Protecting Astronauts from Space Radiation on the Lunar Surface

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Dr. Martha Clowdsley
NASA Langley Research Center

Outline

- Types of Radiation
- Radiation Transport
- Space Environments
- Radiation Exposure Quantities
- Effectiveness of Shielding Materials
- Radiation Protection Requirements and Suggested Design Goals
- Radiation Analysis Methods - OLTARIS
- Protection Methods
  - Wearable Protection
  - Storm Shelters
- Example SPE Protection Analyses
  - ISS-Derived Free Space Habitat
- Summary

Types of Radiation

- Ionizing radiation: subatomic particles, ions, atoms, and electromagnetic waves with enough energy to detach electrons from atoms
  - Sub-atomic particles:
    - alpha particles (helium nuclei resulting from nuclear decay)
    - beta particles (electrons and positrons resulting from nuclear decay)
    - neutrons
    - muons, mesons, etc.
    - Charged ions (atoms spanning the periodic table, which have been stripped of their electrons)
  - Electromagnetic waves:
    - gamma rays
    - x-rays
    - higher end of the ultraviolet part of the electromagnetic spectrum
- Non-ionizing radiation: electromagnetic waves, which can transfer energy to atoms, but do not have enough energy to detach electrons from atoms
  - lower end of the electromagnetic spectrum including visible light, infrared, microwaves, radio waves, and the lower part of the UV spectrum

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    - x-rays
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Most important component of space radiation

- Non-ionizing radiation: electromagnetic waves, which can transfer energy to atoms, but do not have enough energy to detach electrons from atoms
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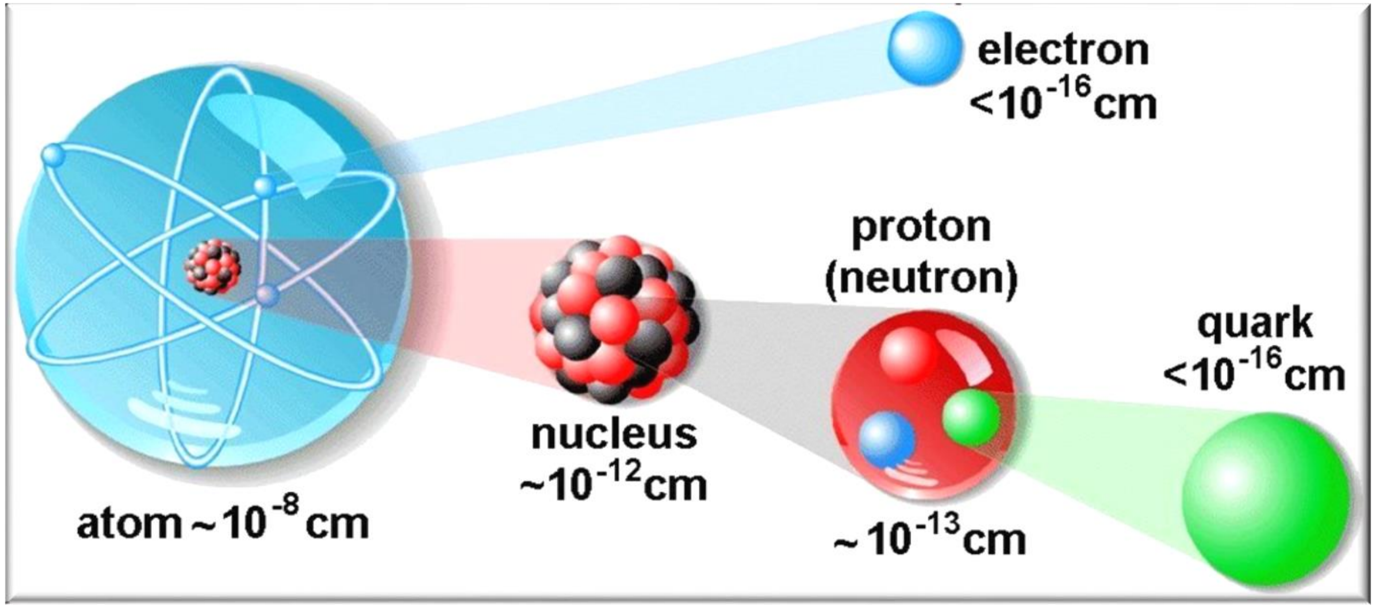
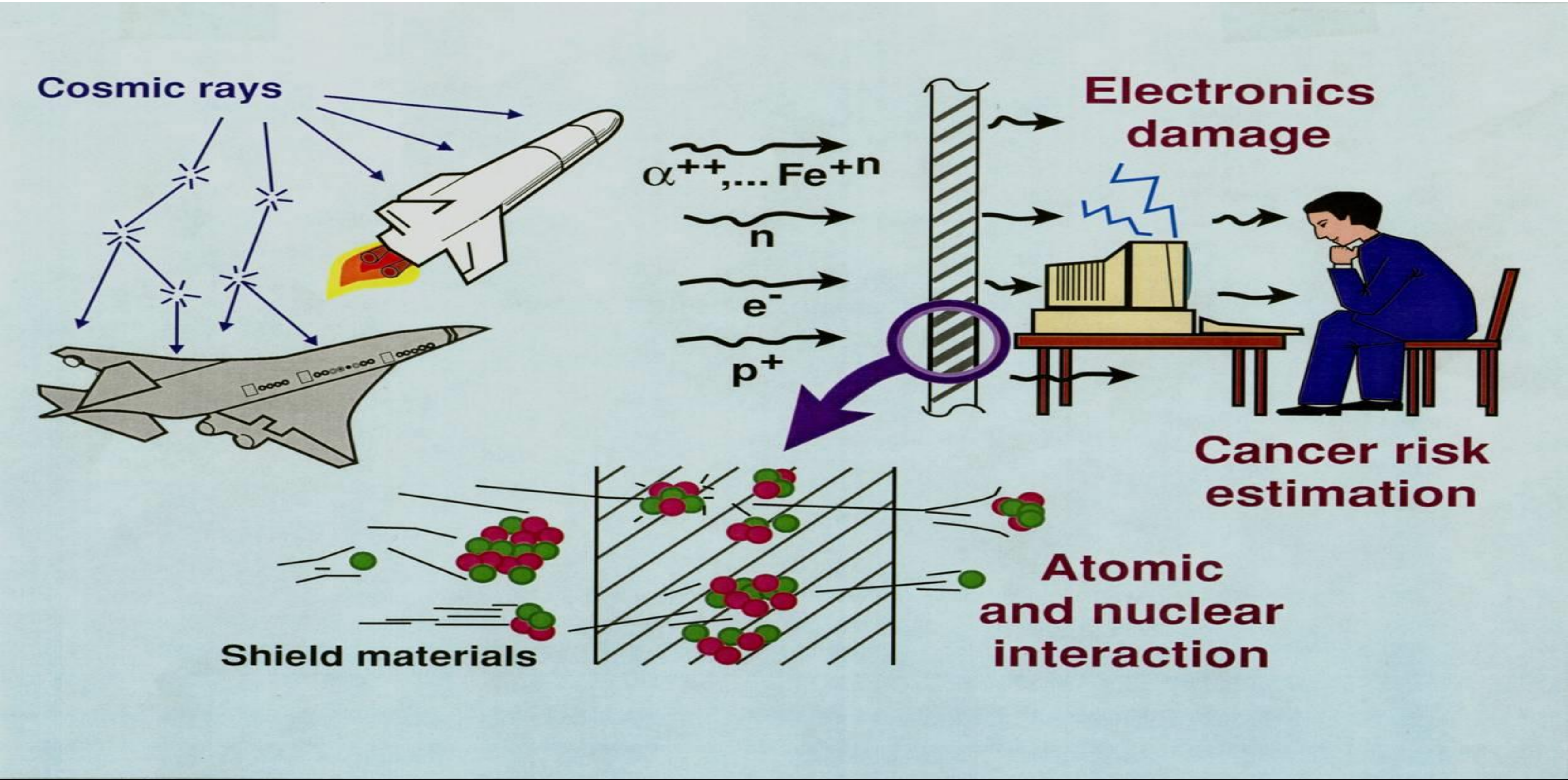
Charged Ions in the Space Environment

Charged ions making up the space environment are atoms spanning the periodic table, which have been stripped of their electrons.



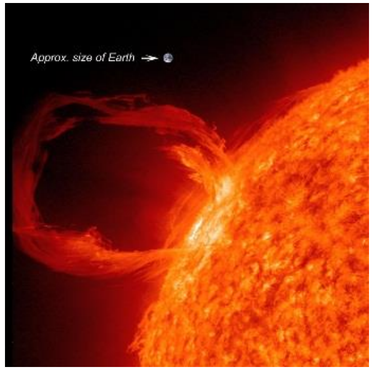
Credit U. of Toronto website: http://www.ehs.utoronto.ca/services/radiation/radtraining/module1.htm

Transport Through Shielding Material

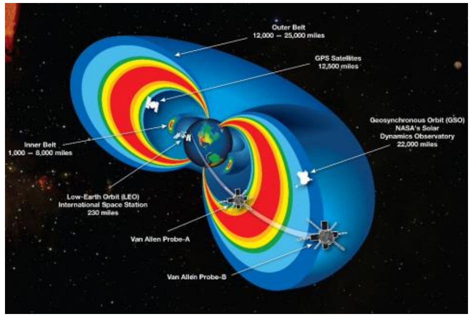


Space Radiation Environments

- Galactic Cosmic Rays (GCR)
  - Energetic charged ions spanning the periodic table
  - Always present, but varies in intensity with the solar cycle
  - Small daily exposure, but increases astronaut health risks for long duration missions
  - Difficult to shield due to deeply penetrating particles
- Solar Particle Events (SPEs)
  - Low to medium energy protons (hydrogen ions)
  - Associated with coronal mass ejections from the sun
  - Large SPE are rare and short lived
  - Size, spectral, and duration vary
  - Effectively shielded but optimization needed to reduce mass
  - Unshielded exposure could result in acute radiation syndrome
- Trapped Radiation (Van Allen Belts)
  - Low to medium energy protons and electrons
  - Effectively mitigated by shielding
  - Mainly relevant to ISS
  - Minimal risk for missions beyond Earth Orbit, if transitions through the belts are short
- Surface Environments
  - The Lunar surface environment is approximately half that of free space, due to the protection provided by the Lunar surface
  - The Martian environment provides some additional shielding for surface operations
    - GCR and SPE ions lose energy
    - Secondary particles are produced
  - Secondary particles, primarily low energy neutrons, are produced in the Martian and Lunar surfaces

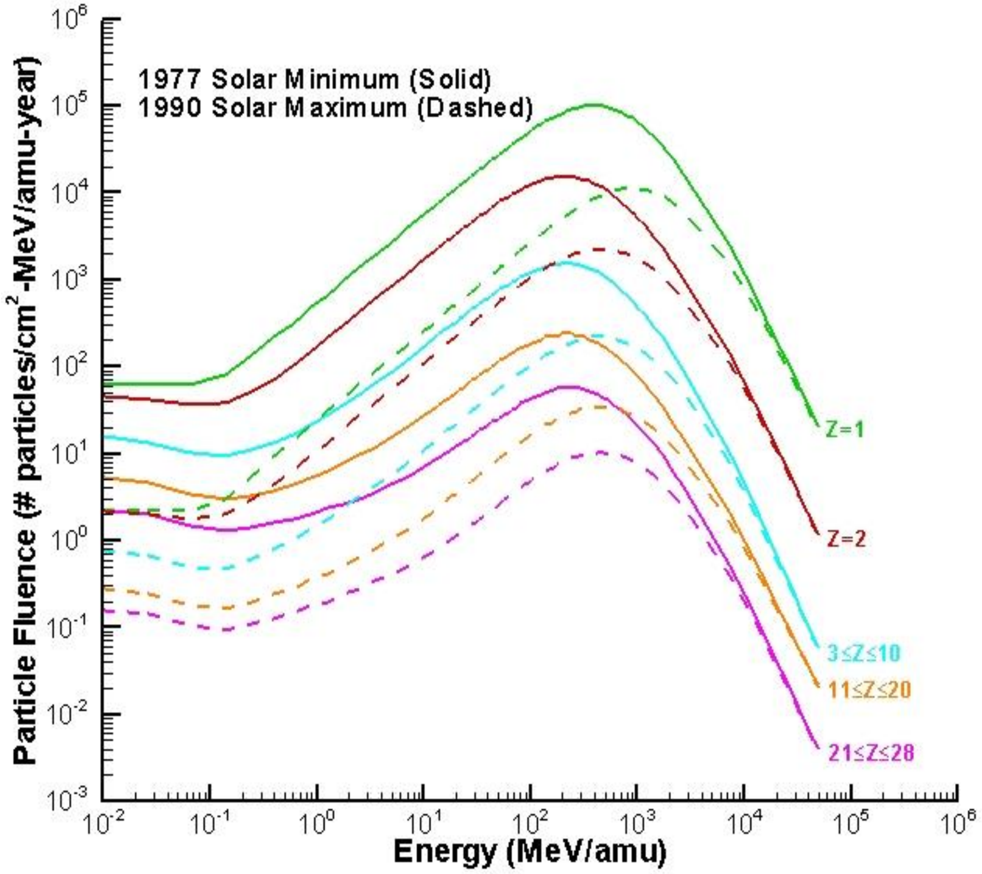


Coronal Mass Ejection

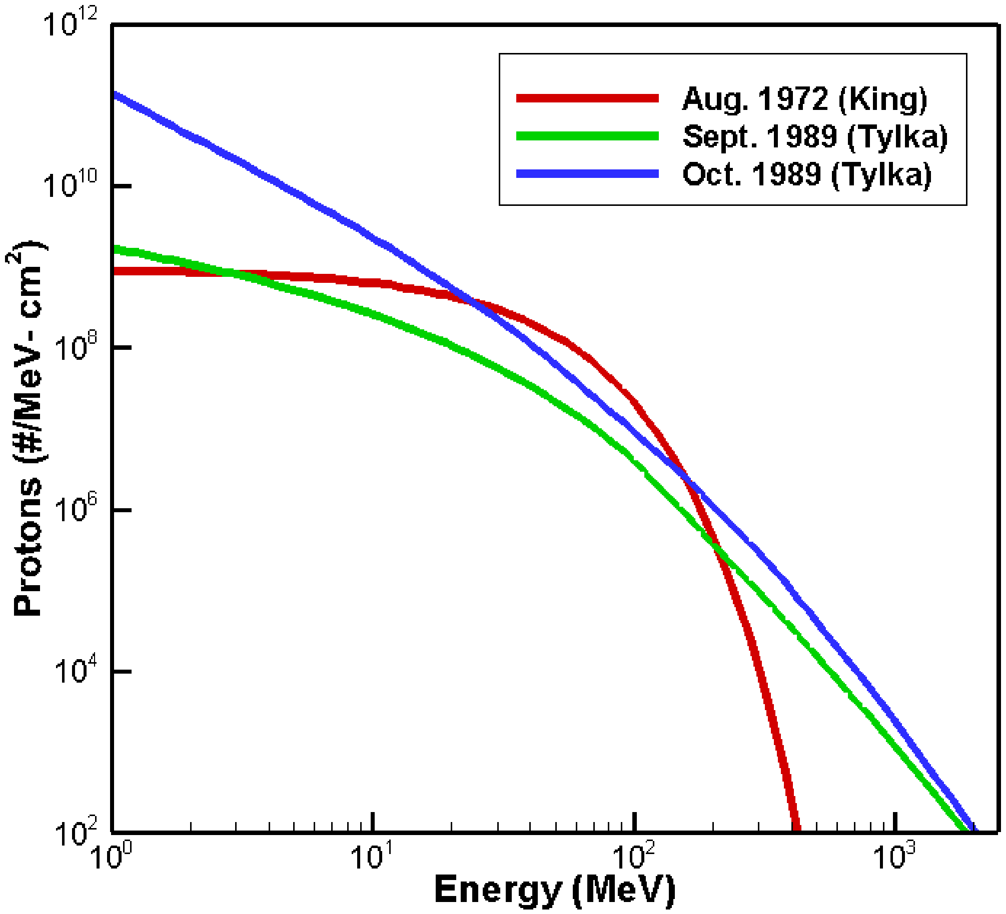


Van Allen Belts

Free Space GCR and SPE Environments

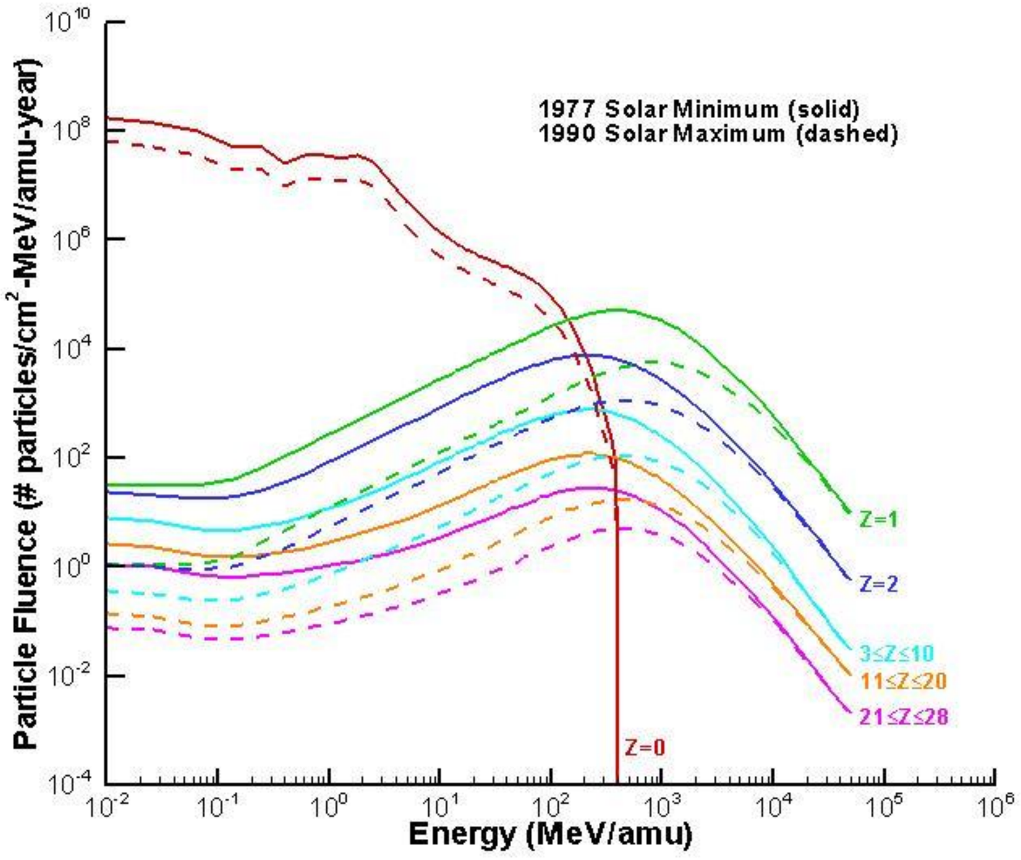


Galactic Cosmic Rays

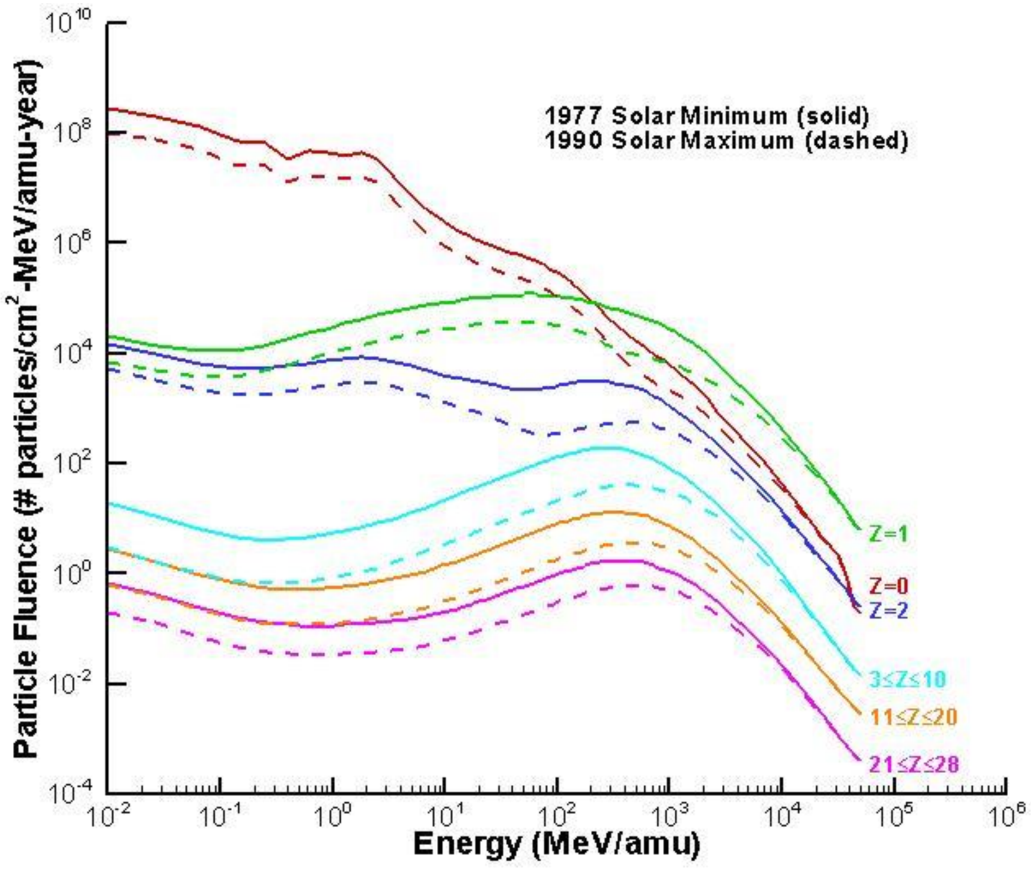


Solar Particle Events

Surface GCR Environments



Lunar Surface GCR Environment



Mars Surface GCR Environment

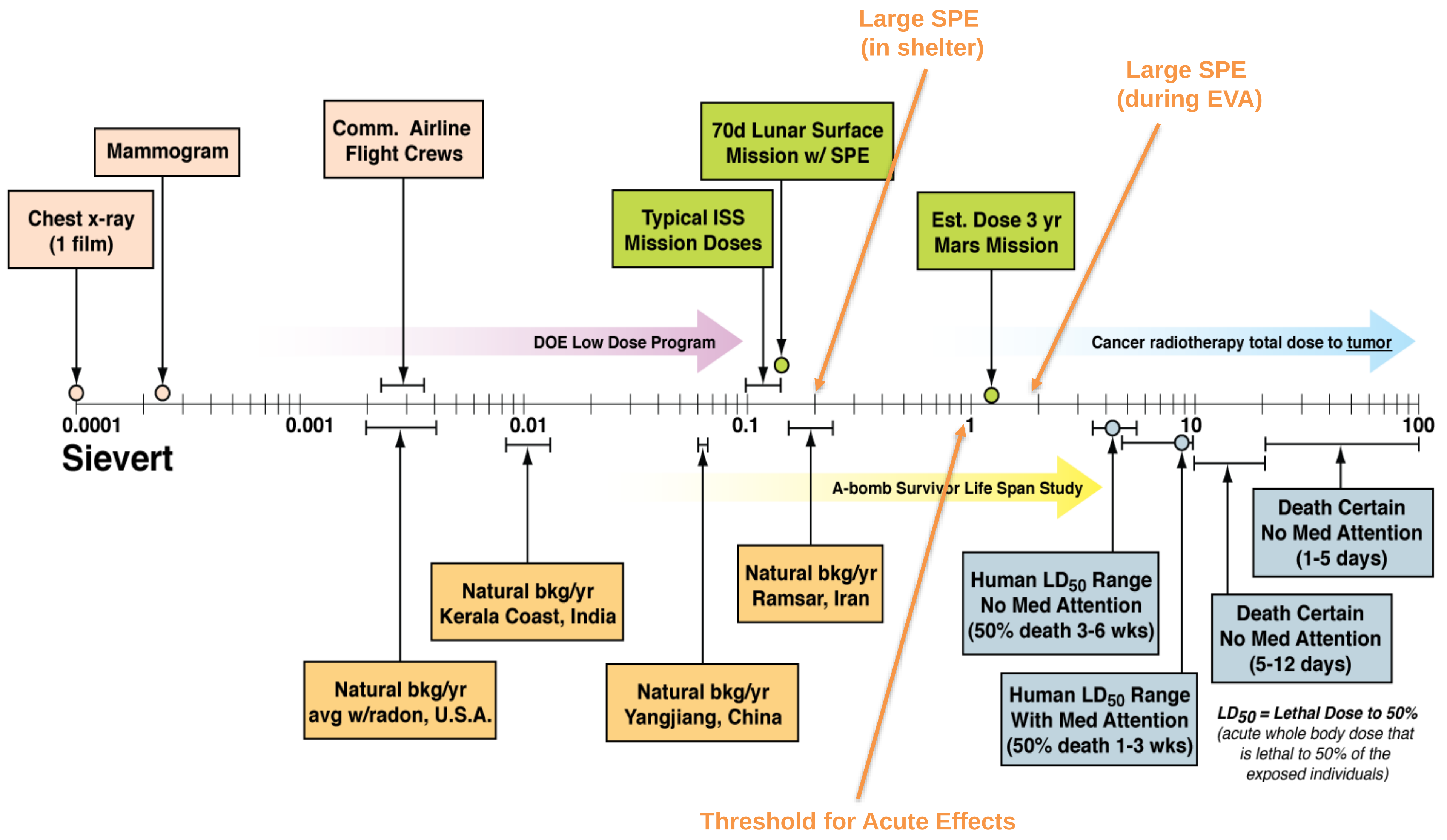
Radiation Exposure Quantities

- A variety of quantities are used to assess radiation exposure
- In some cases, different quantities use the same units
- The human body shields internal organs – Exposure quantities assessed in the human body will differ from point quantities

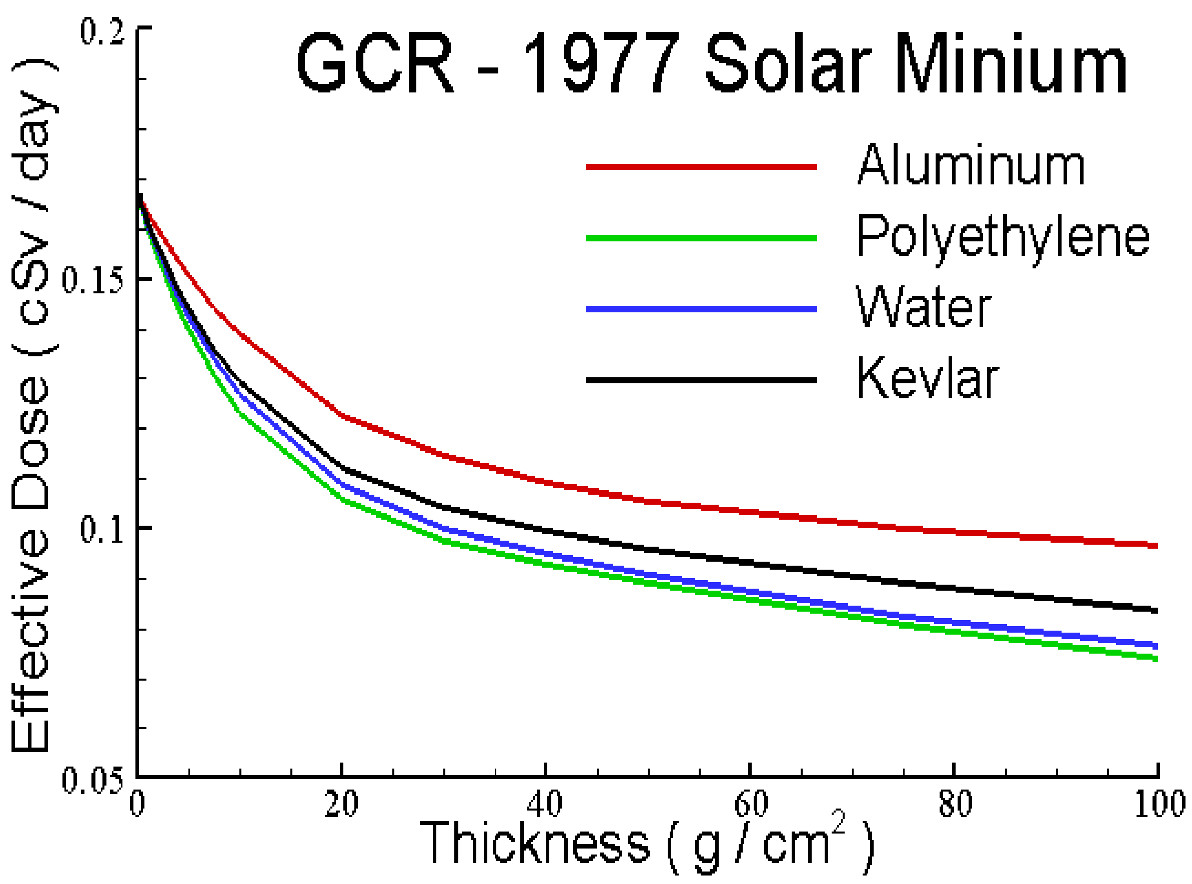
Dosimetric Quantities:

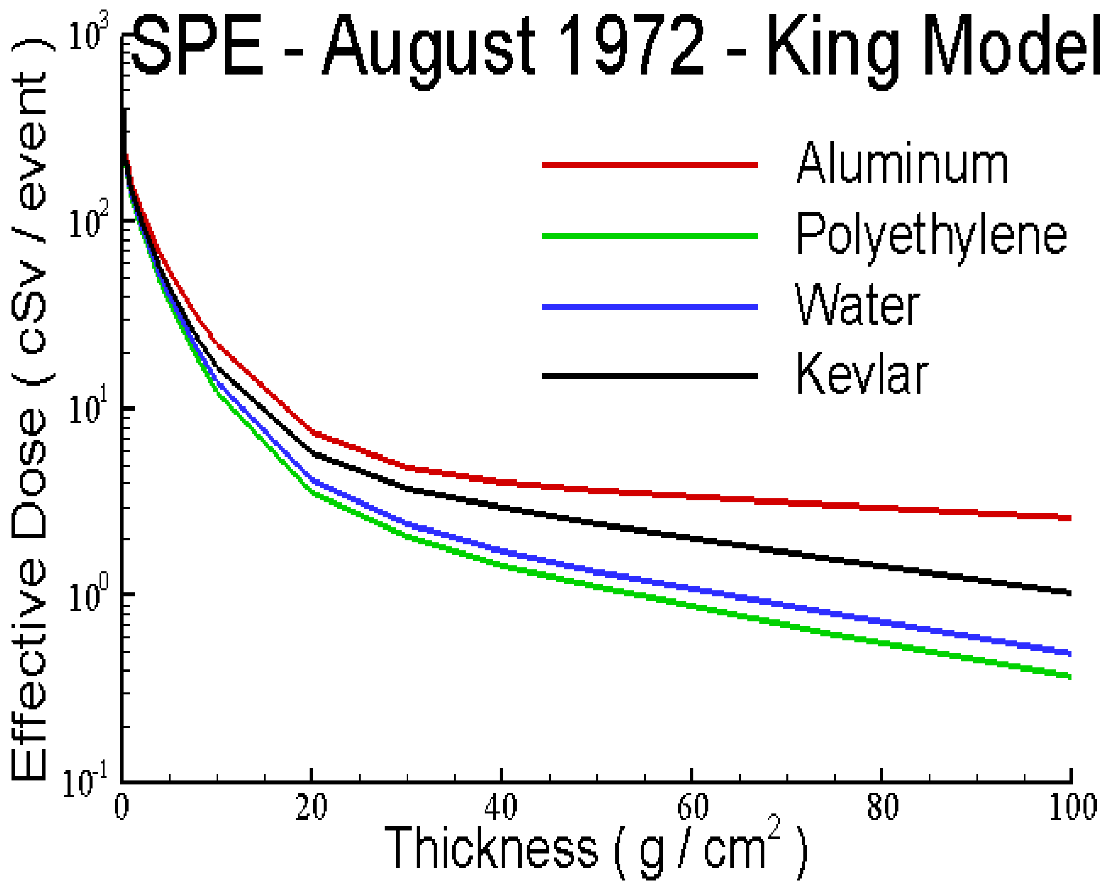
- **Dose (D)** – measured in grays (Gy)
  - Energy absorbed per unit mass of material
  - Point quantity
- **Dose Equivalent (H)** – measured in sieverts (Sv)
  - Dose integrated with a quality factor, which accounts for the varying ability of different types of particles to produce cancer
  - Point quantity
- **Organ/Tissue Averaged Dose Equivalent (H)** – measured in sieverts (Sv)
  - Assessment assumes the organ or tissue of interest is surrounded by a human body
- **Gray Equivalent (Gy-Eq)** – measured in gray equivalent (Gy-Eq)
  - Dose scaled by relative biological effectiveness (RBE) factors, which account for the varying ability of different types of particles to produce deterministic effects
  - Point quantity
- **Organ/Tissue Averaged Gray Equiv. (Gy-Eq)** – measured in gray equiv. (Gy-Eq)
  - Assessment assumes the organ or tissue of interest is surrounded by a human body
- **Effective Dose (E)** – measured in sieverts (Sv)
  - A weighted average of dose equivalent to sensitive organs and tissues
  - Whole body quantity
- **Risk of Exposure Induced Death (REID)** – measured in percent (%)
  - Probabilistic assessment of increased risk of dying of cancer due to radiation exposure
  - Whole body quantity

Space Radiation in Context



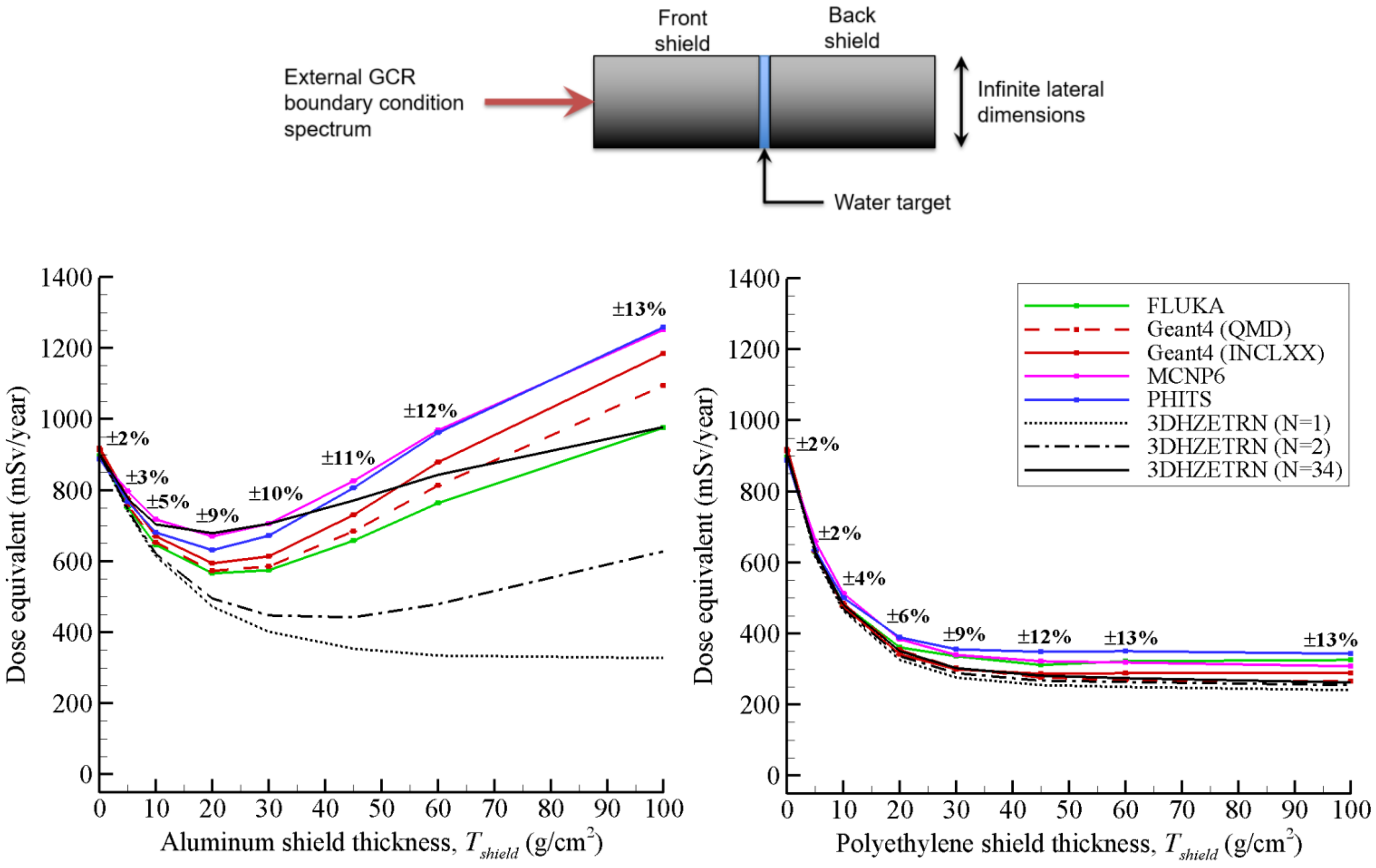
Effectiveness of Shielding Materials – Old Paradigm





Shielding materials are more effective for Solar Particle Events than for the GCR environment and hydrogen rich materials provide better protection.

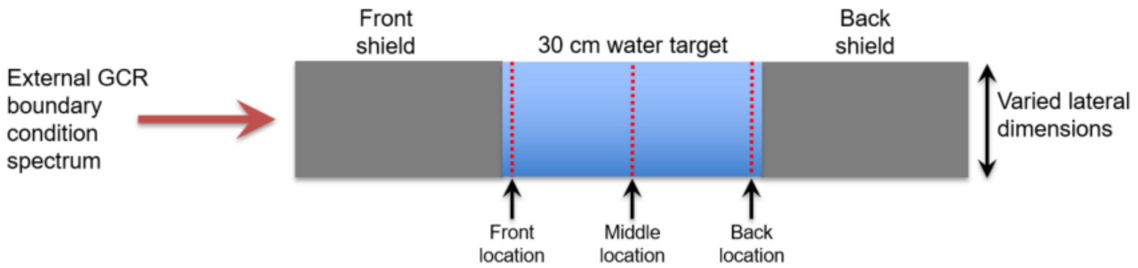
Effectiveness of Shielding Materials – New Paradigm

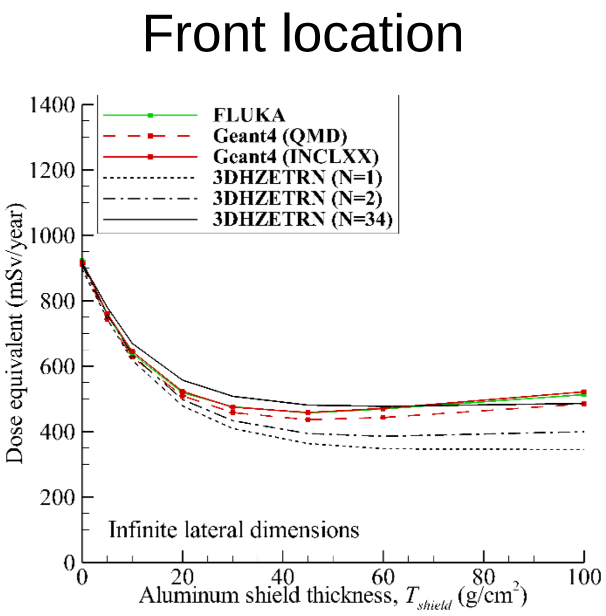


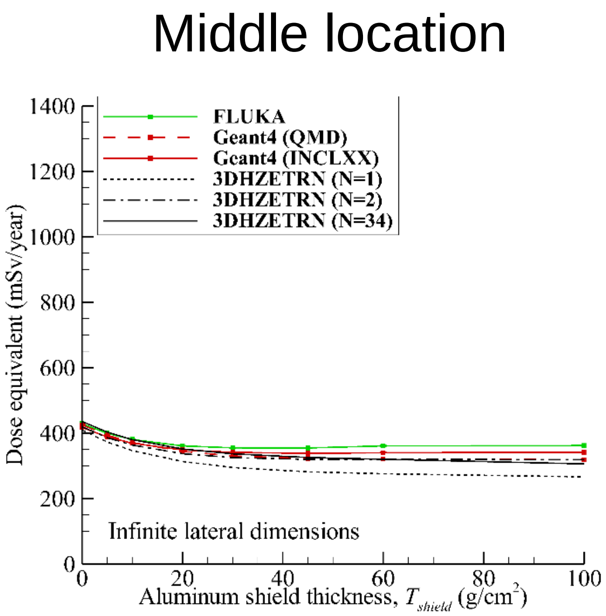
Calculations with 3d-HZETRN and Monte Carlo Transport Codes show dose equivalent increases when non-hydrogenous shielding material beyond 20 g/cm^2 is added.

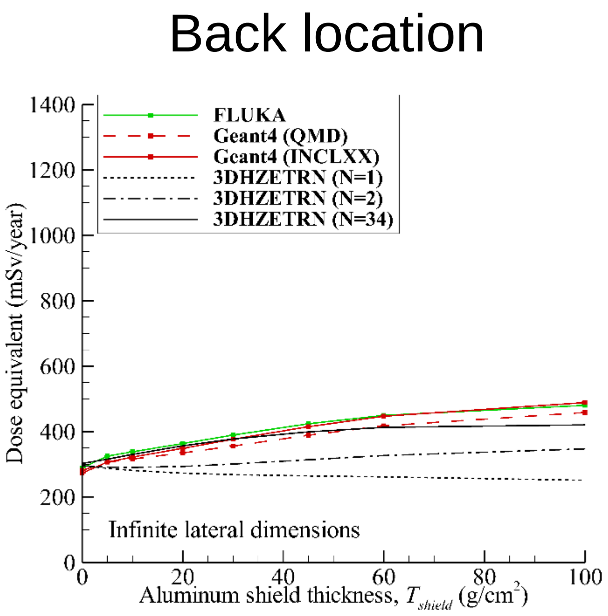
Slaba et al. LSSR (2017)

Effectiveness of Shielding Materials – New Paradigm









Adding water (or human tissue) suppresses the optimal shield thickness, but adding shielding beyond 20 g/cm^2 is not a good way to reduce dose equivalent.

Slaba et al. LSSR (2017)

Radiation Protection Requirements

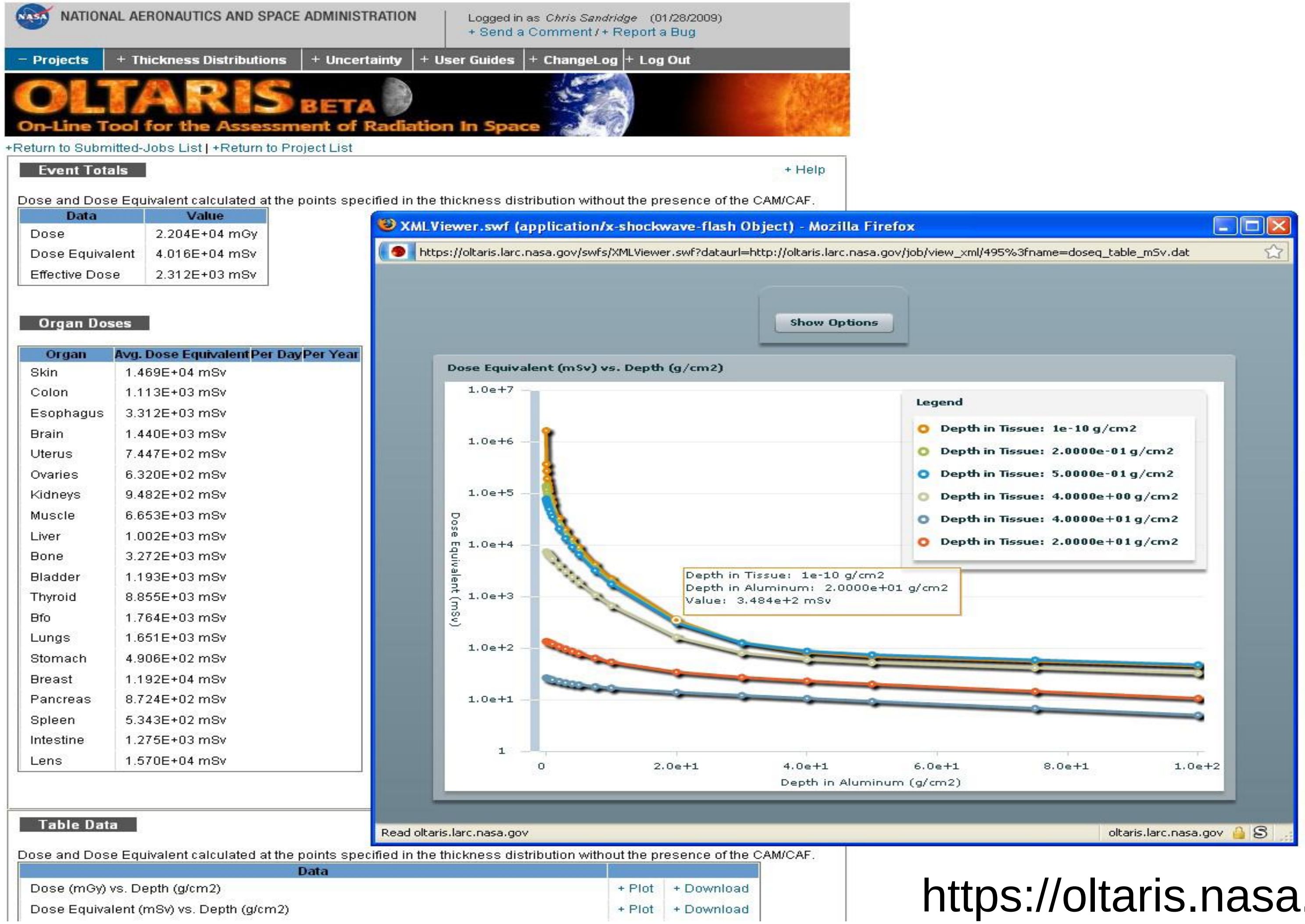
- System design requirements to prevent crew members from exceeding the permissible exposure limits (PELs) defined in NASA Standard 3001 will be set by the program.
- Design requirements have been set for the HLS lander, but those requirements are currently being reviewed and may change.
- Radiation protection design requirements have not been released for other lunar surface habitats or rovers.

- Requirements for human systems will probably include the following (in the opinion of Martha Clowdsley):
  - a requirement that systems be included to ensure that astronaut SPE exposure does not exceed a defined exposure limit for a designated SPE environment,
    - This can be addressed by creating a storm shelter and/or the use of wearable protection
    - The exposure limit is likely to be 250 mGy-eq to blood forming organs (BFO) and the design SPE environment is likely to be a model of the sum of the events that occurred during October 1989 as modeled by Tylka
  - a requirement that protection systems be designed using the As Low As Reasonably Achievable (ALARA) principle,
  - and, for systems for long duration missions, an exposure limit and design environment for GCR exposure.

Suggested Radiation Protection Design Goals

- Develop plan for SPE protection:
  - The entire vehicle or habitat does not need to be shielded.
  - Adequate protection can be provided through the use of a storm shelter and/or radiation protection garments.
  - When the model has reached adequate maturity, perform radiation analyses to ensure that exposure limits are not exceeded and that astronaut exposure is kept As Low As Reasonably Achievable (ALARA).
    - Note: It is not good enough to just meet the exposure limit, if there are reasonable steps that can be taken to further reduce astronaut exposure.
- For GCR protection, focus on ALARA:
  - Try to ensure that astronauts are completely surrounded by 20 g/cm^2 of shielding in all areas of the vehicle or habitat where they will spend time.
  - If that is not possible, minimize the regions providing less than 20 g/cm^2 of shielding and make those regions as thick as is reasonably possible.
  - Focus on using the mass that would already be in the vehicle or habitat.
  - Do not add mass to go beyond 20 g/cm^2 of shielding, unless your concept involves adding meters of shielding (like a surface habitat buried in regolith).

The On-Line Tool for the Assessment of Radiation in Space (OLTARIS)

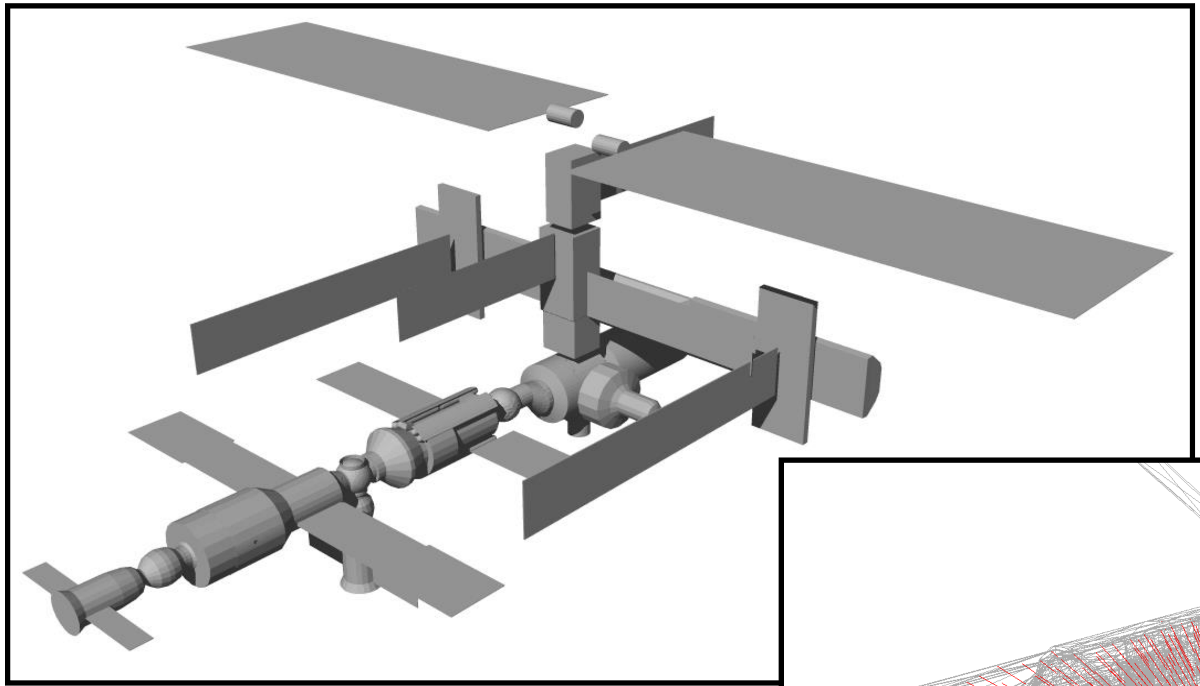


- OLTARIS is a web portal created to supply "best practices" in radiation shielding models, methods, and algorithms to the community.
- It is rigorously developed in a modular framework that is easily maintained and updated.
- It includes space environment models, transport algorithms, human body models, and response functions.
- Users can define their own mission parameters and upload ray-traces of their spacecraft to assess the protection provided.

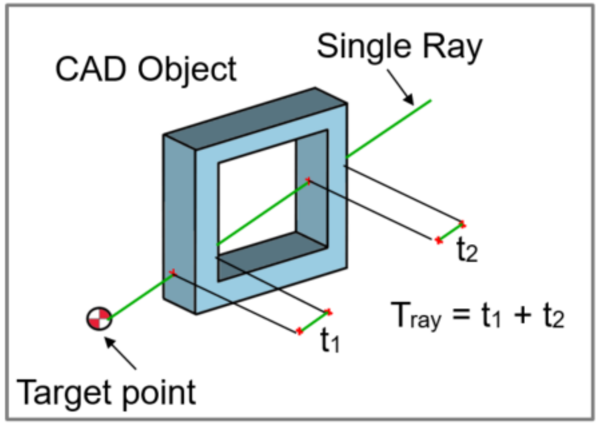
https://oltaris.nasa.gov

The OLTARIS website enables rapid exposure analyses for complex mission architecture.

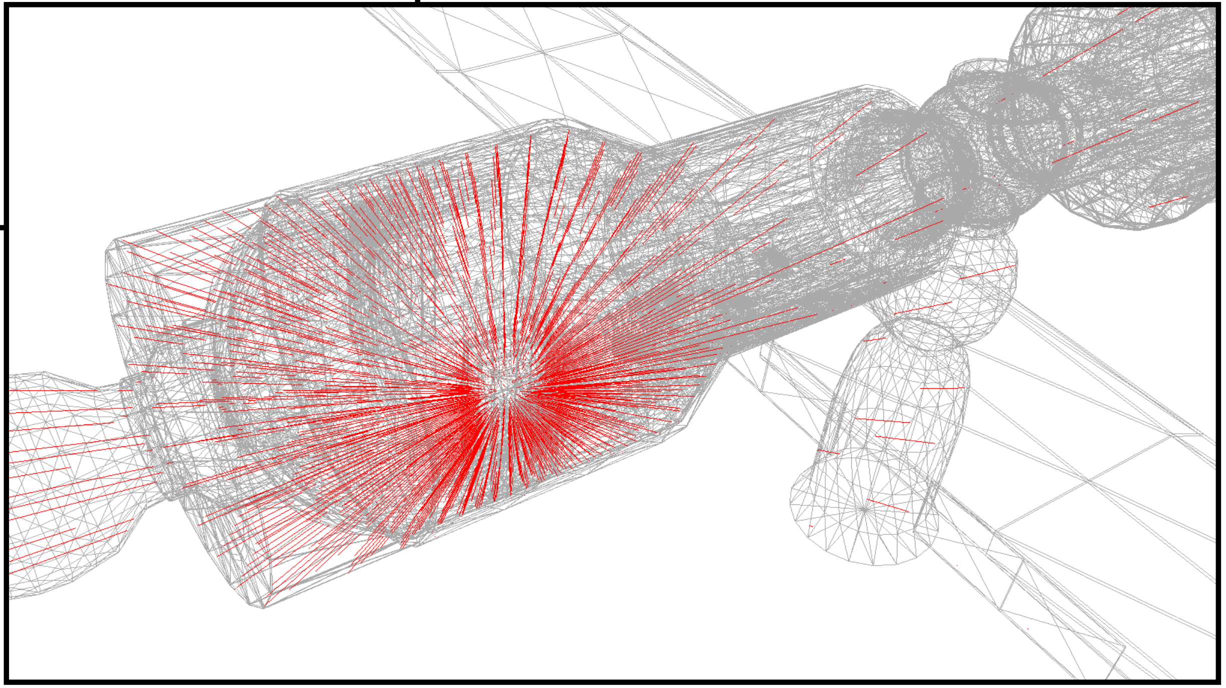
Analyzing Protection Provided by Complex Spacecraft Geometry – Ray Tracing



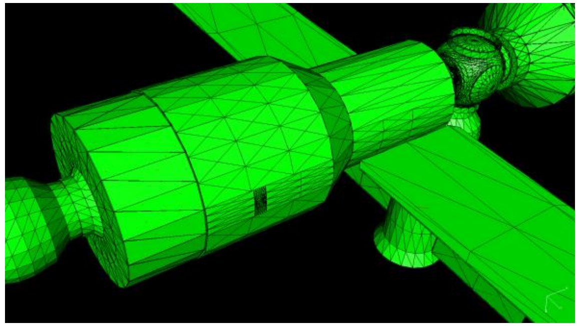
← International Space Station (ISS)



Service Module Ray-Trace ↓



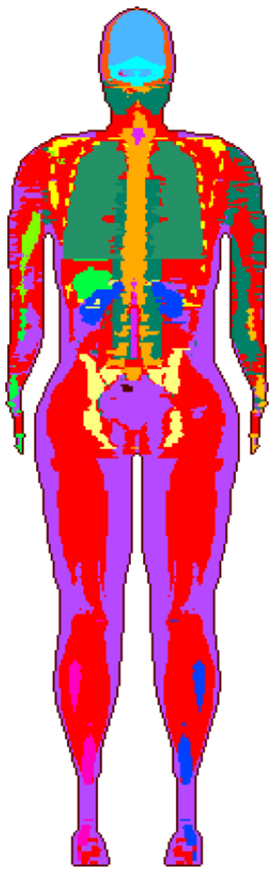
Service Module



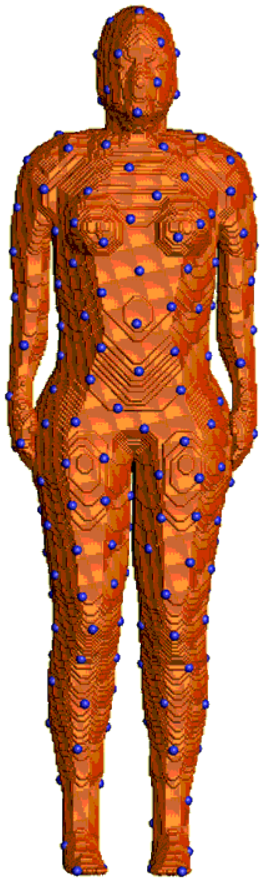
Note:
All of the mass surrounding the astronauts (spacecraft structure, vehicle systems, supplies, fuel, other astronauts, etc.) must be included in the model.

Analyzing Protection Provided by Complex Spacecraft Geometry – Incorporation of Body Models in Vehicle Geometry

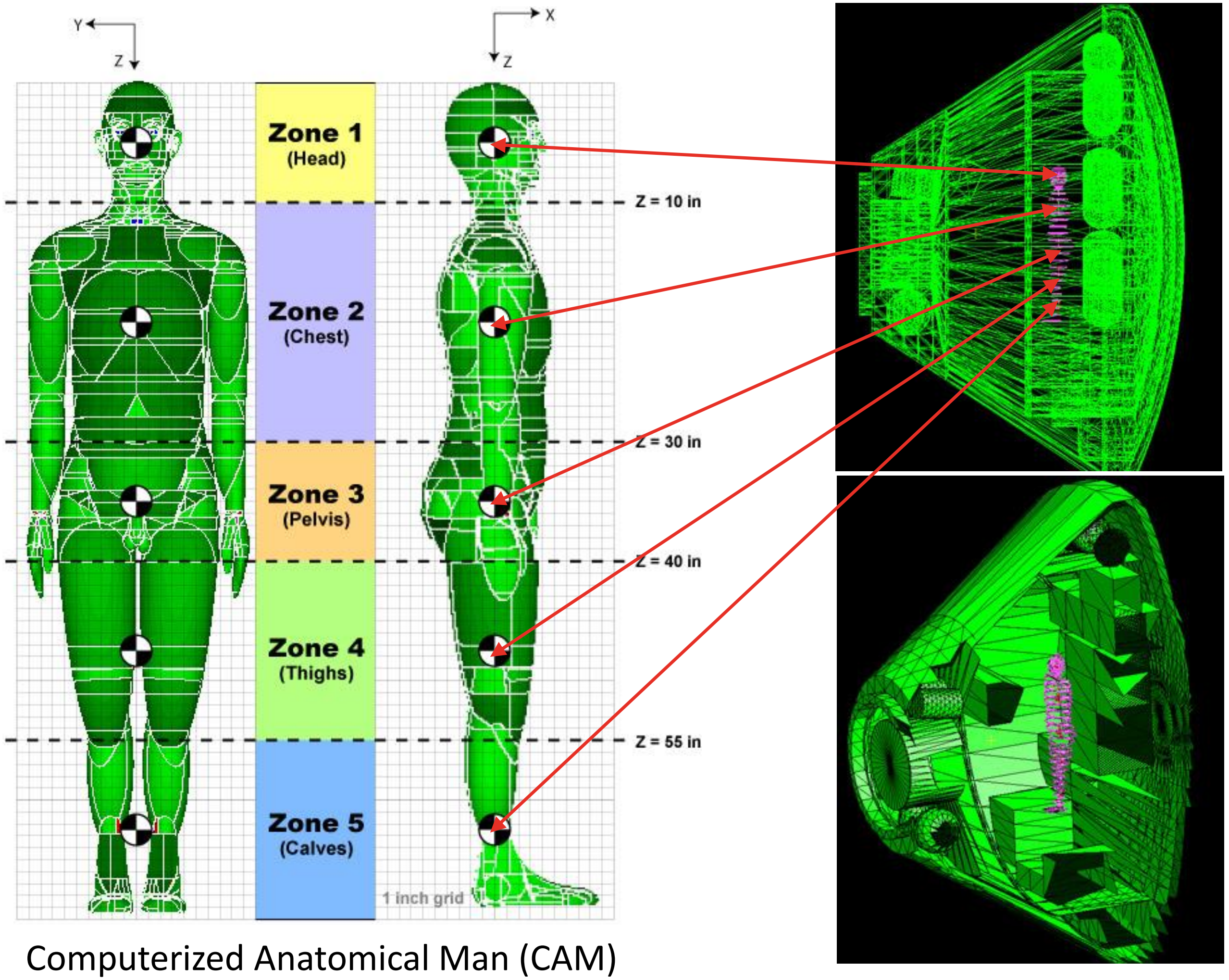
Stored ray traces for ~1100 body points are combined with 5 Spacecraft ray traces



Female Adult voxel (FAX) Model



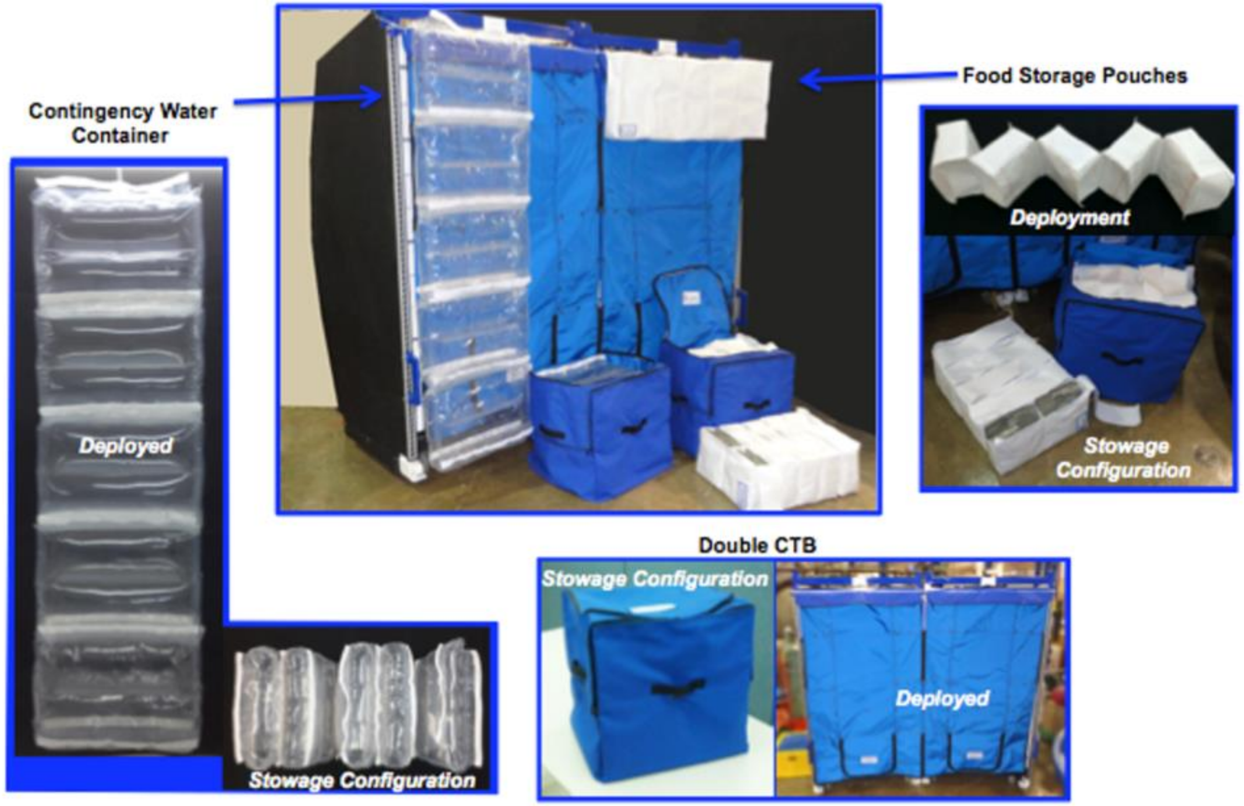
Skin Dose Points in the FAX



Computerized Anatomical Man (CAM)

SPE Protection – Personal Protection

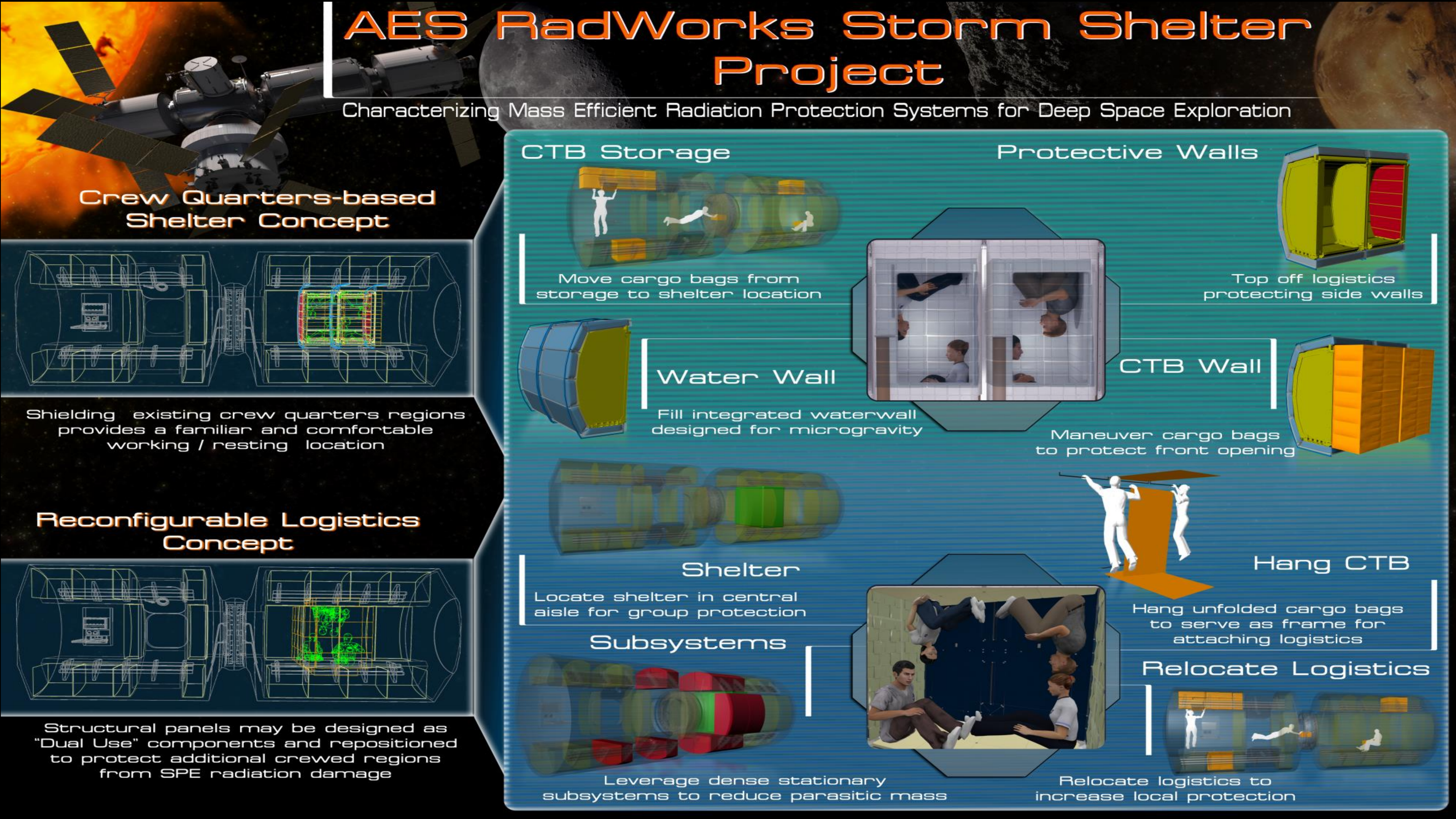
SPE Storm Shelters – Reconfigurable Logistics



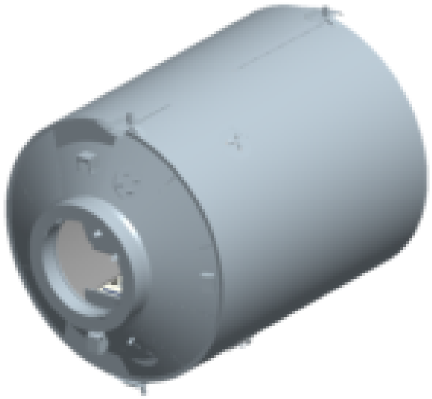
Food, water, and supplies can be reconfigured to create a storm shelter.

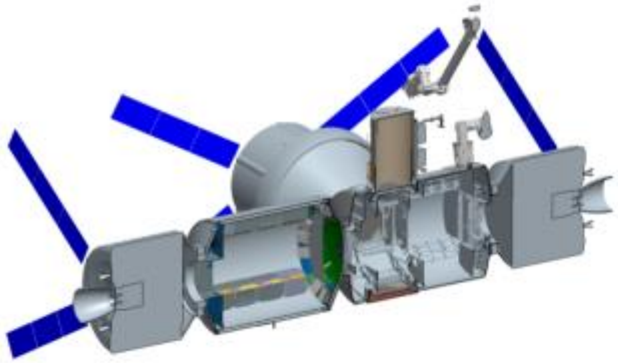
SPE Storm Shelters – Water Wall Systems

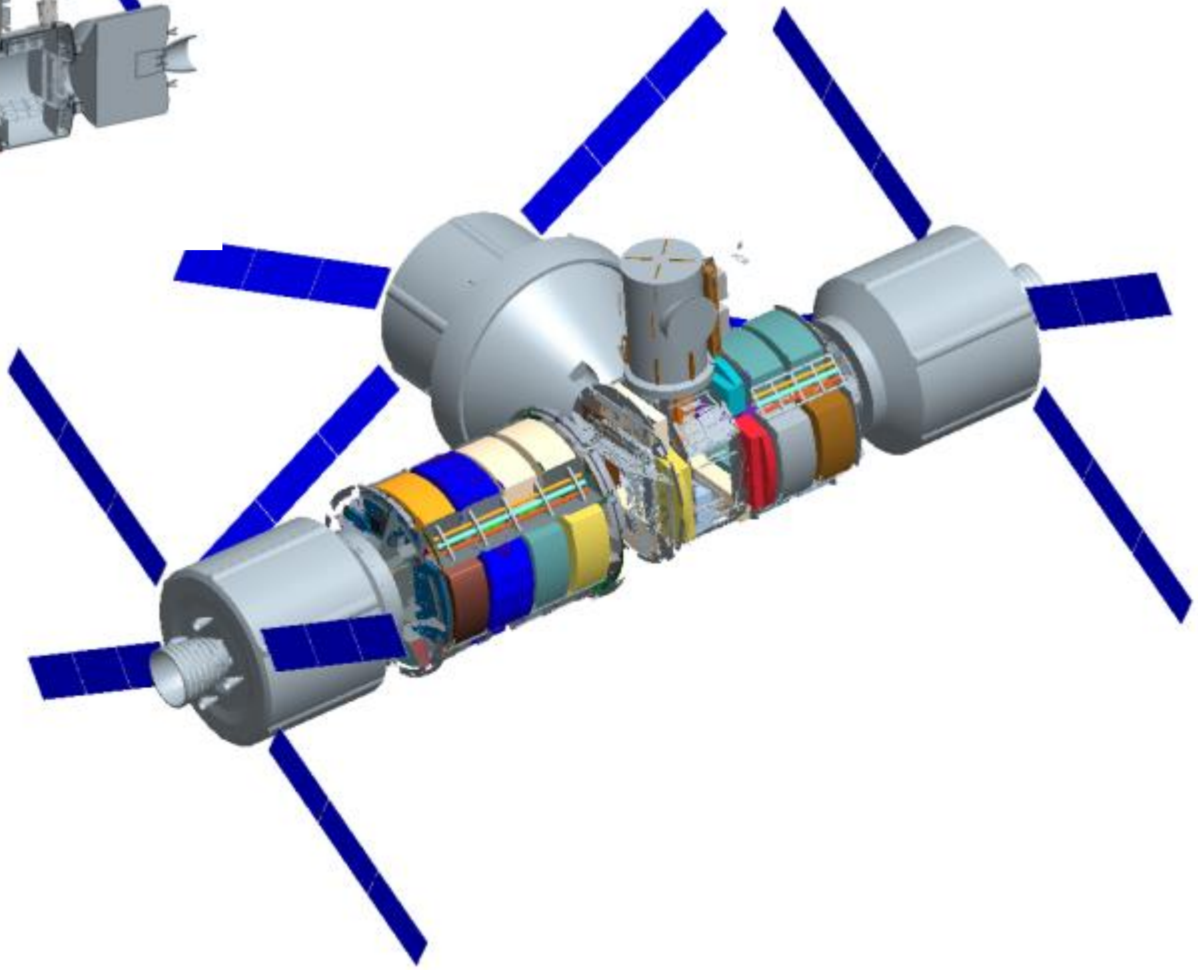
Water walls can be used to augment the shielding in the crew quarters.


AES RadWorks Storm Shelter Project
Characterizing Mass Efficient Radiation Protection Systems for Deep Space Exploration
Crew Quarters-based Shelter Concept
Shielding existing crew quarters regions provides a familiar and comfortable working / resting location
Reconfigurable Logistics Concept
Structural panels may be designed as "Dual Use" components and repositioned to protect additional crewed regions from SPE radiation damage
CTB Storage
Move cargo bags from storage to shelter location
Protective Walls
Top off logistics protecting side walls
Water Wall
Fill integrated waterwall designed for microgravity
CTB Wall
Maneuver cargo bags to protect front opening
Shelter
Locate shelter in central aisle for group protection
Hang CTB
Hang unfolded cargo bags to serve as frame for attaching logistics
Subsystems
Leverage dense stationary subsystems to reduce parasitic mass
Relocate Logistics
Relocate logistics to increase local protection

ISS-Derived Habitat Developed for AES RadWorks SPE Protection Study

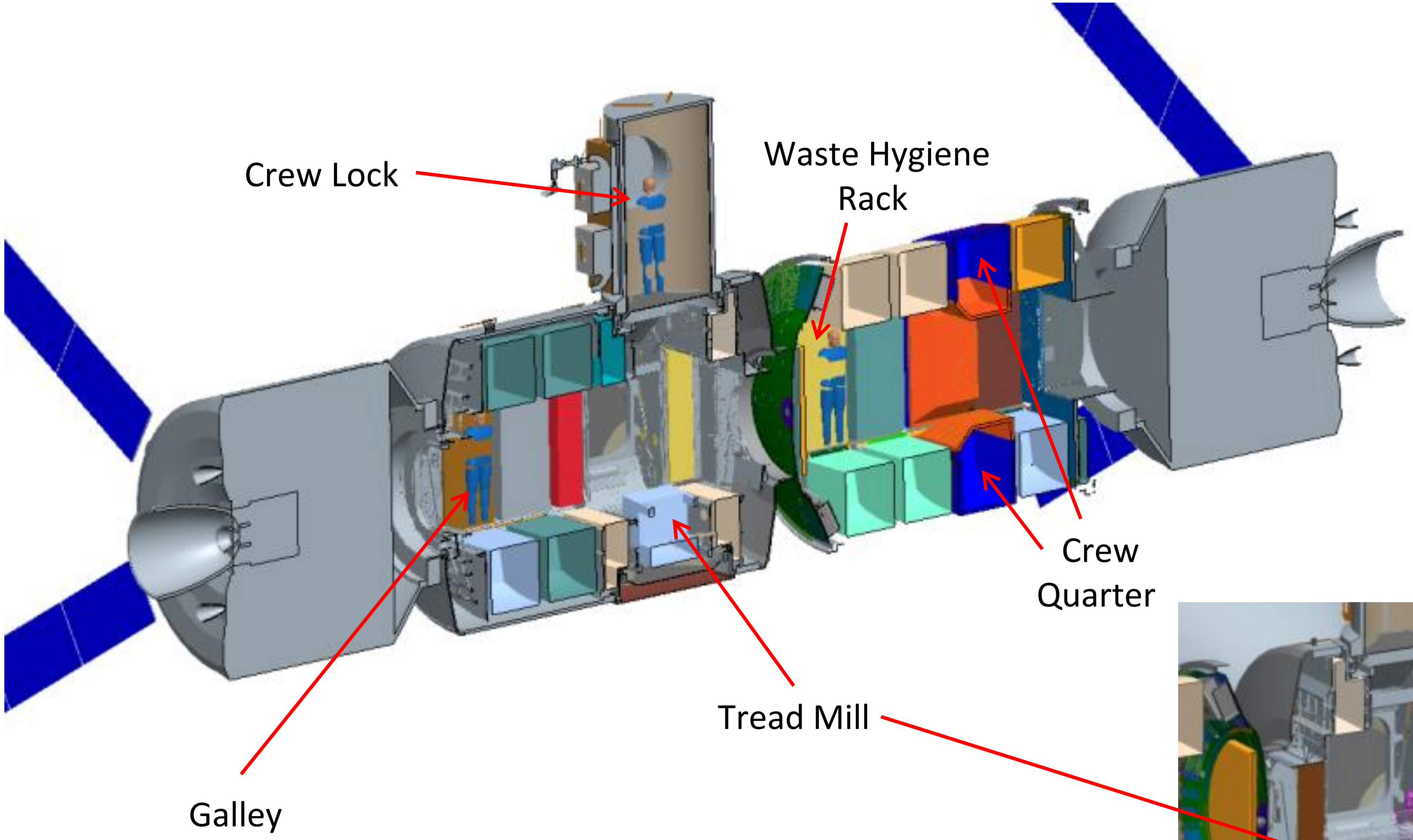


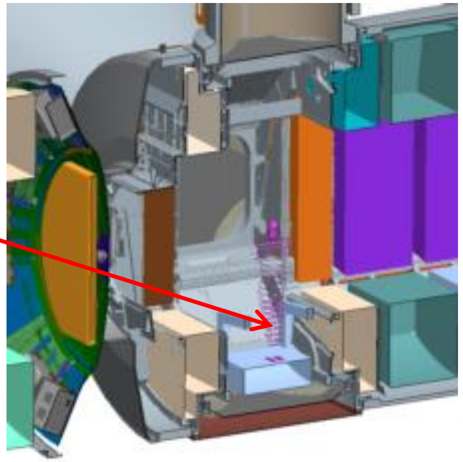




CAD model creation can be an intensive and time consuming effort

Locations Used for Baseline Analysis





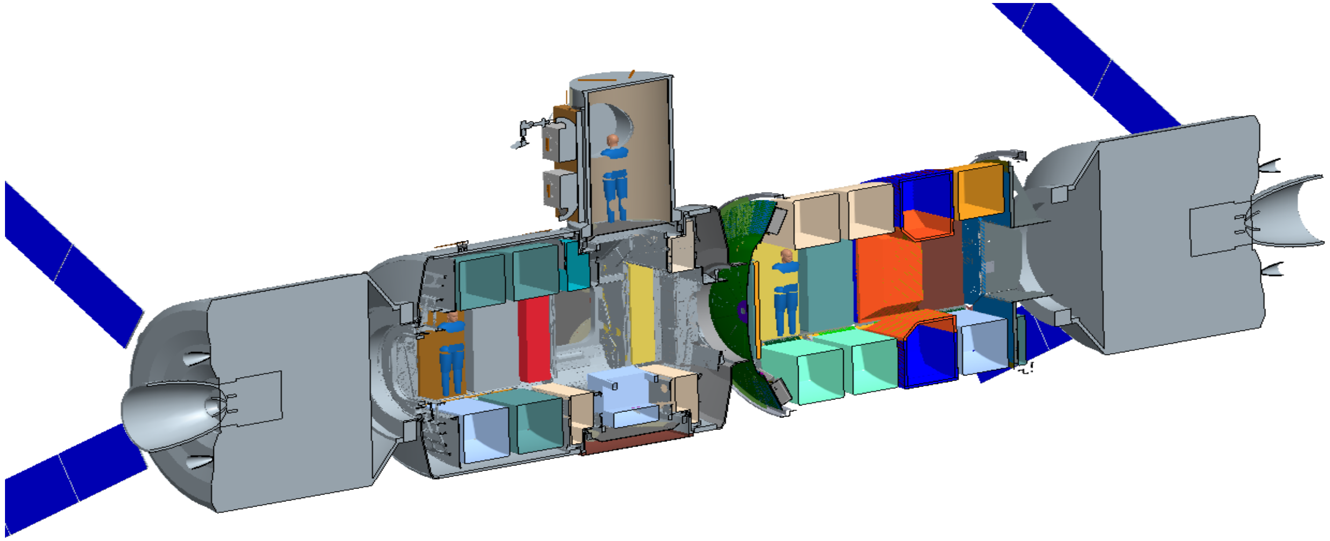
Astronaut Effective Dose in the Crew Quarters

Astronaut effective dose was calculated at multiple vehicle locations for multiple space environments.

	Aug `72 King	Aug `72 Band	Sept `89 OLTARIS	Sept `89 Band	Xapsos 95% Confidence	Oct `89 IMP
Top	480	271	132	136	591	409
Bottom	505	283	133	139	602	412
Left	398	227	121	121	526	373
Right	526	297	138	144	626	427

Astronaut Effective Dose at Other Locations

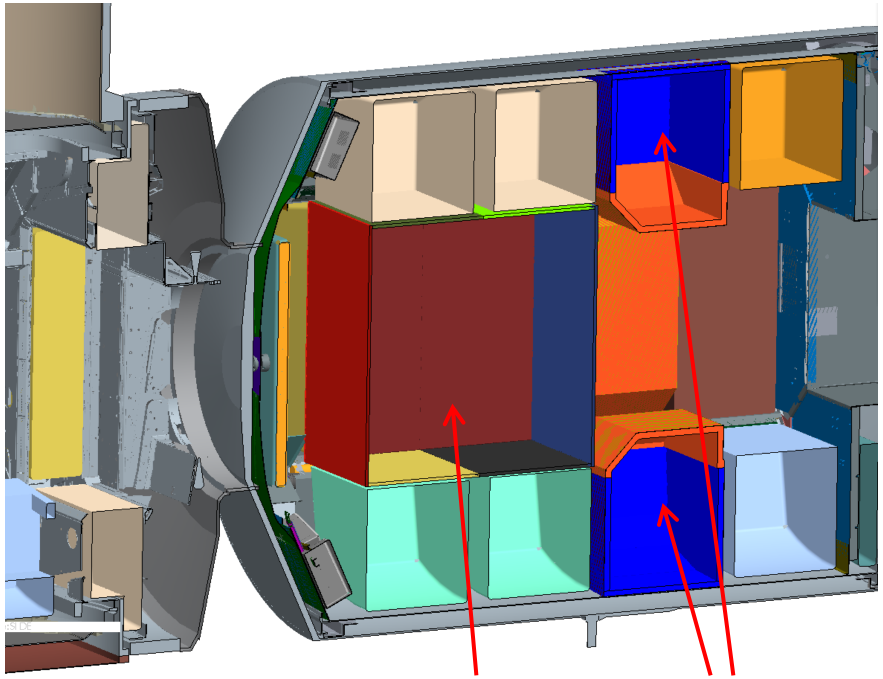
	Aug `72 King	Aug `72 Band	Sept `89 OLTARIS	Sept `89 Band	Xapsos 95% Confidence	Oct `89 IMP
Treadmill	161	108	71	63	275	221
Galley	81	65	47	38	168	149
Hygiene	133	98	74	63	282	229

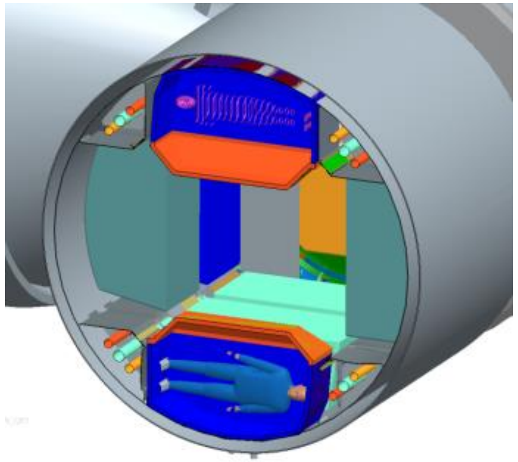


Two Storm Shelter Concepts Examined

- Two Types of Storm Shelters Examined:
  - Astronauts in the four crew quarters
  - All four astronauts in a centrally located "Box"

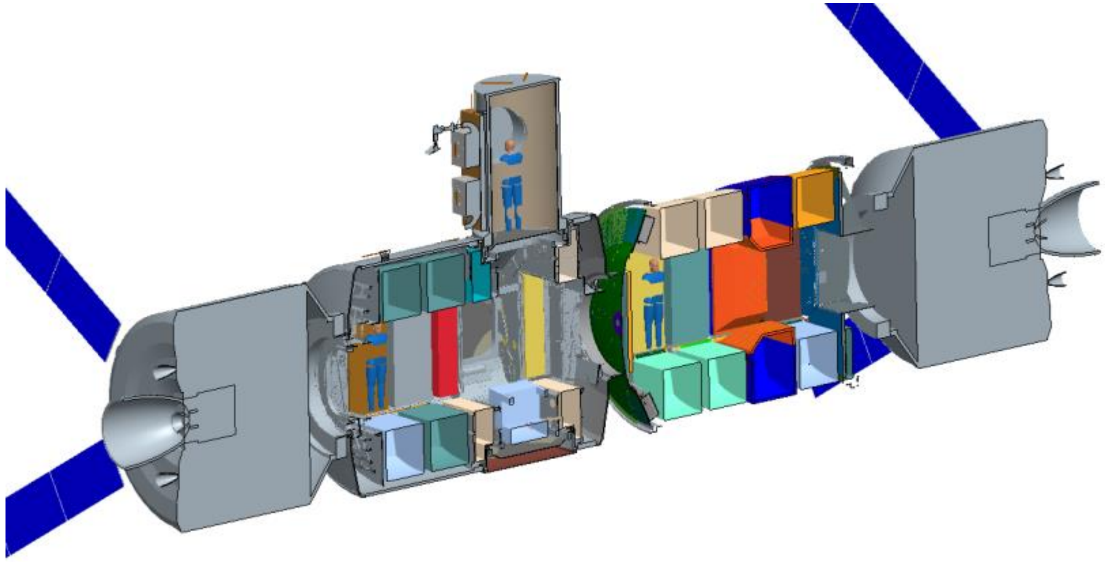
- Results:
  - Too much mass was required to create storm shelters in all 4 crew quarters or in the large box shown
  - Food, water, and supplies planned for this mission could be used to create storm shelter in 2 crew quarters with the astronauts "doubling up" or in a central box type shelter half the size shown





Effective Dose for GCR

Astronaut Location	Effective Dose (mSv/day)
CQ Top	0.95
CQ Bottom	0.95
CQ Left	0.94
CQ Right	0.95
Treadmill	0.86
Galley	0.82
Hygiene	0.87



- The interior locations (treadmill, galley, and hygiene) are better protected than the crew quarters (~10% reduction in effective dose).
- Moving the crew quarters to more protected locations could result in more safe days in space.

R&D for Lunar and Mars Surface Missions – Martha's List

- Improved modeling of human risk - currently funded under HRP
- Biological countermeasures - currently funded under HRP
- Dosimeters - currently funded under AES
- Space weather forecasting tools for operations - currently funded under AES
- Ongoing SPE modeling and risk analysis
- Improved methods for estimating astronaut risk based on onboard measurements
- Improvements to NASA's radiation transport code
  - Pion transport - currently funded under AES
  - Cross section measurements to improve physics models
  - Measurements for code validation – some measurements planned under AES
- Uncertainty modeling and integration of radiation uncertainty with other design uncertainties
- Development of wearable protection - currently funded under AES
- Novel storm shelter approaches
- Logistics tracking for reconfigurable shielding
- Habitats and vehicles designed using the ALARA process
- Active Shielding - currently funded under AES and STMD

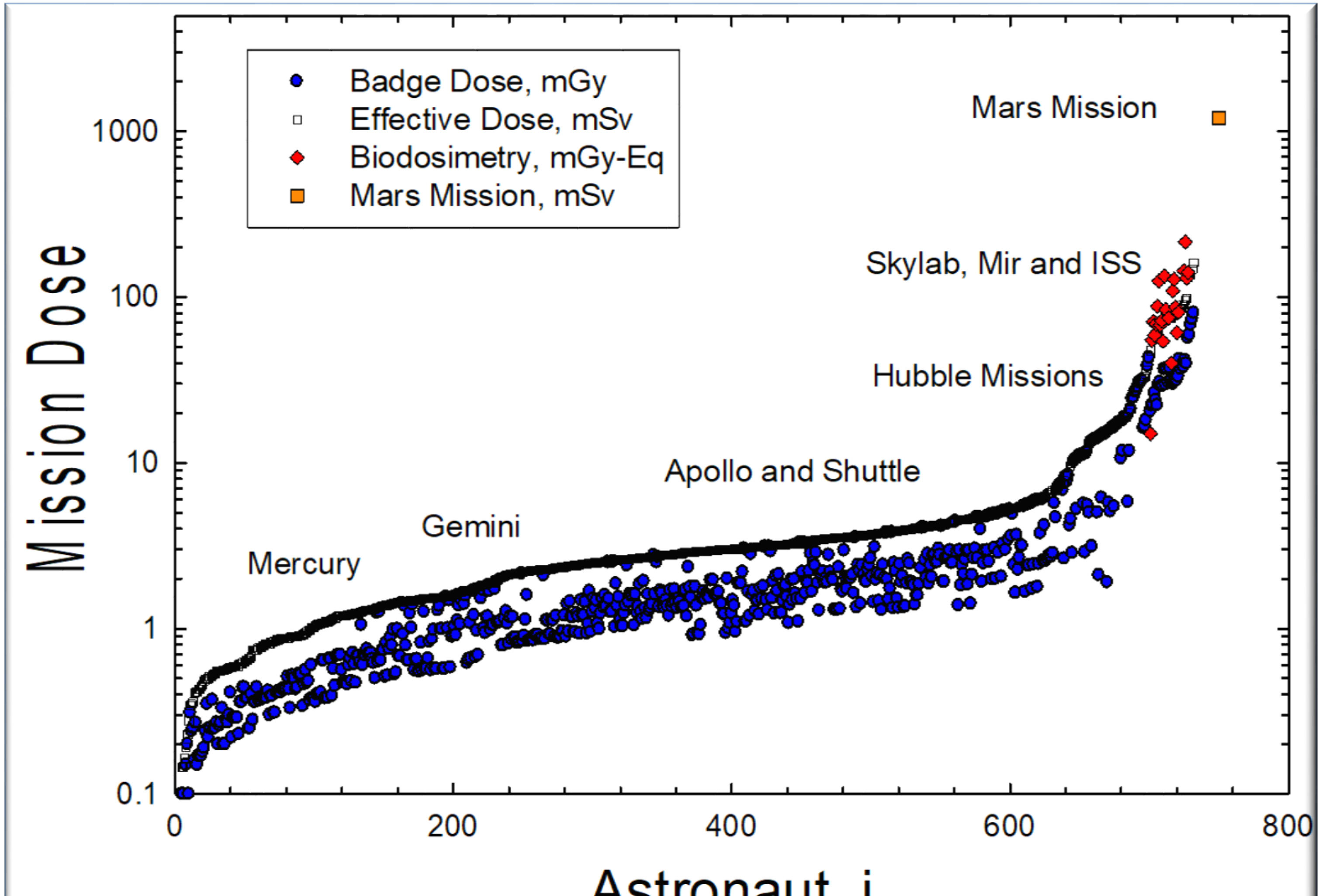
Summary

- Lunar habitats should provide SPE protection (storm shelter and/or wearables).
- Habitat designers should strive to surround astronauts with 20 g/cm^2 of hydrogen rich shielding for GCR protection.
  - Adding more than 20 g/cm^2 is not helpful, unless you are adding meters of material.
- Protection should be designed using ALARA.
- OLTARIS enables the assessment of protection provided by complex vehicle/habitat geometries.
- NASA is and has been developing technology to protect astronauts from space radiation and accurately model crew risk, but there is still work to be done.

Questions?

Backup Information

Crew Doses



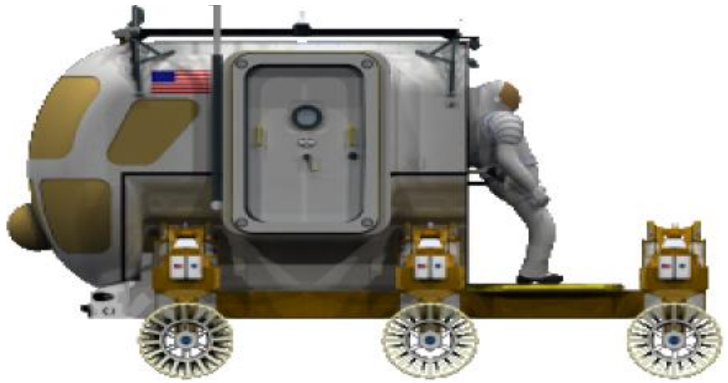
Update from Cucinotta et al. Radiat Res (2008)

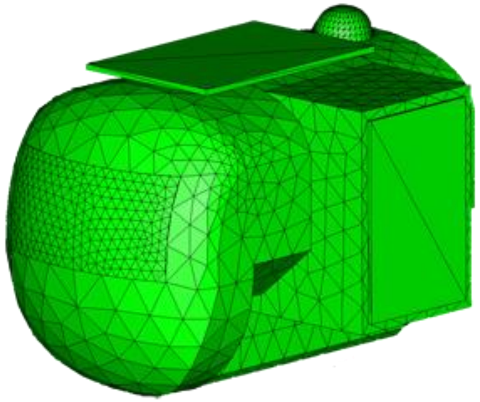
Small Pressurized Rover (SPR) Analysis

Model used:

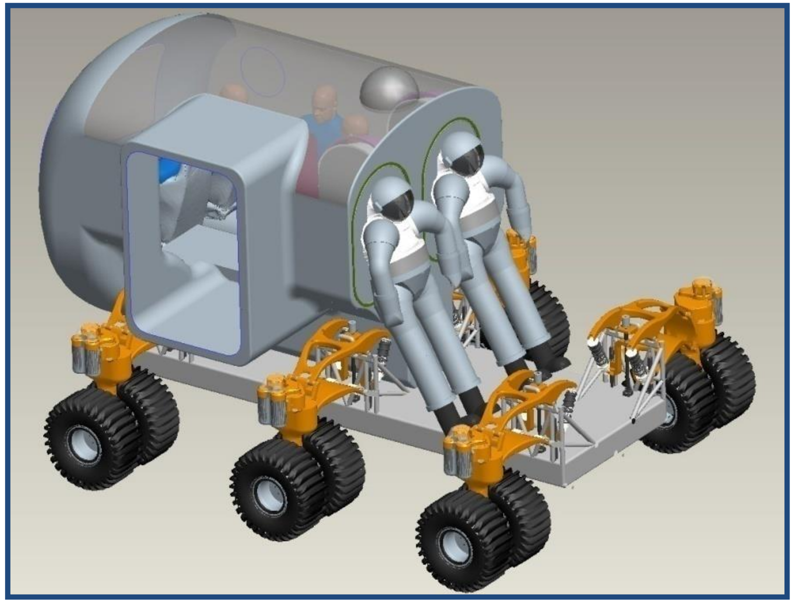
- SPR_CxAT_Lunar_MEL_3-3-08 mass equipment list
- Total mass (including 30% margin) modeled: 2881kg
- Total thermal control water to use as shielding 226 kg (500 lbs)

Detailed CAD Model





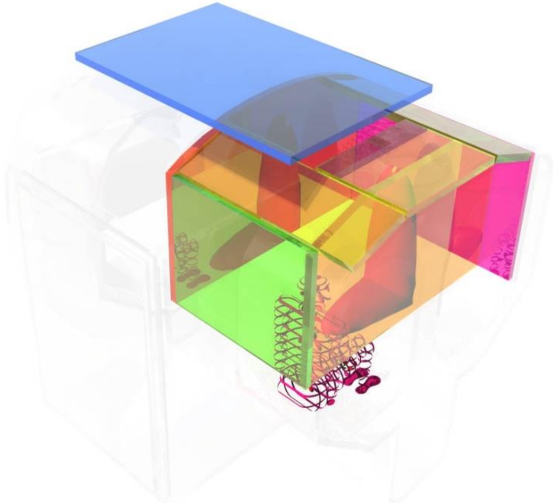
ProE model of concept utilized for analysis:



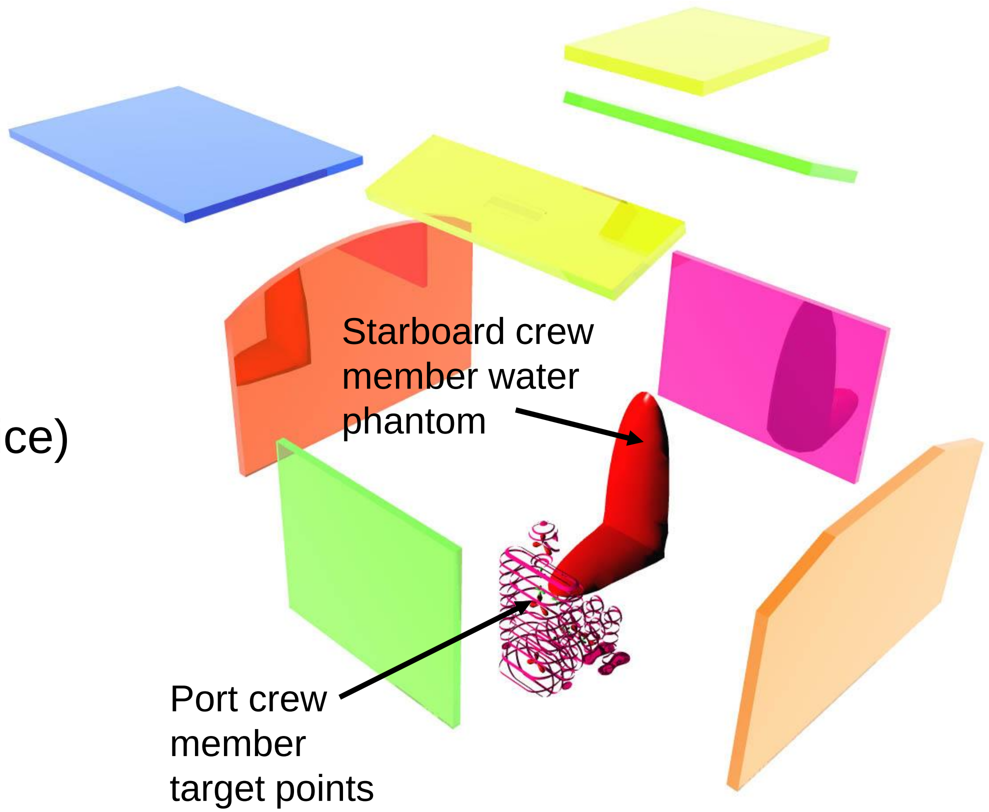
SPR Shield Model Views

Shield Panel Arrangement Forming Shelter

Baseline Case Utilizes Only Radiator (ice) and Vehicle Shielding



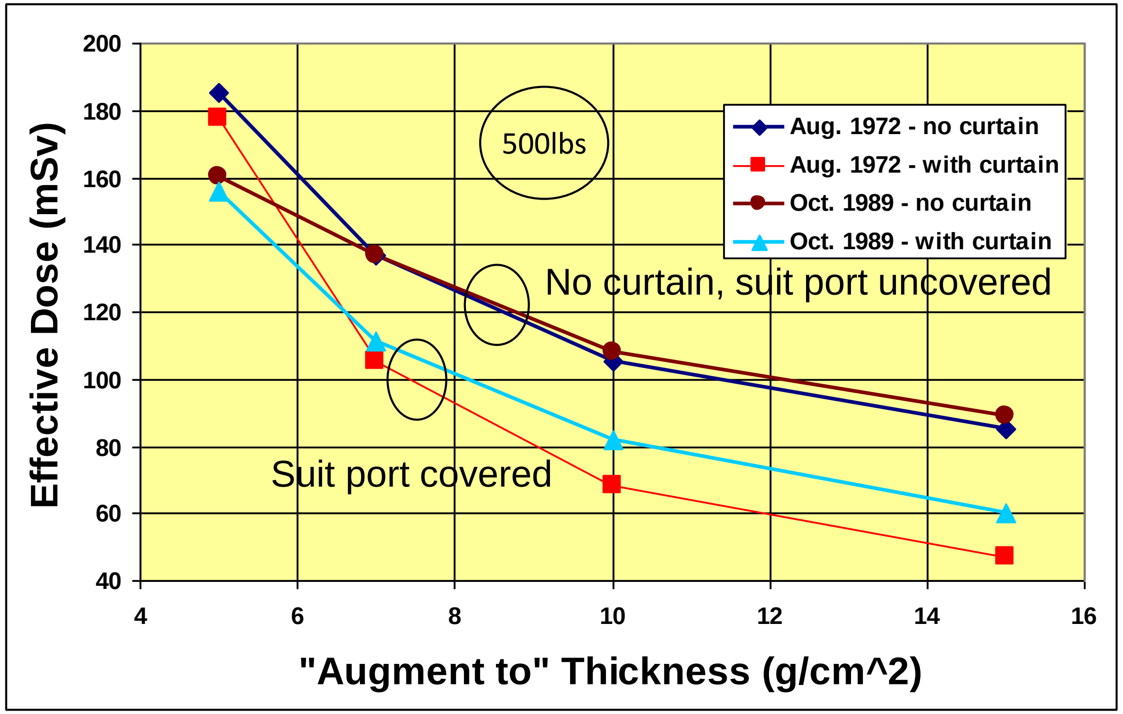
Exploded View of Water Panels and Flexible Shielding



Flexible shield curtain
option considered to cover suit port

Effective Dose for a Female Astronaut in the SPR on the Lunar Surface

			SPE - Aug. 1972 King		SPE - Oct. 1989	
Augment to (g/cm^2)	Water (lbm)	Curtain (lbm)	Effective Dose no Curtain (mSv)	Effective Dose wth Curtain (mSv)	Effective Dose no Curtain (mSv)	Effective Dose wth Curtain (mSv)
Radiator Only	500		170.7		148.6	
5	53	15	185.4	177.7	160.1	155.9
7	292	137	136.9	105.3	136.9	111.1
10	665	320	105.4	68.1	108.0	81.6
15	1285	626	85.1	46.9	88.9	60.1



- 500 lbs of distributed water expected to reduce exposure from August 1972 flare event to ~100 mSv
- Allocating portion of shield mass across back suit port wall reduced exposure by ~20%