National Aeronautics and Space Administration

# *Radiation Health Risk Projections*

**Briefing to**
**NAC HEOMD/SMD Joint Committee**

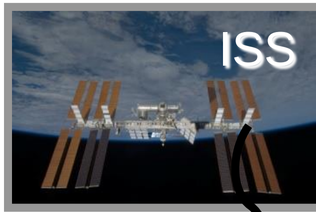
April 7, 2015

Eddie Semones • HEOMD • NASA JSC

# Space Radiation Analysis Group (SRAG) Flight Interfaces

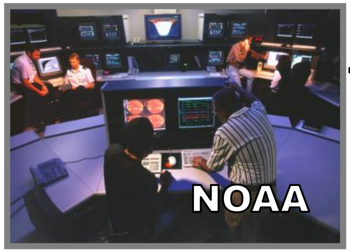
## Flight Surgeon/BMEs
- Evaluate EVAs for Exposures (ALARA)
- Maintain status of mission exposure trends
- During Solar Energetic Particle Events (SEPs)
  - Advise Surgeon on Magnitude of events
  - Time intervals of SEP Exposure Risk
  - Recommendations regarding Crew Shelter
- Training for SRAG Operations and Hardware

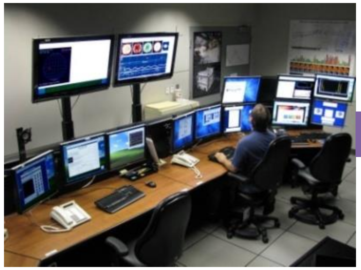
## Flight Director
- Notification of SPEs for hardware concerns
- Time intervals of SPE exposure risk




## Payload Operations
- Conduct technology demonstration of new radiation hardware development

## International Partners
- Data sharing
- Alerting
- Coordinated contingency response



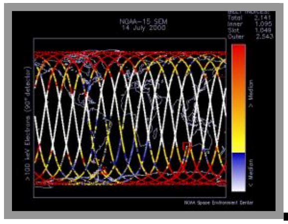



SPACE RADIATION ANALYSIS GROUP

## SRAG

Telemetry

## Crew
- ASCAN Training
- Pre/Post-mission Training
- Flight Hardware Training
- Risk Communication

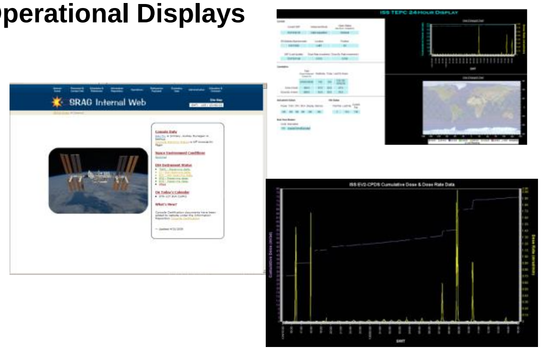


**Alerting**

**Continuous Space Weather Data**

**Space Weather Prediction Center, Boulder, CO National Oceanic and Atmospheric Administration – SMD Assets**

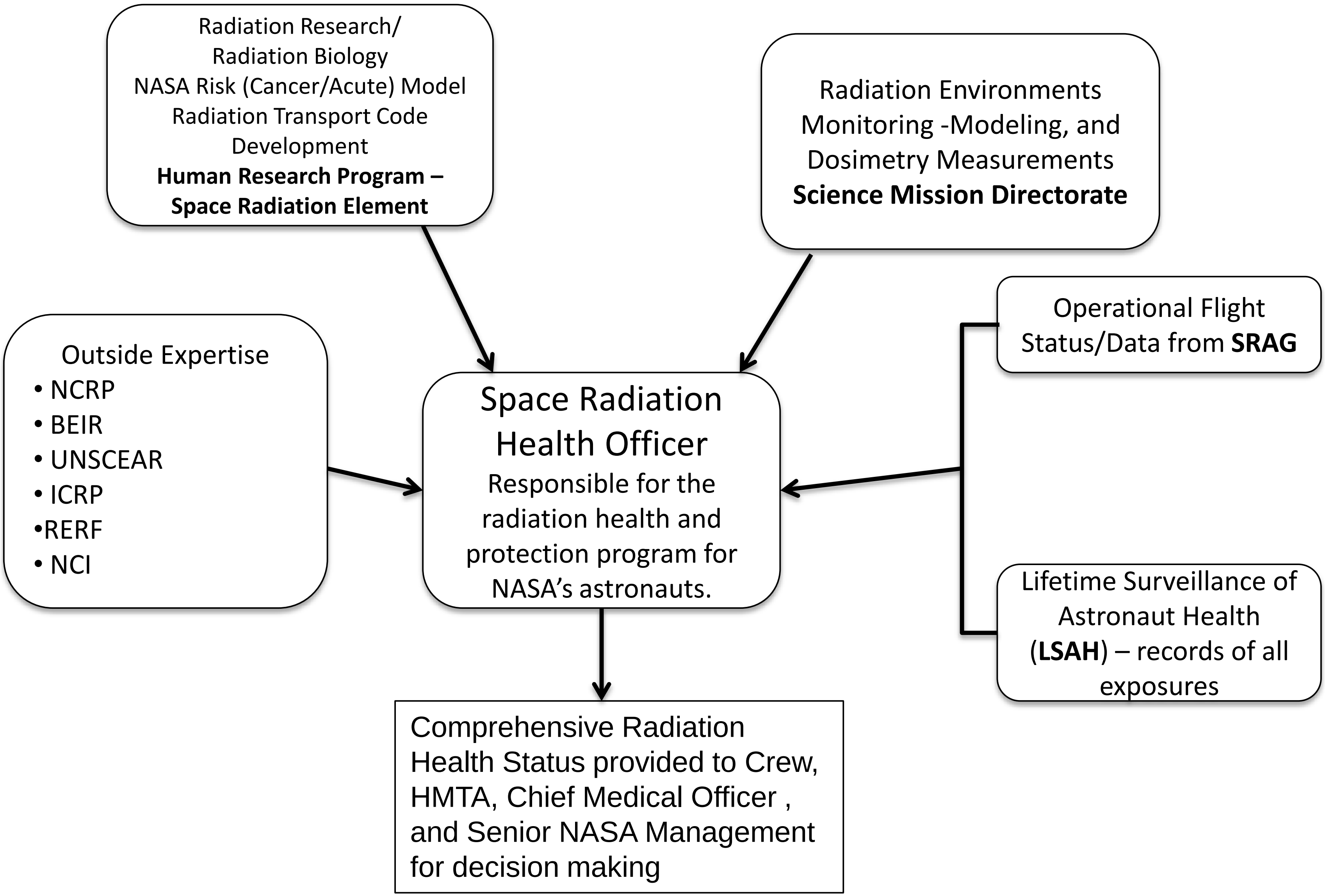
**Operational Displays**



**Telemetered ISS Data**

MCC
ISPX Servers

# Space Radiation Analysis Group – Radiation Health Officer Role Management



# Space Radiation Health Summary

- **Congress has chartered the National Council on Radiation Protection (NCRP) to guide Federal agencies on radiation limits and procedures**
  - NCRP guides NASA on astronaut dose limits
- **Current dose limits correspond to a projection of tissue weighted exposure to permissible limit of 3% fatal cancer at 95% confidence**
  - Confidence level depends on exposure type (GCR, SPE, etc)
  - Best estimate is 15-years average life loss for space radiation attributable cancer
- **Short term and non-cancer risks**
  - Prevent clinically significant health effects including performance degradation, sickness, or death in-flight
  - Lifetime limits for lens, circulatory system, and central nervous system are imposed to limit or prevent risks of degenerative tissue diseases
  - Gray Equivalent quantity is used to limit non-cancer effects and is largely unknown for cardiovascular and CNS effects
- **Mission and Vehicle Requirements in place**
  - Shielding configuration, dosimetry, operations and countermeasures
- **NASA programs must follow the ALARA principle as astronauts approach dose limits**

NASA effectively uses national external advisory panels (IOM, NCRP)

Research Program informs the development of Space permissible exposure limits and provides models to Operations to implement. Operations ensures individual crew members do not exceed PELs and are informed of their risks.

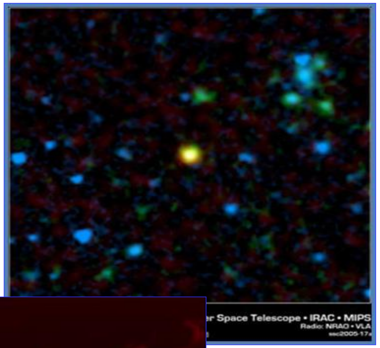
RBE's to assess risks/limits for the cardiovascular and CNS are largely unknown – research program must inform.

Mission and vehicle requirements derived from PELs – HEOMD, SMD, and STMD provide technologies to meet requirements.

Optimization techniques employed for cost/benefit analysis in support of ALARA principal. Minimum mass solutions to enable missions.

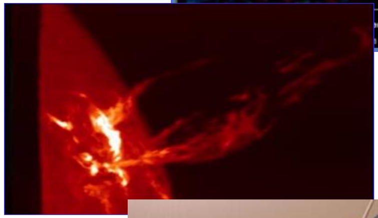
# Sources of Exposure

**Spaceflight**



### Galactic Cosmic Rays (GCR)

- Penetrating protons and heavy nuclei with a broad energy spectra of interest - primarily from ~10 MeV/u to 10,000 MeV/u



### Solar Particle Events (SPE)

- Largely low to medium energy protons

### Mars Surface Environment

- Mixed field environment (neutrons and charged particles)

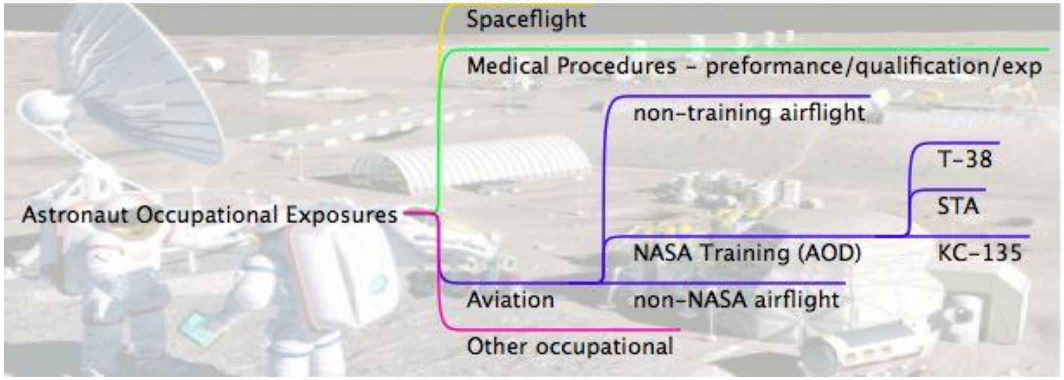
### Medical

- Diagnostics, Research Studies, Corps selection, Flight Qualification

### Aircraft Operations (non-commercial)

- Training, operations, research

### Prior Occupational Sources



# NASA Relevant NCRP Reports

*Ongoing - Radiation Exposures in Space and the Potential of Central Nervous System Effects– Committee SC-1-24*

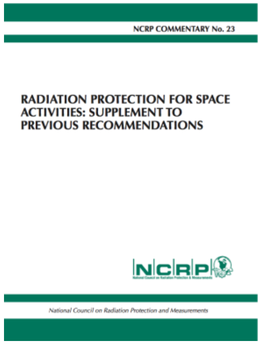
**Published**:
NCRP Commentary No. 23 (2014)
Radiation Protection for Space Activities: Supplement to Previous Recommendations.

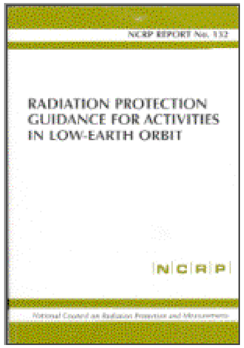
NCRP Report No. 167 (2010)
Potential Impact of Individual Genetic Susceptibility and Previous Radiation Exposure on Radiation Risk for Astronauts

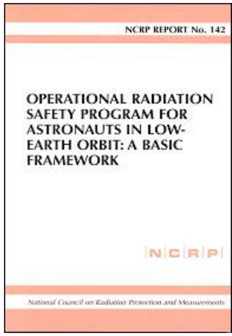
NCRP Report No. 153 (2006)
Information Needed to Make Radiation Protection Recommendations for Space Missions Beyond Low-Earth Orbit

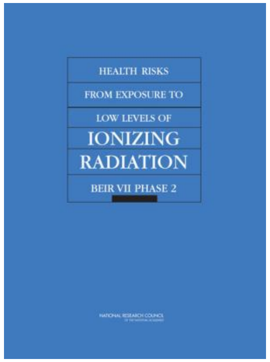
NCRP Report No. 142 (2002)
Operational Radiation Safety Program for Astronauts in Low-Earth Orbit: A Basic Framework

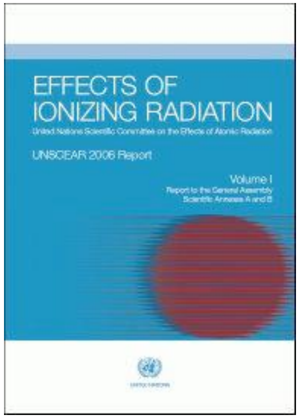
NCRP Report No. 132 (2000) - Current Basis of NASA Std 3001 Limits
Radiation Protection Guidance for Activities in Low-Earth Orbit

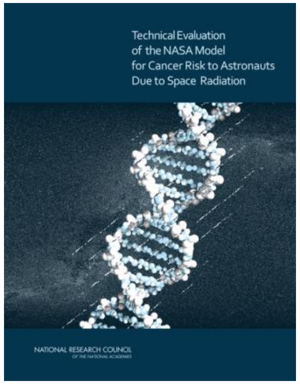


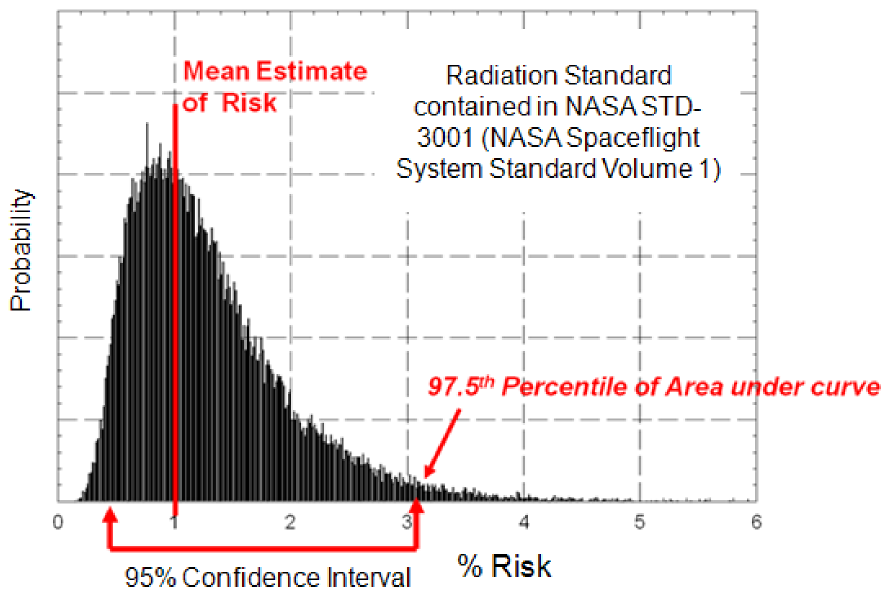

# NASA Permissible Exposure Limits (PELs)

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

# Limits on Tissue Reactions (Deterministic Effects) Short-term or Late Non-cancer Effects

•**Short-term dose limits** are imposed to prevent clinically significant non-cancer health effects including performance degradation, sickness, or death in-flight.

•**Career dose limits** for cataracts, heart disease, and damage to the central nervous system are imposed to limit or prevent risks of degenerative tissue diseases (e.g., stroke, coronary heart disease, etc.)

•Both the probability and severity of non-stochastic effects increase with dose above a threshold dose where clinical effects can be observed

•The protections unit for the tissue reaction effects is the *Gray-Equivalent:*

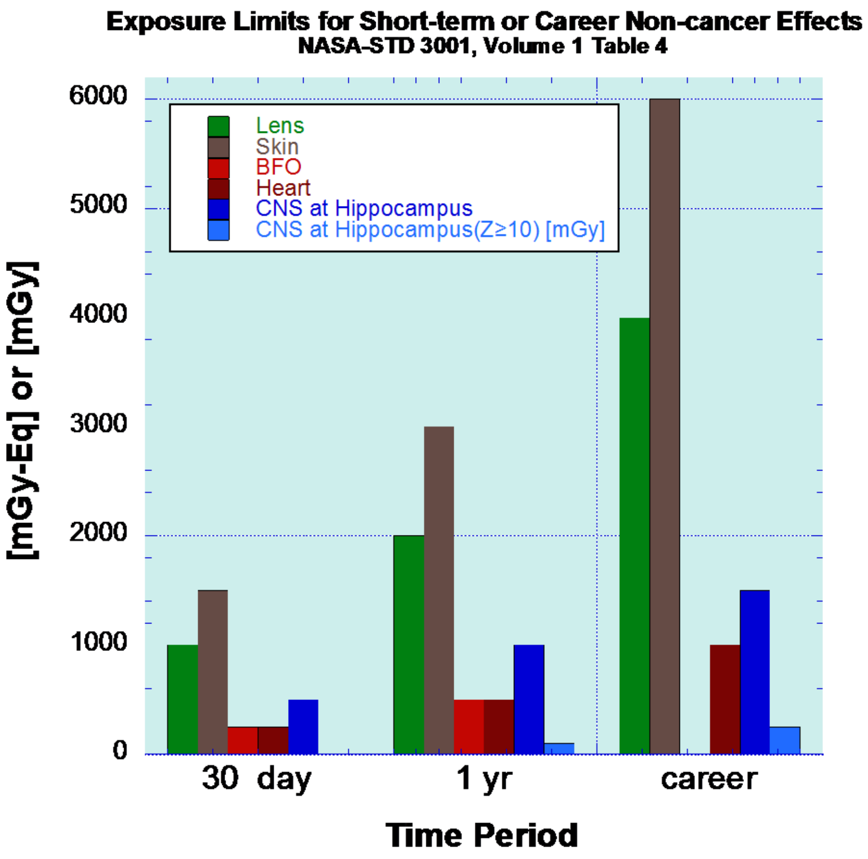
$$G_T = RBE \cdot D_T$$

*RBE* = Relative Biological Effectiveness  $D_T$= Tissue dose

| *Radiation Type* | *Recommended RBE*[b] | *Range* |
|---|---|---|
| 1 to 5 MeV neutrons | 6.0 | (4-8) |
| 5 to 50 MeV neutrons | 3.5 | (2-5) |
| Heavy ions | 2.5[c] | (1-4) |
| Proton > 2 MeV | 1.5 | - |

# Space Permissible Exposure Limits for Early or Late Non-cancer Effects

| Organ | 30 day limit | 1 Year Limit | Career |
|---|---|---|---|
| Lens * | 1000 mGy-Eq | 2000 mGy-Eq | 4000 mGy-Eq |
| Skin | 1500 | 3000 | 6000 |
| BFO | 250 | 500 | Not applicable |
| Heart** | 250 | 500 | 1000 |
| CNS *** | 500 | 1000 | 1500 |
| CNS*** (Z≥10) | | 100 mGy | 250 mGy |



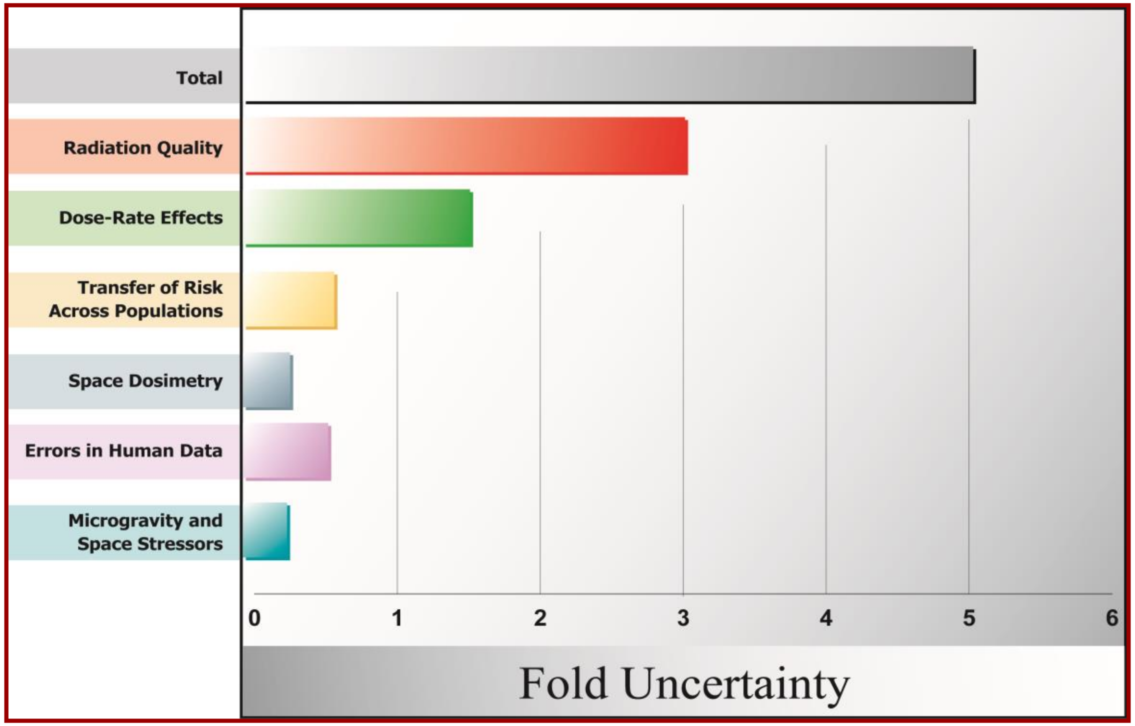

*Lens limits are intended to prevent early (< 5 yr) severe cataracts (e.g., from a solar particle event). An additional cataract risk exists at lower doses from cosmic rays for sub-clinical cataracts, which may progress to severe types after long latency (> 5 yr) and are not preventable by existing mitigation measures; however, they are deemed an acceptable risk to the program.

**Heart doses calculated as average over heart muscle and adjacent arteries.

***CNS limits should be calculated at the hippocampus.

# Radiation Carcinogenesis

- Cancer risk is a major driver (limiter) for Space Radiation PELs
- Morbidity and mortality risks for a wide variety of cancers including lung, breast, colon, stomach, esophagus, the blood system , liver, bladder, skin, and brain
- A-bomb survivor cancer incidence used as basis for risk modeling
- Dose limits correspond to permissible limit of 3% fatal cancer at 95% confidence
- Research results support development of an integrated risk model with acceptable uncertainty for exploration missions




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

# 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), 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

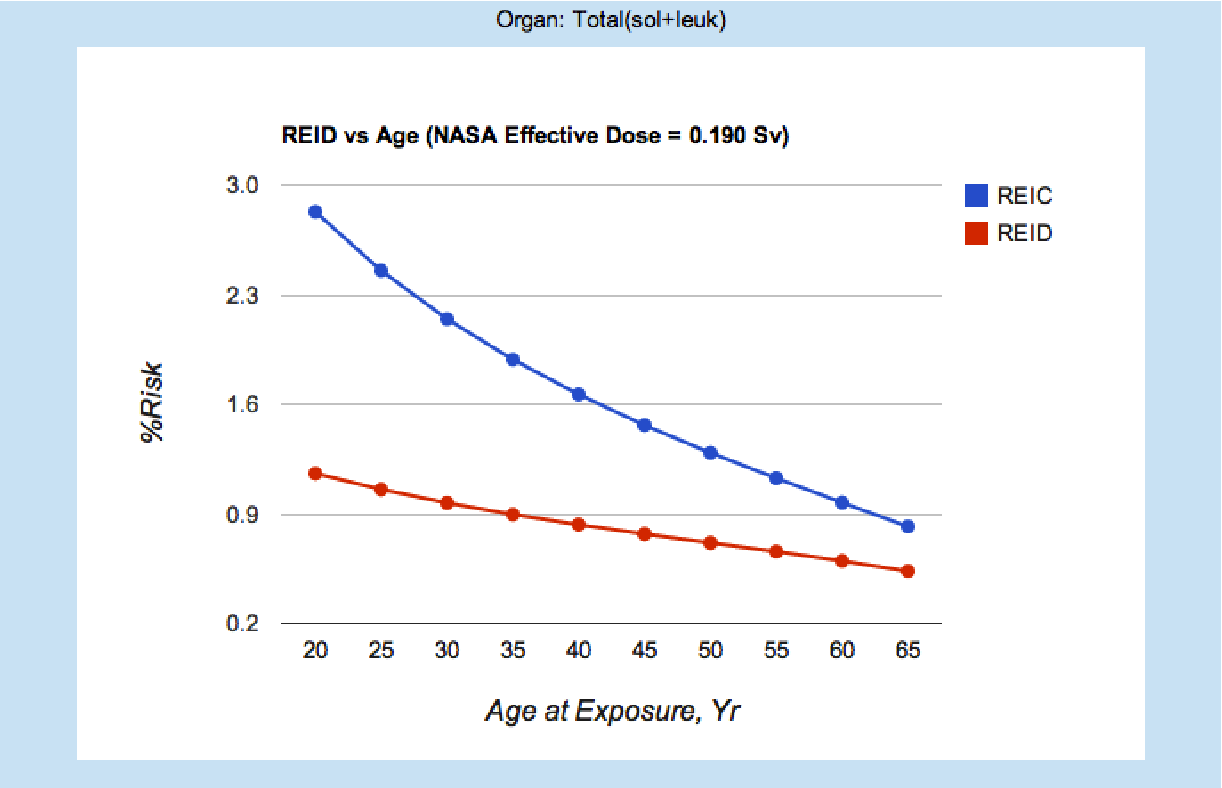
**Terrestrial Research**
-NIH/NCI – Terrestrial Cancer Research
-DOE/DOD/DARPA – Radiation Effects Research
-International Research Activities

**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).

# Cancer Risk vs. Age Model Output

Example model outputs:



# Gender Dependence – per NCRP Commentary 23

TABLE 1.1—Sex-specific differences in the excess relative risk (ERR) per gray for major cancers (adapted from Ozasa *et al.*, 2012).

| Cancer Type | ERR $Gy^{-1}$ (averaged over both sexes)[a] | Female to Male Ratio (sex-specific ERR $Gy^{-1}$ estimates) |
|---|---|---|
| All solid cancers | 0.42 | 2.1[b] |
| Esophagus | 0.60 | 4.3 |
| Stomach | 0.33 | 3.7 |
| Colon | 0.34 | 1.4 |
| Liver | 0.38 | 1.6 |
| Gallbladder | 0.48 | 0.43 |
| Lung | 0.75 | 2.7 |
| Bladder | 1.19 | 1.7 |
| **Cancer Type (sex-specific organs)** | **ERR $Gy^{-1}$ (age averaged)** | **Not Applicable** |
| Female breast | 1.5 | |
| Ovary | 0.79 | |
| Prostate | Little evidence for an association with radiation (UNSCEAR, 2008) | |
| Testicular | Little evidence for an association with radiation (UNSCEAR, 2008) | |

[a]The sex-averaged ERR $Gy^{-1}$ is shown for subjects at the attained age of 70 y after exposure at age 30 y.

[b]A ratio of 2.1 can be interpreted as females having a risk of radiation-induced cancer death that is 2.1 times that of males. These patterns generally hold when estimates are based on excess absolute risk per gray and for cancer incidence data as well (Preston *et al.*, 2007).

# Individual Organ and Tissue Contributions to Cancer Risk

For crew members at mid-mission age 47y ISS at 400 km during Solar Minimum Activity

| | Males | Females | |
|---|---|---|---|
| >20% | **LUNG** | **LUNG** | >35% |
| >10% | BFO (leukemia) | stomach | |
| | **COLON** | BFO (leukemia) | |
| | stomach | **COLON** | |
| | bladder | **OVARIAN** | |
| | liver | **BREAST** | |
| >5% | remainder organs | remainder organs | |
| | prostate | liver | |
| | esophagus | bladder | |
| | brain | brain | |
| | oral mucosa | esophagus | |
| | skin | uterus/cervix | |
| | testes | oral mucosa | |
| | thyroid≈0 | skin | |
| | | thyroid≈0 | |

For the organs listed in ALL CAPS, improved curability may be affected with frequent cancer screening for early-stage tumor detection.

# NSCR-2012 Dosimetry Results

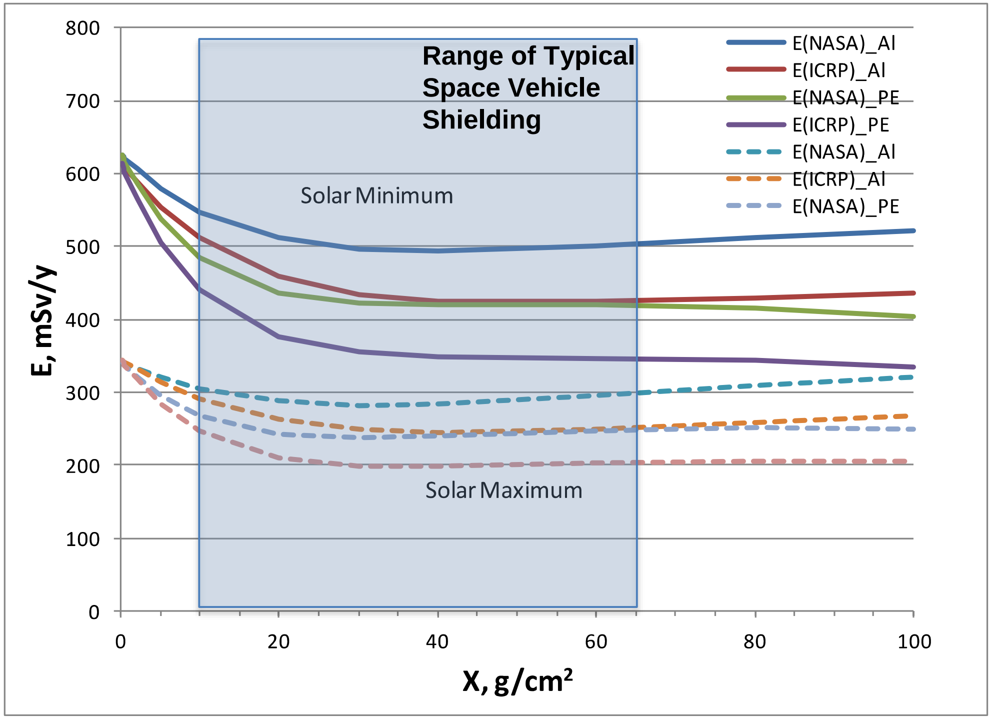
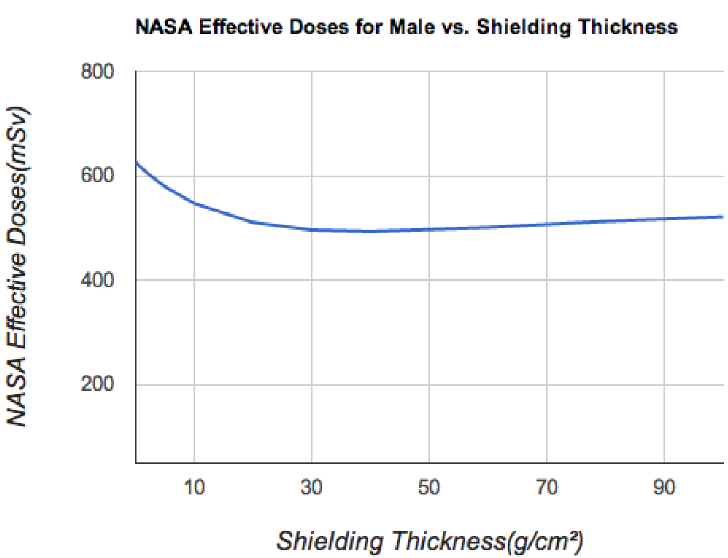



**Figure 6.6.** Annual GCR Effective doses or NASA Effective dose in deep space vs. depth of shielding for males. Values for solar minimum and maximum are shown.

## 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**

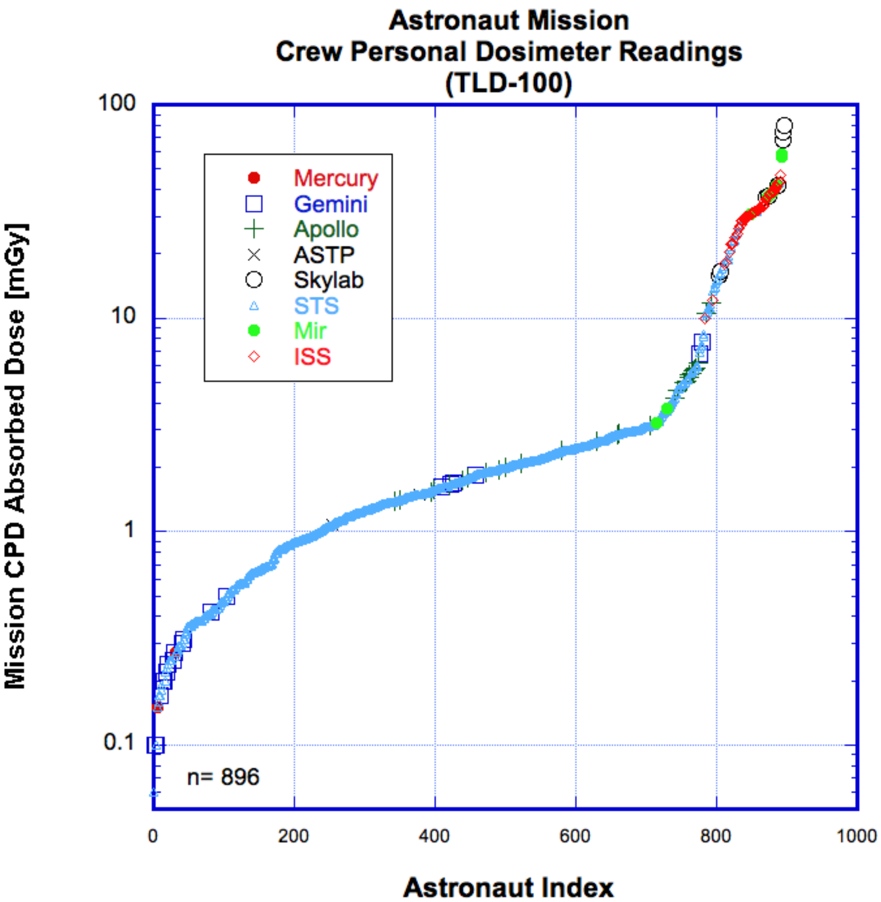
in Deep Space to have 95% Confidence Level to be below the NASA Limit of 3%. Calculations are for average solar maximum assuming large August of 1972 SPE with 20g/cm$^2$ aluminum shielding. Values in parenthesis without the 1972 SPE event and ideal storm shelters/monitoring which would reduce SPE doses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

# Individual Mission Doses/ Informing Crew of Radiation Risk




## Astronaut Annual Radiation Risk Report & Safe Days

*This information is subject to the Privacy Act of 1974, as amended.*

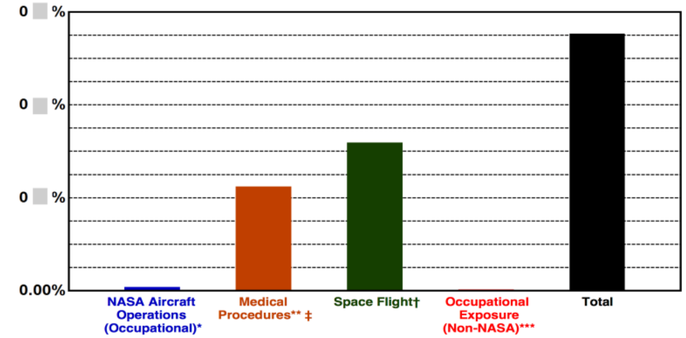
**Name:** 　　　　　　　　**Date of Report:** 8/29/2014

### Radiation Exposure History and Cancer Risk Summary

| | Radiation Source | | | | |
|---|---|---|---|---|---|
| | NASA Aircraft Operations (Occupational)* | Medical Procedures** ‡ | Space Flight† | Occupational Exposure (Non-NASA)*** | Total |
| Effective Dose (mSv) | .85 | .62 | .56 | 42 | .44 |
| Projected Increased Risk of Cancer Incidence | 0. % | 0. % | 0 % | 0. % | % |
| Projected Risk of Exposure Induced Death (REID) | % | % | % | % | % |

### Projected REID

(NASA SPEL = 3% REID at a 95% CI)




**Findings:**

1. **This astronaut has a 0.55% increased REID from occupational radiation exposure.**
2. **REID point estimate is approximately 48.0% of the NASA SPEL.**
   (The NASA SPEL is represented by the upper limit of the 95% confidence interval around a 1.15% REID point estimate)

* Estimated using 0.0026 mSv per hour of air-time logged
** Cancer risk from medical exposures is provided for informational purposes; some exposures may not affect flight eligibility.
*** Includes documented occupational radiation exposure received outside of NASA
† This report was created from data through the complete mission beginning in Expedition-
‡ Contains preliminary Medical results that will be updated upon receipt of additional data.

ISS Mission Projection
Number of Safe Days remaining on ISS

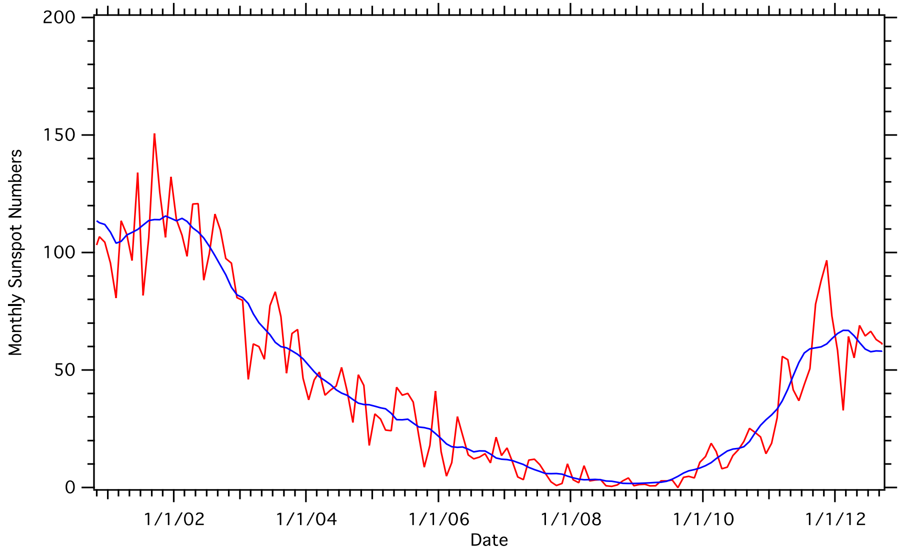
Mission beginning ~2014: 8 days
Mission beginning ~2019: 4 days

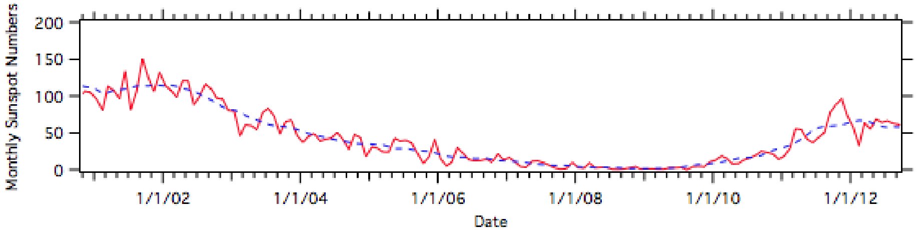
Edward J. Semones, RHO

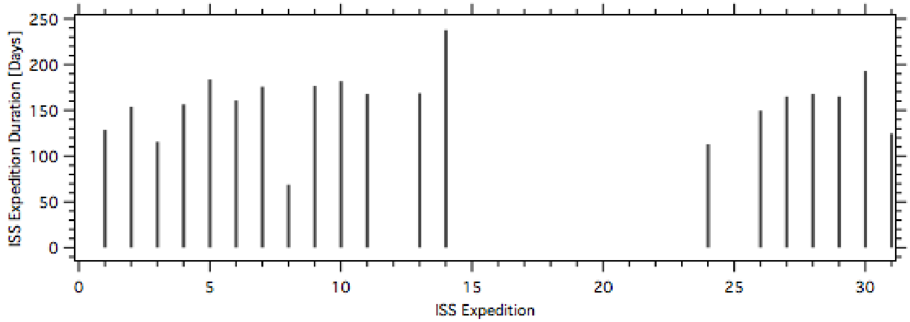
# Acute Radiation Effects from a Solar Particle Event

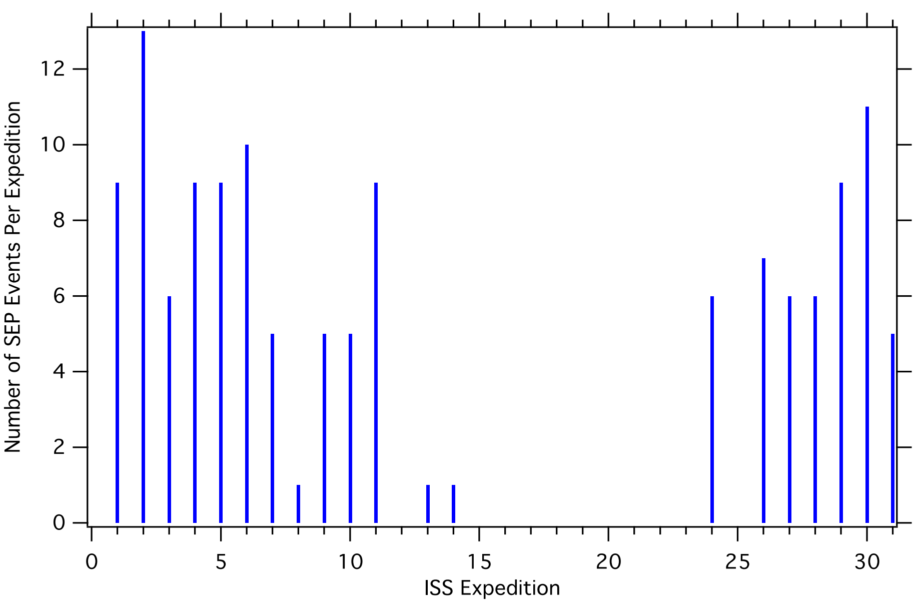
- 30-day and yearly limits to the BFO and skin are intended to protect astronauts from acute radiation syndromes (ARS) including the prodromal risks (i.e., nausea, vomiting, anorexia, and fatigue), alterations to the hematopoietic system, and skin injury resulting from exposure to a large solar particle 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

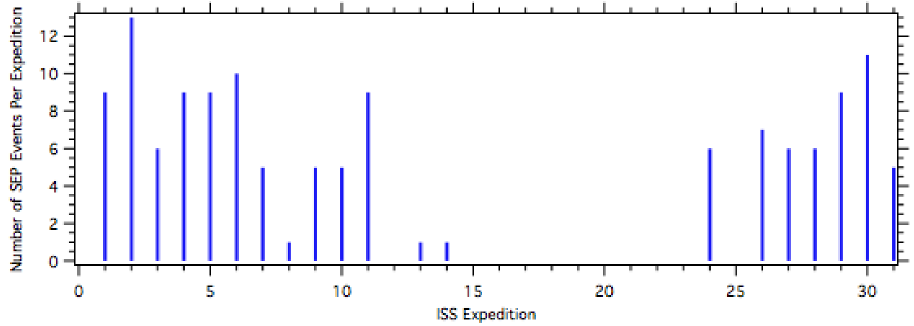
# SPE Impacts during ISS era

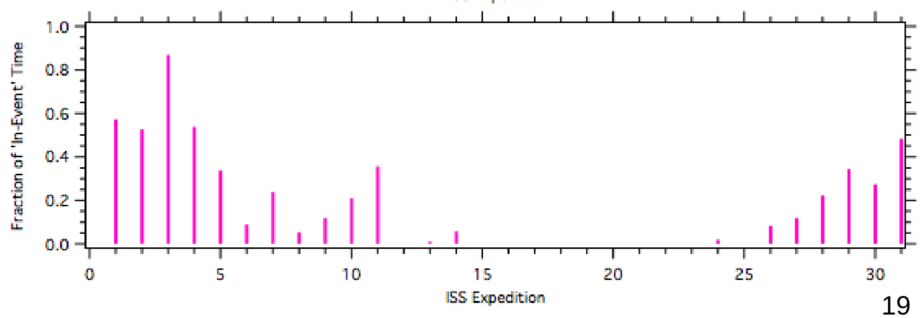


# HEOMD SPE Now-casting Needs

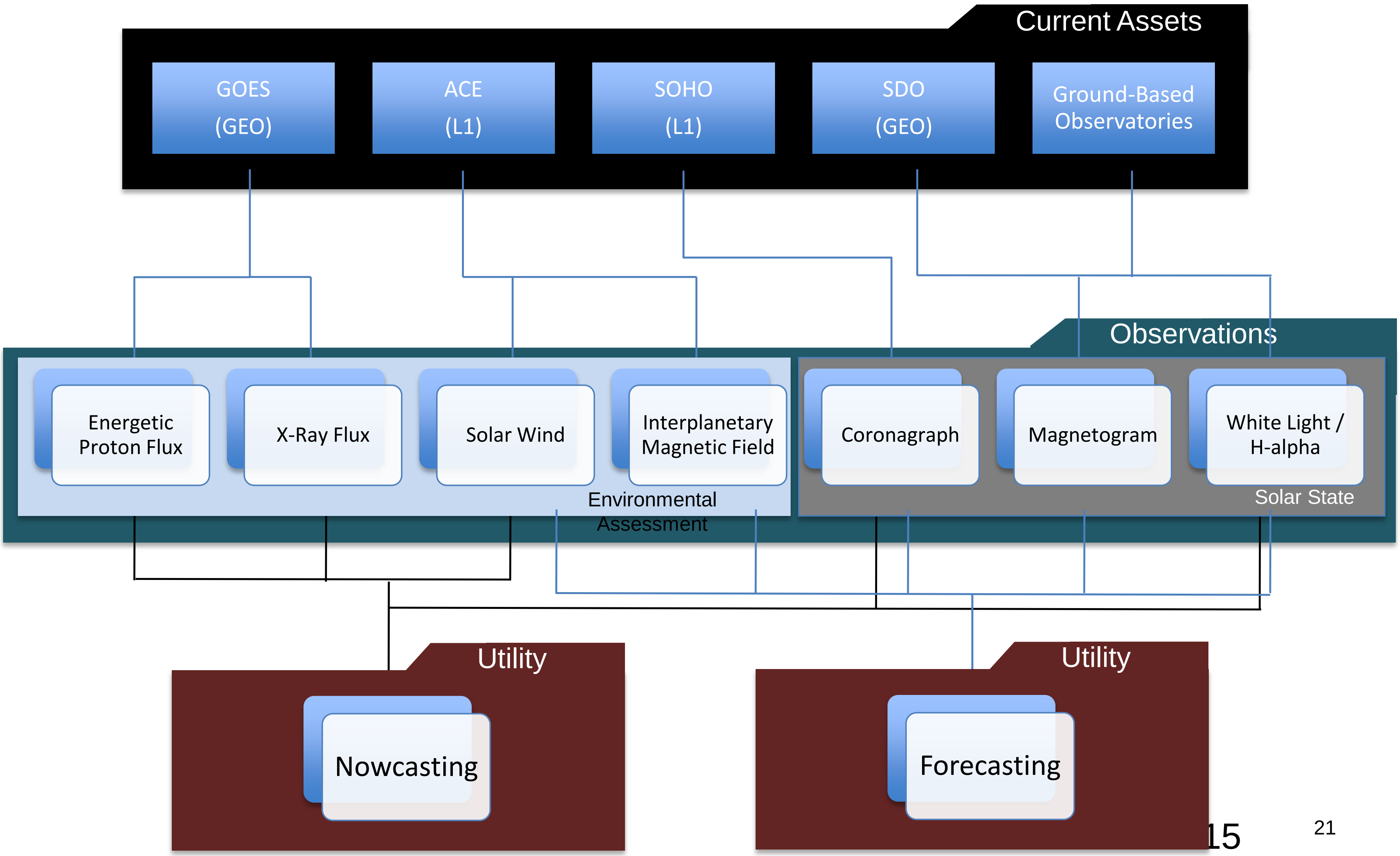
| Nowcasting Data Streams* (ordered in terms of decreasing priority) | | | |
|---|---|---|---|
| **Data Stream** | | **Utility** | **Current Asset**** |
| Energetic Proton Flux | | Real-time situational awareness | GOES/ACE/STEREO |
| X-Ray Flux | | Real-time SPE pre-cursor | GOES |
| H-alpha | | Active region identification and characteristics | Mt Wilson, GONG |
| White Light Imagery | | Identification of x-ray flare origination | Mt Wilson, GONG, other international observatories (all ground-based) |
| Coronagraph | | Real-time observation of CME onset; determination of speed, direction and spread | SOHO/STEREO |
| Solar Wind | Speed | Real-time assessment of CME characteristics and impact | ACE |
| | Density | | |

Assets in red denote SMD missions either past expected lifetime or lifetime reached in next 5 years.

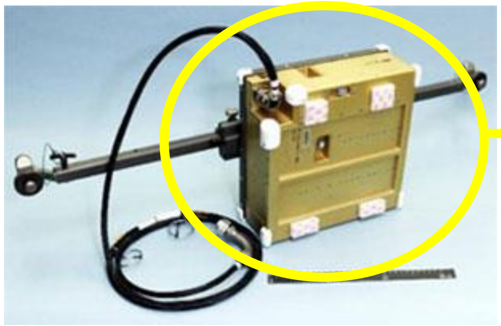
*The need is not mission specific. All assessment based upon the current state of knowledge of fundamental solar activity drivers, forecasting model maturity, and operational need.

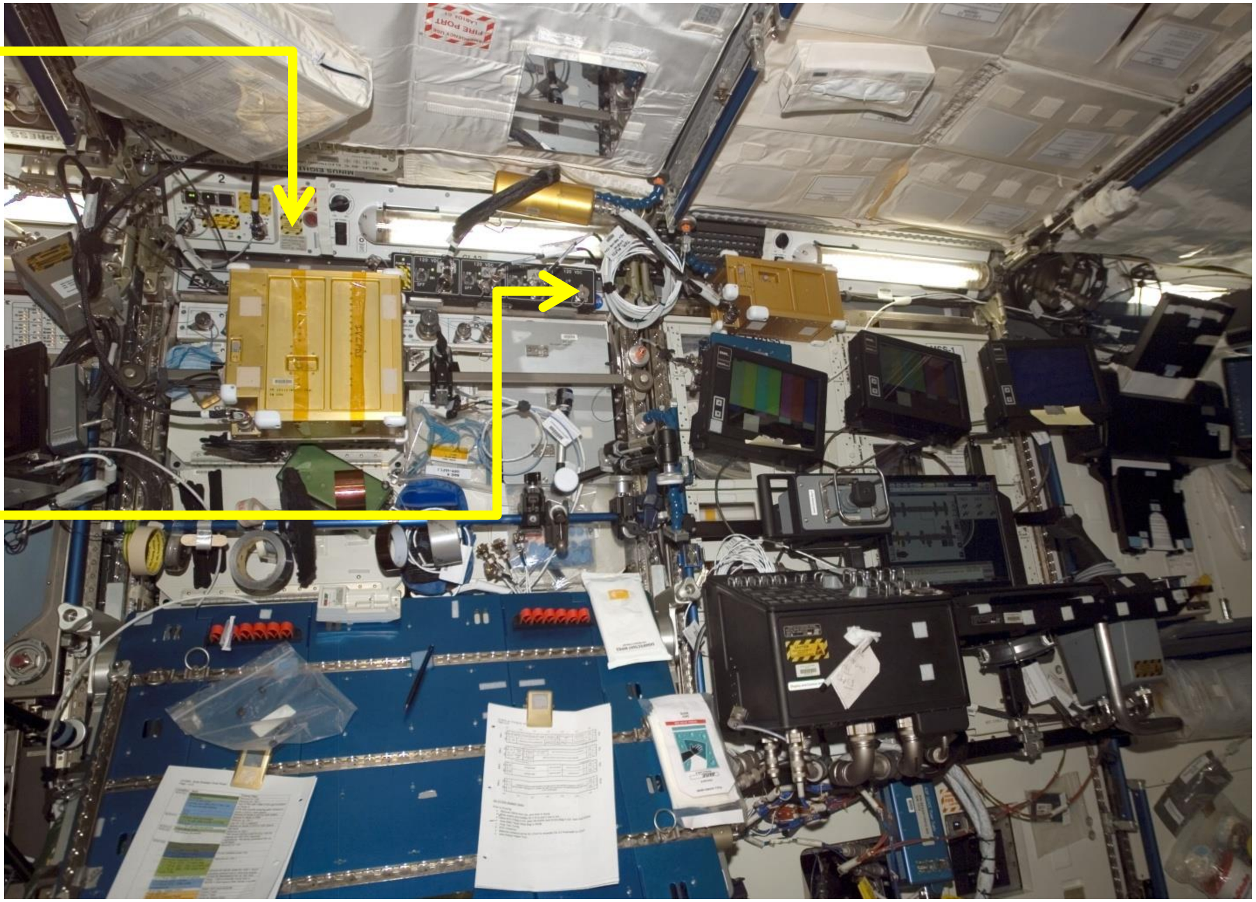
**The only dedicated operational asset with planned replenishment resources is GOES. ACE, SOHO, STEREO, and SDO are science missions. ACE and SOHO have already far exceeded expected lifetime. SDO science mission till 2015 but enough fuel to last till 2018. STEREO is currently around back side of Sun.

# SPE Data Utility – current suite



# ISS Operational Instruments Provide Real-time Dosimetry and Alarming



**EV/IV detailed radiation survey information**

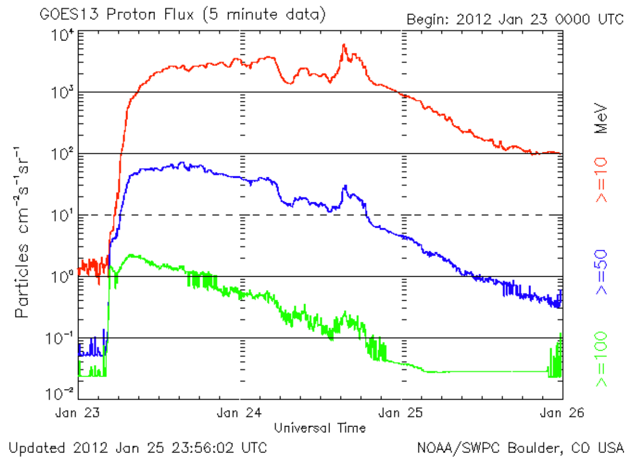
# Protecting ISS Crew: Solar Particle Event (SPE) Action Summary

- 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

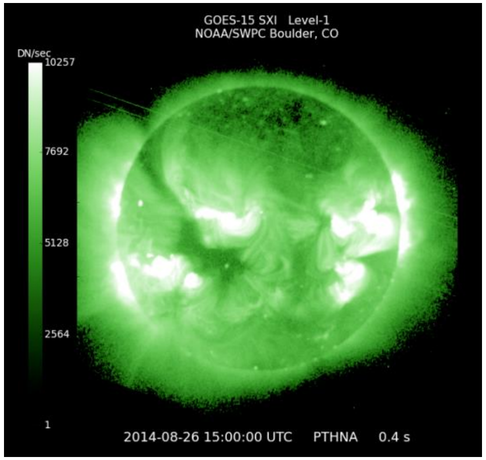
- If SPE dose projection is determined to be negligible, then no action will be taken

- 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.

- 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*



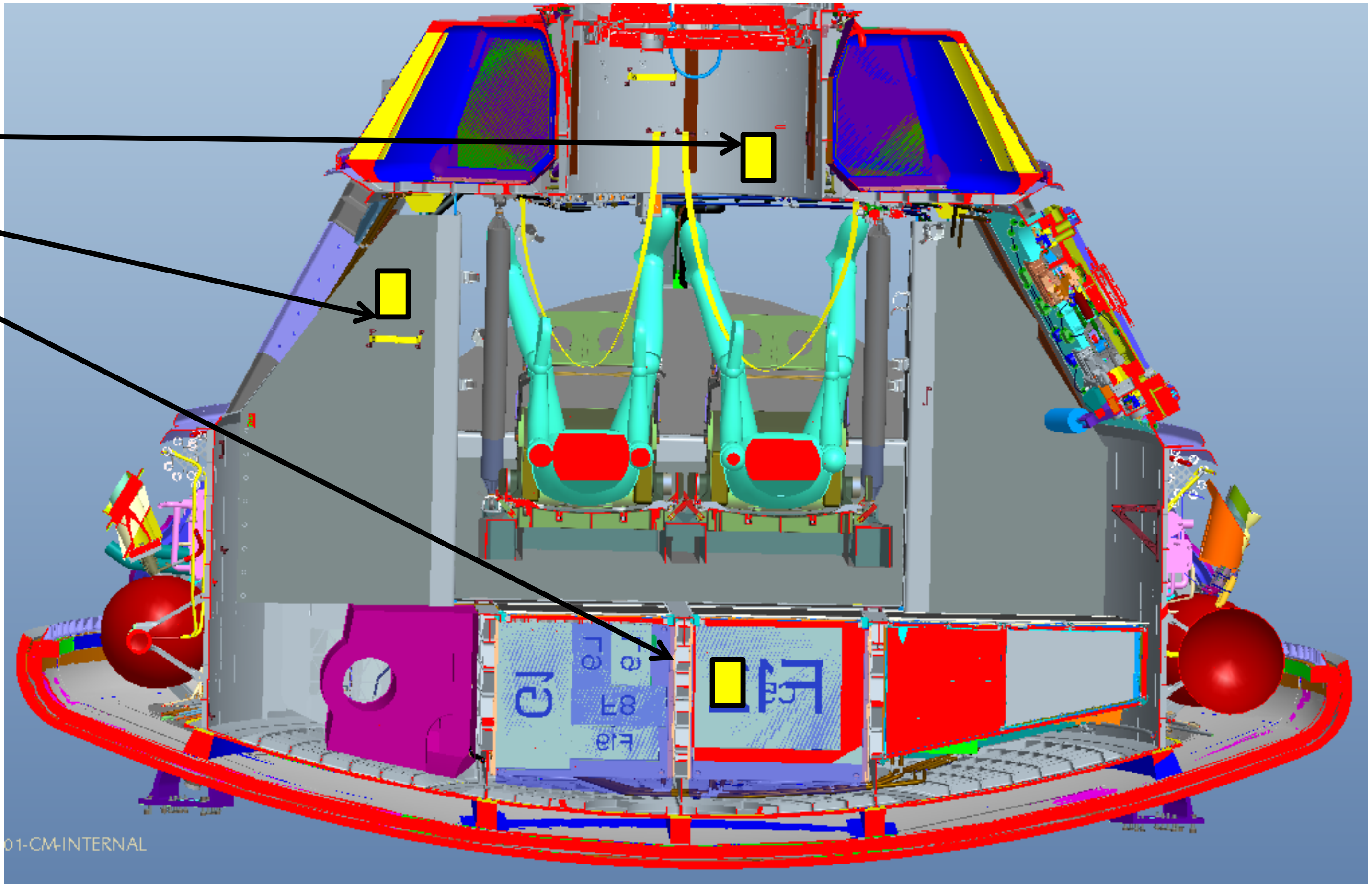

*GOES Solar X-ray Image for the early detection of solar flares and coronal mass ejections*

# MPCV Radiation Monitoring System Concept

Distributed Detectors embedded within vehicle to provide continuous real-time dosimetry and alarming

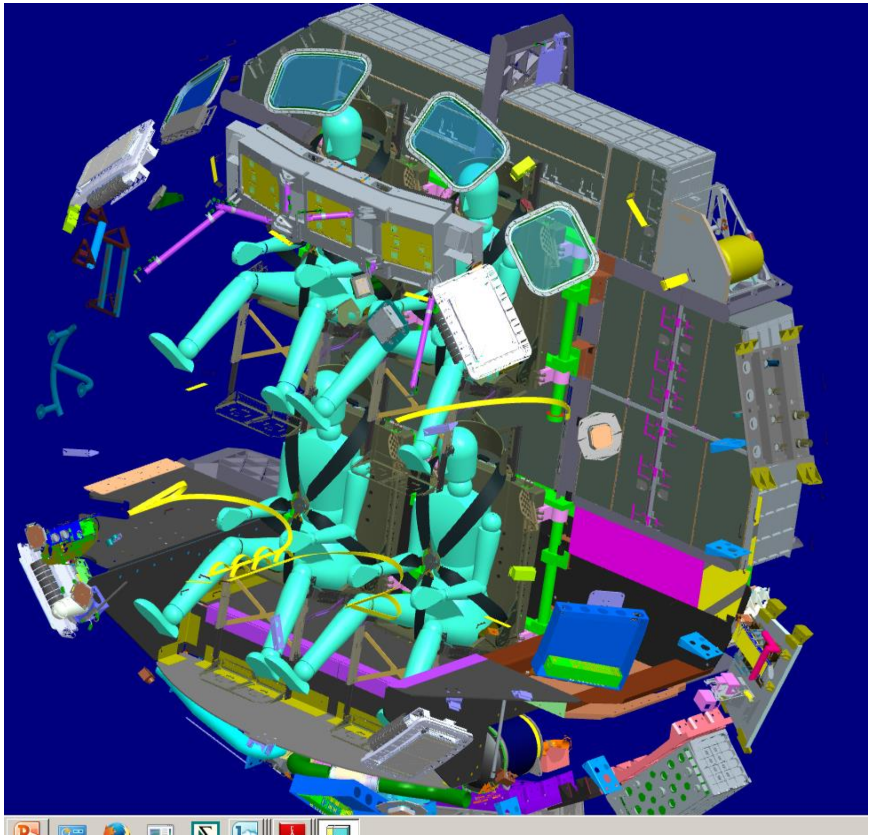
- Example Advanced Exploration Systems (AES) Developed HERA Sensor Units (HSUs) Mounting Locations:

HSUs

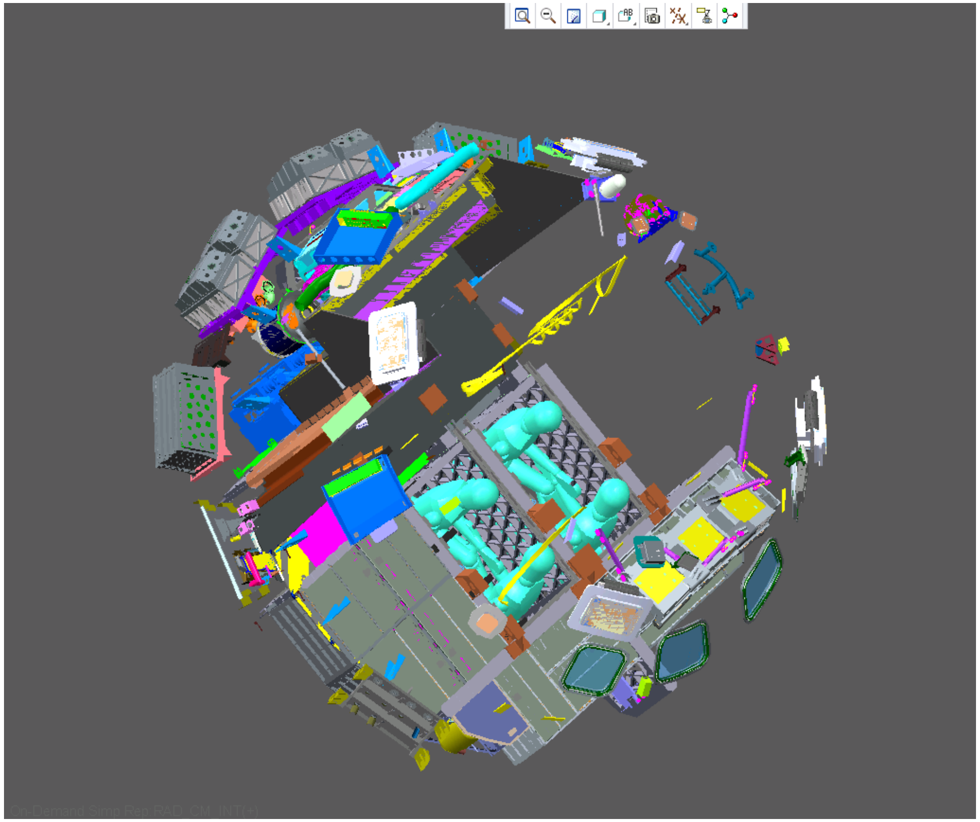


# MPCV SPE Operational Response

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