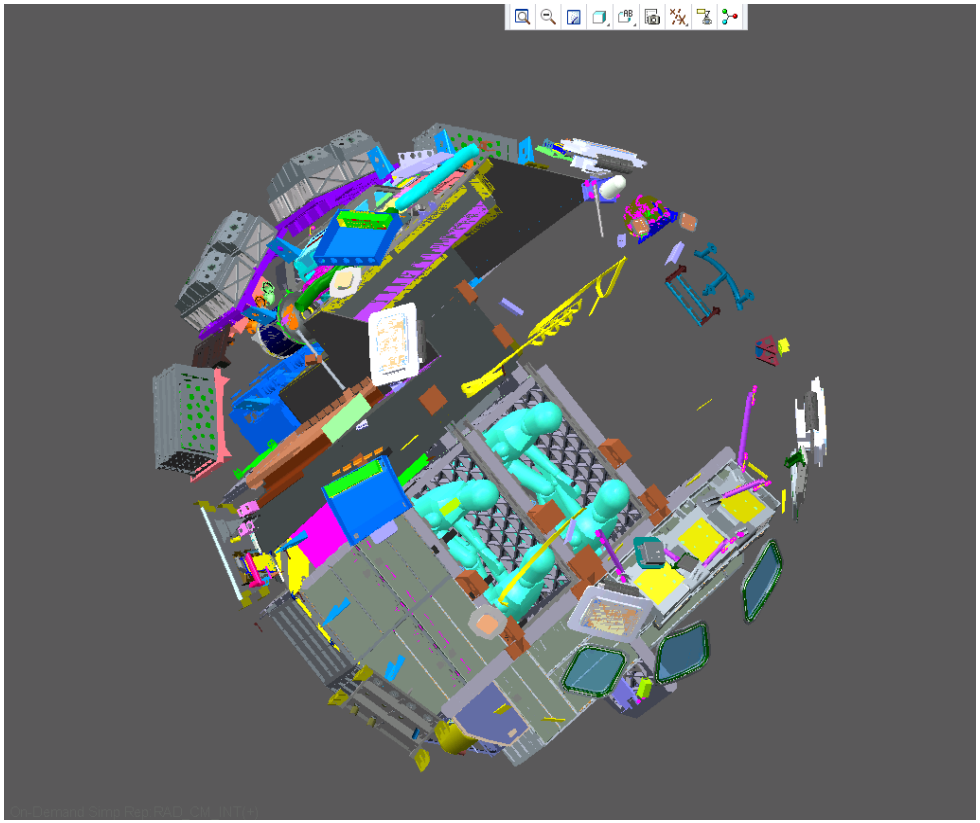
ORION MPCV

MPCV SPE Operational Response

Similar to locating to higher shielded locations on ISS to protect crew, relocating and reconfiguring MPCV stowage can provide SPE protection for crew



Nominal Seated Position



SPE Contingency Position

Solar Particle Event Storm Shelter Technology Maturation (AES)

Goal: Minimal Mass Shield Concepts

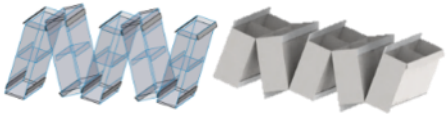
Approach:

- Design concepts utilizing onboard mass (water, equipment, consumables, waste, etc.)
- Evaluate radiation protection
- Fabricate of prototypes
- Perform operational evaluations

Concepts developed:

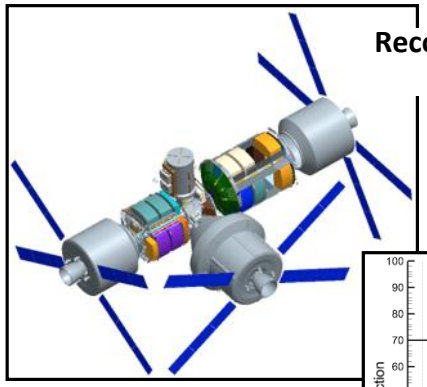
- Water walls and pantries in the crew quarters
- Reconfigurable logistics concepts
- Wearable vests and augmented sleep restraints

Reconfigurable Logistics

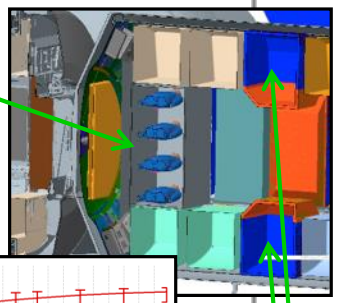


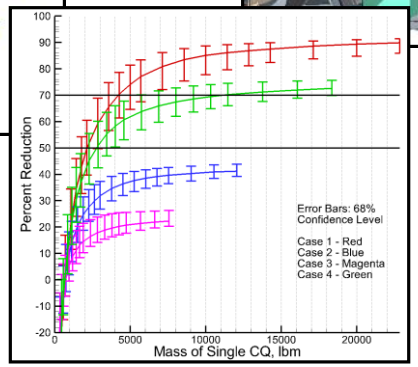
Water Walls

Radiation Protection Analyses

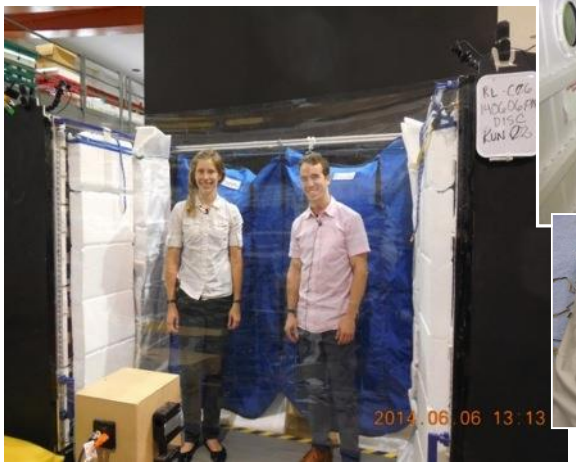


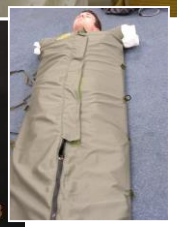
Multiple versions analyzed in realistic vehicle architecture to identify options requiring least parasitic mass.





Operational Testing





Mitigation of Galactic Cosmic Rays: STMD GCR Thick Shield Project

Problem being Addressed:

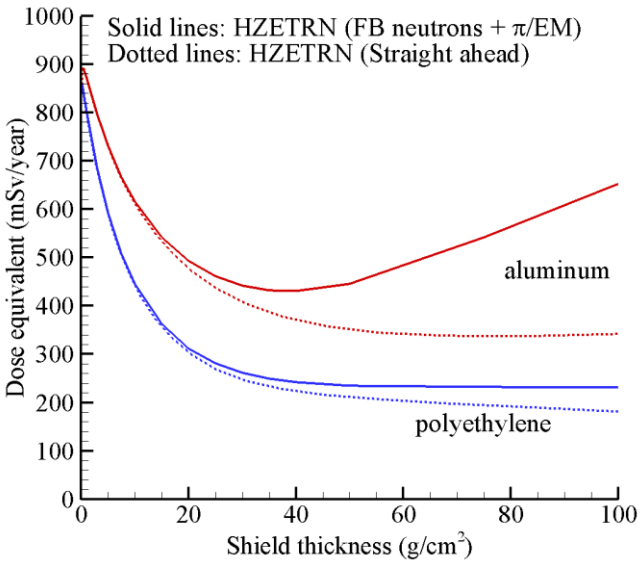
- Cost/mass effective radiation shield solutions against galactic cosmic radiation to enable NASA's exploration DRMs beyond LEO do not exist

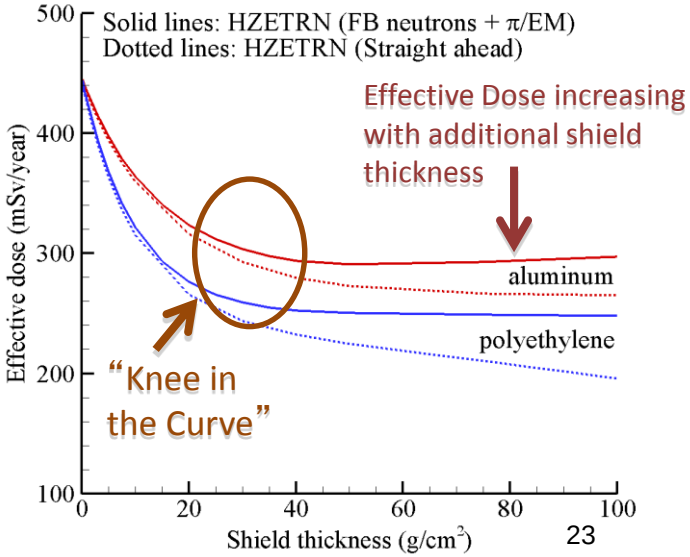
Project :

- Establish first shield thickness requirements for exploration taking passive shielding out of design trade space.
- Validate multi-purpose GCR thick shielding material systems and technologies that offset the mass and volume penalties of parasitic shielding by performing other mission essential functions.

Why now?

- New analytical evidence of minimum in dose equivalent at depths important to shield design allowing for optimization.
- NASA radiation facility upgrades allows experimental validation of thick shield approaches.





Integrated Radiation Protection Strategy Enables Human Mars Exploration

Integration across Research and Technology Required…

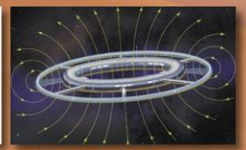
National Aeronautics and Space Administration

Mission and Architecture Systems Analysis


Near Earth Asteroid Systems

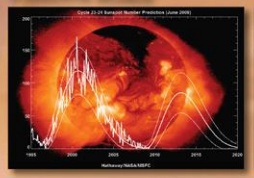

Mars NTV


In-situ Resource Utilization


Active Shielding Concepts

Environmental Modeling, Monitoring, and Prediction

Predictive Models



Precursor Data — MSL RAD

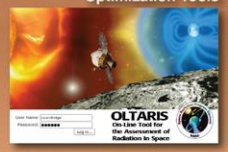
On-board Dosimetry– ISS TEPC

Crew Selection and Operations

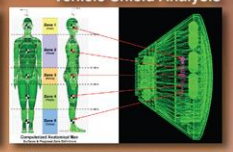

Individualized Risk Assessment

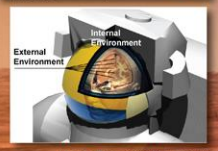
Integrated Radiation Protection System Design and Analysis

Design and Optimization Tools



Crew Exploration Vehicle Shield Analysis

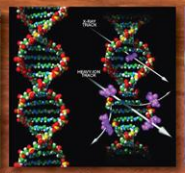


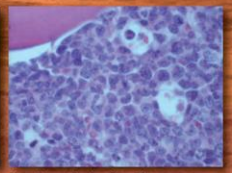


High Energy Nuclear Physics and Transport

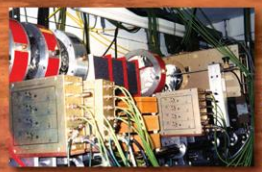
Radiobiology and Biological Countermeasures


NASA Space Radiation Lab at Brookhaven National Laboratory


X-ray vs. Heavy ion Track Damage to DNA

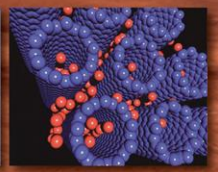

Leukemia induction with GCR — Mouse Model

Innovative Multi-Purpose Shield Solutions


Heavy Ion Testing of Inflatable Shield Prototype


Water Filled Composite Shield Sections


Reconfigurable Personal Shielding


Hydrogen Storage BNNT