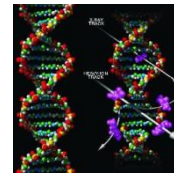Image credit: John Frassanito & Associates, Inc

Estimating the Effects of Astronaut Career Ionizing Radiation Dose Limits on Manned Interplanetary Flight Programs

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Presentation Outline

- **I. Introduction**
  - **Overview of Space Radiation and Radiation Effects**
- **II. Space radiation environments for interplanetary flight**
  - **Dose as a function of shielding mass for 3 year Interplanetary flights**
  - **Solar particle events**
  - **Solar Cycle modulation of GCR dose**
- **III. Space Radiation Crew Dose Limits – Present and Future**
  - **Astronauts as radiation workers**
  - **Limiting risk of cancer**
- **IV. Approaches to Space Radiation Effects Mitigation for Long Term Human Interplanetary Flight**
  - **Problem Statement**
  - **Risk Management and the necessity for compromise**
    - **International Space Station MM/OD shielding design process as an example**
  - **Space Radiation Human Dose Mitigation Technologies**
    - **Low TRL solutions with long development times**
  - **Shielding with Materials**
    - **TRL "now" solution**
- **V. The Hybrid Inflatable Deep Space Habitat – an approach to implementing a TRL "now" solution**
- **VI. How the Hybrid Inflatable DSH Enables Affordable Multi-Mission Architectures**
- **VII. Summary and Conclusions**

I. Introduction

- The natural space radiation environment affecting astronaut ionizing (IR) radiation dose consists primarily of **energetic charged particles**
  - The space radiation environment is radically different from the radiation environments encountered on Earth.:
  - Galactic cosmic rays (GCR), solar cosmic rays (solar particle events (SPE)), and magnetically trapped charged particles (e.g. the Van Allen Belts)
  - Secondary neutrons produced by GCR, SPE and trapped radiation interaction with spacecraft materials are major contributors to crew dose
  - Energetic X-ray and gamma ray photons are negligible contributors to astronaut IR dose in the vast majority of space flight scenarios and will not be addressed here
- Geo-magnetically trapped radiation and solar particle events do not constitute an insurmountable obstacle to manned interplanetary flight at this time
  - Relatively **soft kinetic energy spectrum** and limited exposure times, so…
  - Manageable with reasonable masses of shielding material and operations planning
- In contrast, GCR IR dose has been identified as a "show stopper" for long term manned interplanetary flight
  - Long term defined as greater than 180 to 300 days exposure (< 3 years)
  - Extremely **hard kinetic energy spectrum** and continuous exposure, so…
    - Only limited mitigation is possible with "reasonable" masses of spacecraft shielding
    - Enormous uncertainty in GCR dose-effect relationships for human health and safety
    - Drives "unreasonably" high shielding mass and so program launch costs

# Cosmic ray effects on human health and safety

- **Exposing cells to ionizing radiation leads to lethality, mutation induction, and carcinogenesis**
- **Primary and secondary cosmic ray particles transfer energy, proportional to charged particle LET = dE/dx, to atoms and molecules in the cellular structure, along the particle ionization track so as to:**
  - Produce free radicals
  - Break chemical bonds
  - Produce new chemical bonds and cross-linkage between macromolecules
  - Damage molecules and molecular assemblies that regulate vital cell processes (e.g. DNA, RNA, proteins, and membrane lipid structures)
  - Kill cells
- **Ionizing radiation induces both direct biomolecule damage and indirect biomolecule damage through the radiolysis of water.**
  - At low doses (i.e. damage rates), such as what we receive every day from background radiation, the cells repair the damaged molecules rapidly enough to survive
  - At higher doses (up to 1000 mSv), the cells might not be able to repair the damage rapidly enough , and the cells may either be changed permanently or die.
- **Cells changed permanently may go on to produce abnormal cells when they divide. In the right circumstance, these cells may become cancerous. This is the origin of our increased risk in cancer, as a result of radiation exposure.**
  - Bystander cells can also be affected via intracellular signal transduction pathways
  - Effects include increased risk of cancer, heart disease, and possible early onset dementia an/or Alzheimer's


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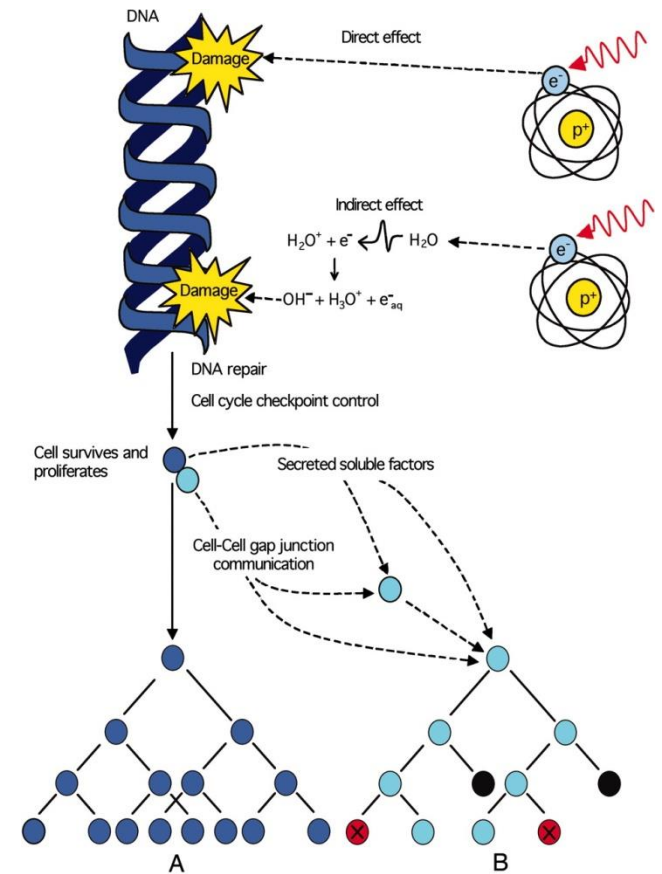
Can flight during solar maximum reduce flight crew GCR dose and reduce shielding mass requirements?   The GCR flux is lower at solar maximum than solar minimum
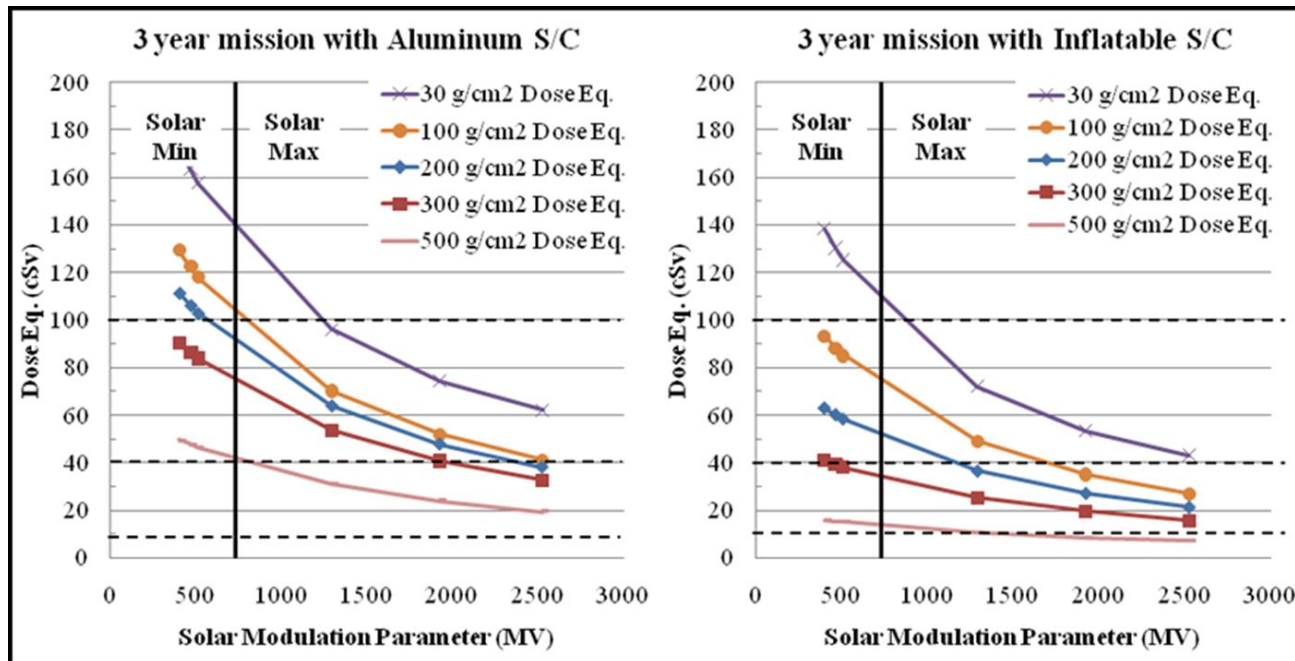
Blood Forming Organ (BFO) Dose Equivalent as a function of the solar modulation parameter and spacecraft shielding mass for a 3 year Mars mission. The left graph is for an aluminum spacecraft and the right graph is for a hybrid inflatable spacecraft using water as shielding mass. The dose equivalent is the result of three years of GCR exposure and three major SPEs. The horizontal dashed lines show possible crew dose limits that will need to be met
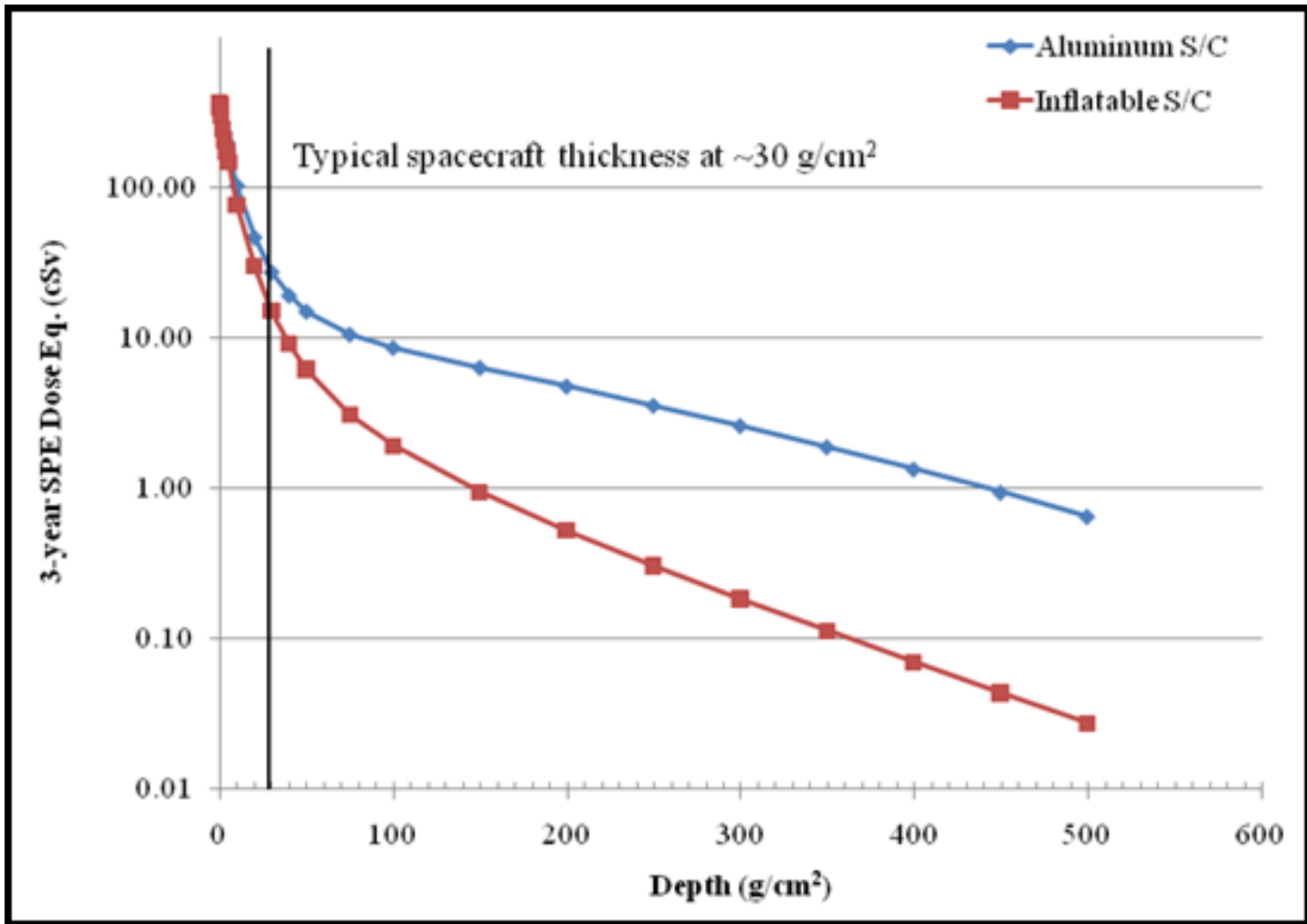
**SPEs are not a major contributor to the three year dose shown on the previous slide – GCRs crew IR dose during long term interplanetary flights**
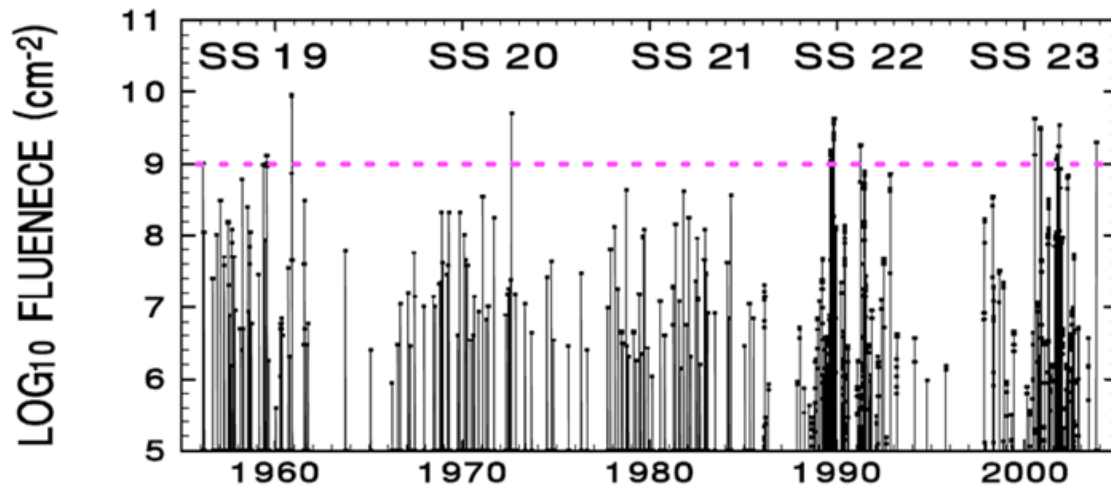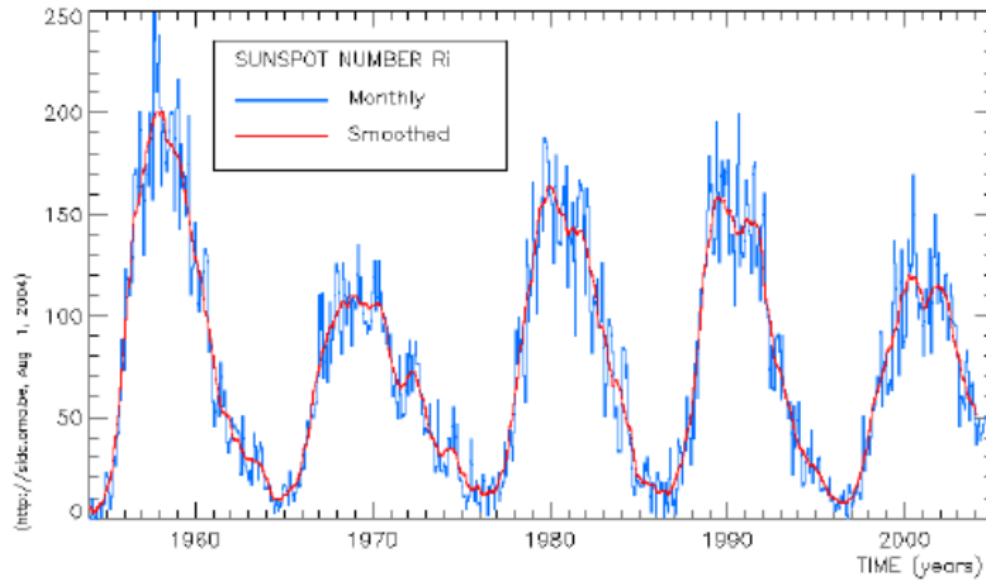
The sunspot number (top graph) and SPE history over several years (bottom graph), depicting the solar cycle. The horizontal (magenta) dashed line in the bottom graph represents the fluence for which an event is categorized as a very large or major event.

Solar cycle 24 has lower intensity than the lowest prediction leading to much higher GCR flux than expected.
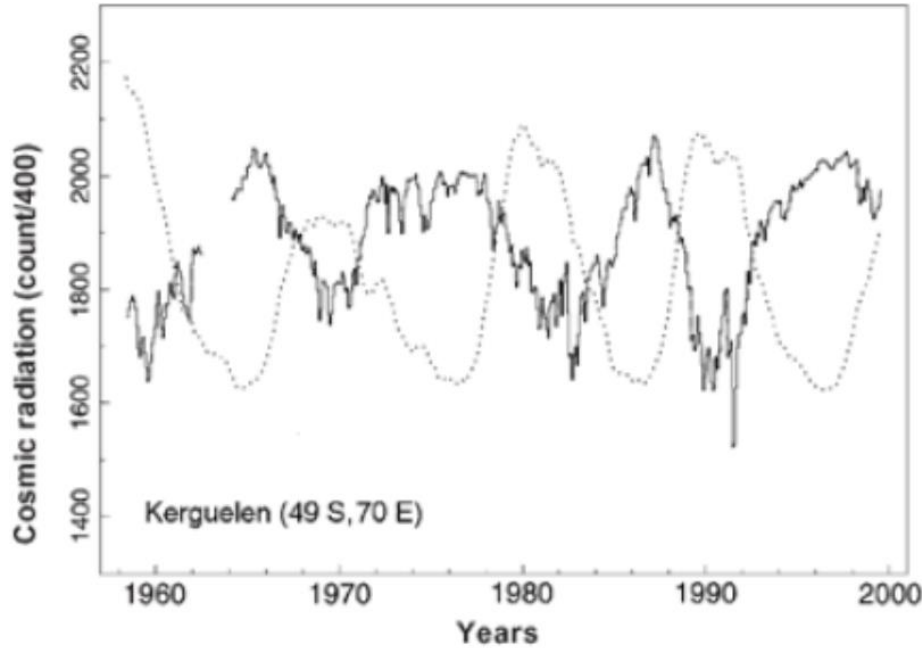
Plot of the solar cycle (dots) and corresponding GCR secondary particle shower neutron measurements on Earth's surface (solid line).

Cycle 24 sunspot prediction in March 2007 (left) and the most current data on Cycle 24 sunspot progression (right).
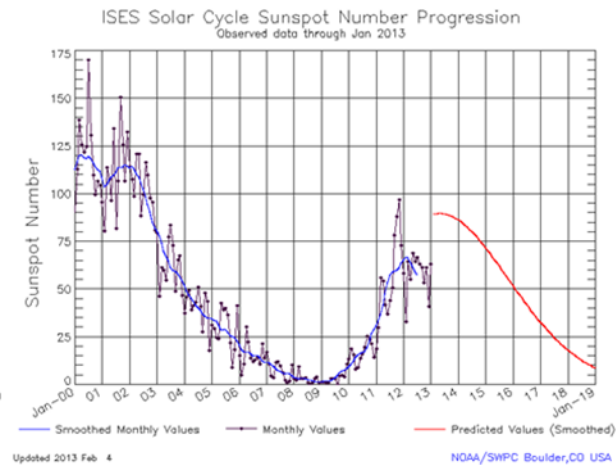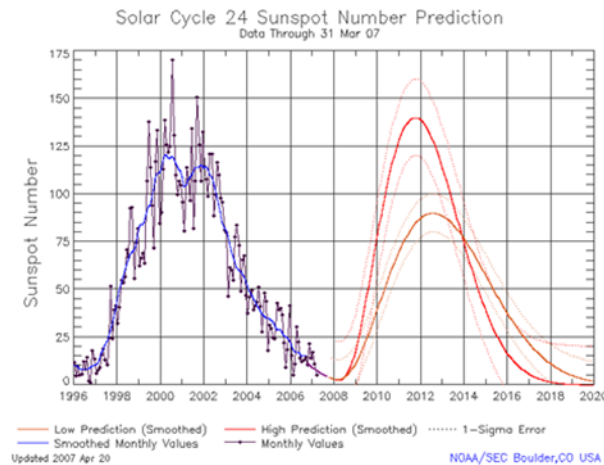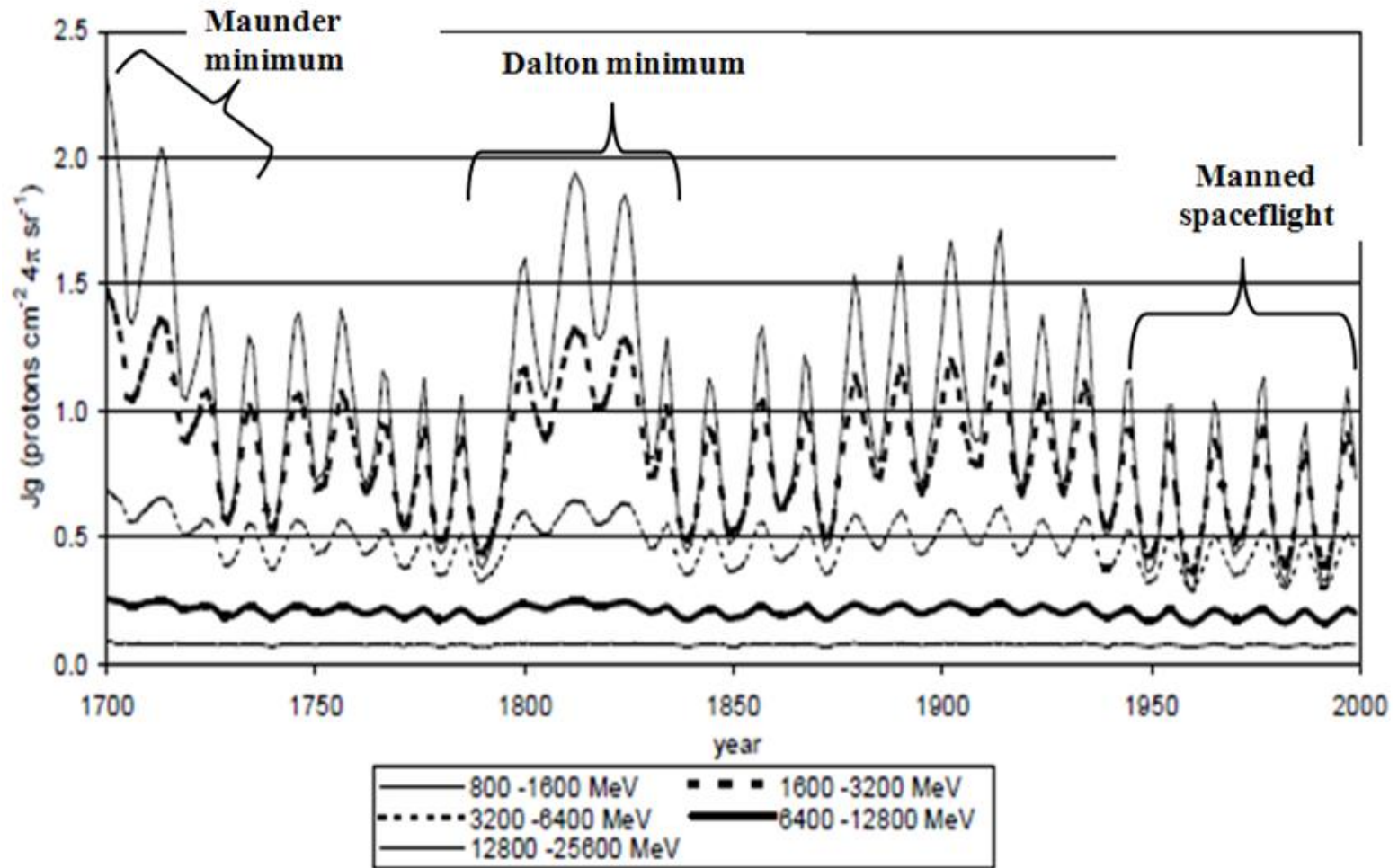
Proton flux of the historical GCR environment as a function of GCR proton kinetic energy.
Historical GCR flux has often been well above that observed during the age of manned space flight
so that using a solar maximum GCR design environment for manned interplanetary spacecraft is not
reasonable at this time, especially since the solar physics community believes that another
Maunder minimum is a very real possibility at this time

III. Space Radiation Crew Dose Limits – Present and Future

Space flight radiation exposure standards, requirements, and guidance are documented in NASA Standard 3001, Volume 1 and 2, and include.

➢ Planned career exposure for radiation shall not exceed 3 percent risk of exposure induced death (REID) for fatal cancer.

➢ **NASA shall assure that this risk limit is not exceeded at a 95 percent confidence level using a statistical assessment of the uncertainties in the risk projection calculations to limit the cumulative effective dose (in units of Sievert) received by an astronaut throughout his or her career.**

➢ Exploration Class Mission radiation exposure limits shall be defined by NASA based on National Council on Radiation Protection (NCRP) recommendations.

➢ Planned radiation dose shall not exceed short-term limits as defined Appendix F.8, NASA Standard 3001, Vol. 1.

➢ In-flight radiation exposures shall be maintained using the "as low as reasonably achievable" (ALARA) principle. The ALARA principle is a legal requirement intended to ensure astronaut safety. ALARA is especially important for space missions in view of **the large uncertainties in cancer and other risk projection models.**

➢ Note that only cancer risks are managed under the CFR at this time. Other health effects, e.g. central nervous system (CNS) damage leading to cognitive impairment during the mission, heart disease, and reproductive health among others are still under investigation

Regulations and GUIDELINES

- **Code of Federal Regulations**
- **Crew & Area Dosimetry**
- **ALARA – "As Low As Reasonably Achievable"**
- **NASA Flight Rules, e.g., No EVAs in South Atlantic Anomaly**
- **Crew annual and career dose limits**

CREW DOSE LIMITS

Career exposure by age and sex for missions of one year duration or less from NASA Std. 3001

Sex	Age			
	25	35	45	55
Male	52 cSv	72 cSv	95 cSv	147 cSv
Female	37 cSv	55 cSv	75 cSv	112 cSv

These flight crew exposure limits have been legally adopted as NASA's supplementary standard in accordance with 29 Code of Federal Regulation (CFR) 1960.18. The 95% confidence interval has not been applied to the doses in the table above

-Based on a limit of 3% radiation exposure induced (premature) death (REID) with 95 % confidence level (Code of Federal Regulations)
-Also, the new Crew Exploration Vehicle (CEV) design objective is 150 mSv per year, down from historical 500 mSv per year as driven by uncertainty in the dose-REID relationship in the primary GCR dominated space radiation environment

Spaceflight Radiation Examples - Human Spaceflight Mission Type Radiation Dose:

Assuming 20 to 50 g/cm^2 Al shielding and not including secondary particle shower effects internal to the human body which can increase effective dose by about 50%

Space Shuttle Mission 41-C	**0.559 cSv**
(8-day mission orbiting the Earth at 460 km)	
Apollo 14	**1.14 cSv**
(9-day mission to the Moon)	
Skylab 4	**17.8 cSv**
(87-day mission orbiting the Earth at 473 km)	
International Space Station (ISS) Mission	**16.0 cSv**
(up to 6 months orbiting Earth at 353 km)	
Estimated Mars mission (3 years)	**120.0 cSv**

Slow accumulation of whole body dose from GCR (expressed in Effective equivalent Sv) and including secondary particle showers in the human body) <u>presently limits the duration of manned space operations outside earth's magnetosphere to times on the order of 100 to 300 days (assuming 20 to 30 g/cm^2 shielding mass and a 1977 Solar Minimum GCR environment).</u>

The overall programmatic cost of the available active or passive shielding needed to extend that limit is likely prohibitive at this time

IV. Approaches to Space Radiation Effects Mitigation for Long Term Human Interplanetary Flight

- **Problem statement - Controlling Program Schedule and Costs Despite Dynamic and Uncertain Human Radiation Dose Requirements**
  - **Space IR dose limits can drive spacecraft and operations design**
  - **Space IR dose limits are in flux so that no fixed design target can be assumed for a multi-year development program**
    - **Space IR dose corresponding to 3% REID highly uncertain at this time so requirements reflect worst case assumptions**
    - **REID based dose limits are expected to relax in future as space biomedical research progresses**
    - **Additional presently unregulated health effects (e.g. CNS damage, early dementia) may also drive additional requirements**
- **How to minimize/eliminate re-design and re-work driven by changing requirements?**
  - **Single core habitat design with designed-in variable passive shielding capability**
  - **Shielding mass can be increased or decreased and even changed in character as progress is made on dose requirements and mitigations**
  - **A single core habitat design can be adapted, at low cost, to different missions and mission scenarios**

Radiation Risk Management and the Necessity for Compromise
International Space Station MM/OD risk management process as an analogue

- **The process for solving the problem of protecting the ISS from MM/OD can be used as a guide for developing the strategy to protect humans traveling in deep space from radiation.**

    - **Environment Definition Compromise**
        - **The ISS Program baselined an MM/OD environment for design in SSP 30425. This environment has been revised several times and a Program risk is in place to reassess the on-orbit ISS hardware as needed. For future missions, consensus SPE and GCR environments must be baselined for hardware design and the vehicle program must have a process for incorporating environment revisions into their crew risk assessments and shielding performance evaluations.**

    - **Level of Risk Acceptance Compromise**
        - **The BUMPER analysis code was used by the ISS Program to assess MM/OD shield performance. A 0.81 Probability of Non-Penetration risk for 10 years was accepted for the initial ISS MM/OD shielding designs. Each square meter of exposed surface area for the ISS MM/OD Critical items was allocated an "equal area penetration risk". For future missions, an analytical tool for evaluating radiation shield effectiveness must be agreed to by all stakeholders. The ALARA principle will have to be codified into design requirements so that different radiation shielding concepts can be traded taking into account risk, weight and cost.**

    - **Test and Verification Compromise**
        - **To manage MM/OD shield performance verification costs, a representative MM/OD particle material, velocity and shape as well as a single ISS altitude, solar flux and extrapolation criteria beyond the ground testing were used to provide ballistic limit equations for the BUMPER analysis. For future missions, similar compromises will have to be made to meet verification cost constraints. Worst case events will have to be excluded and representative vehicle configurations, solar fluxes and in-space lifetimes will have to be chosen to use limited test resources most effectively.**

    - **Shielding Augmentation Compromise**
        - **The ISS Vehicle is scarred for EVA installation of additional MM/OD shielding. Augmentation shielding has been added to the Russian Segment. Since both the ISS on-orbit lifetime and the MM/OD environment are increasing, shielding may have to be added in other areas. For deep space missions, the ability to augment the pre-integrated radiation shielding by using water, trash or by rearranging internal equipment should be considered an absolute requirement.**

    - **Political Compromise**
        - **The ISS can avoid certain size particles that can be tracked by ground-based assets and shield against particles up to a given size, but there is a residual risk for the particles too large to be shielded from and too small to be tracked. This risk is quantified and accepted by all ISS Program stakeholders. For deep space missions, the radiation risk will be mitigated to the greatest amount possible within the technological and programmatic constraints at that time. The stakeholders must accept a non-zero risk due to the SPE and GCR environments while knowing that the best possible efforts have been made to mitigate it.**

# Space Radiation Human Dose Mitigation Technologies

- Candidate solutions to the long term GCR IR dose problem generally fall into two categories
  - New technology (low TRL) development
    - Long, high-risk and high-cost development timelines
    - If successful, dramatically reduces launch cost and risk of flight operations
  - TRL "now" technology
    - Short low-cost and low-risk development timelines
    - High (possibly prohibitive) launch costs
  - Note that launch costs are an important (possibly the most important) program cost driver here
    - **~ $5000/kg to LEO**
    - **~ $20,000/kg to GTO**
    - **~ $100,000/kg to EM L1/L2**
- New technology (low TRL – long lead time) developments
  - Reducing transit (IR exposure) time needed for interplanetary mission objectives - Nuclear electric VASIMR
  - Active Shielding - very high field (high weight, complexity and power consumption also)
  - Space Biomedical Research
    - Reduce uncertainty in Dose-REID relationship
    - IR protectant pharmaceuticals

Assumed Hybrid DSH Dimensions for "TRL Now" Water Shield Analysis

- Pressurized Core Volume (excludes any inflatable envelope outside)
  - Cylinder
    - 4.5 meters (450 cm) diameter
    - 6 meters (600 cm) long
    - Volume = 95.43 cubic meters
    - Lateral surface area = 8.48×10^5 square centimeters
    - Total end cap surface area = 3.18×10^5 square centimeters
- Crew quarters located on one end of the pressurized core volume
  - Cylinder
    - 4.5 (450 cm) meters diameter
    - 3 meters (300 cm) long
    - Volume 47.7 cubic meters
    - Lateral surface area 4.24×10^5 square centimeters
    - End cap (2 of) surface area = 3.18×10^5 square centimeters
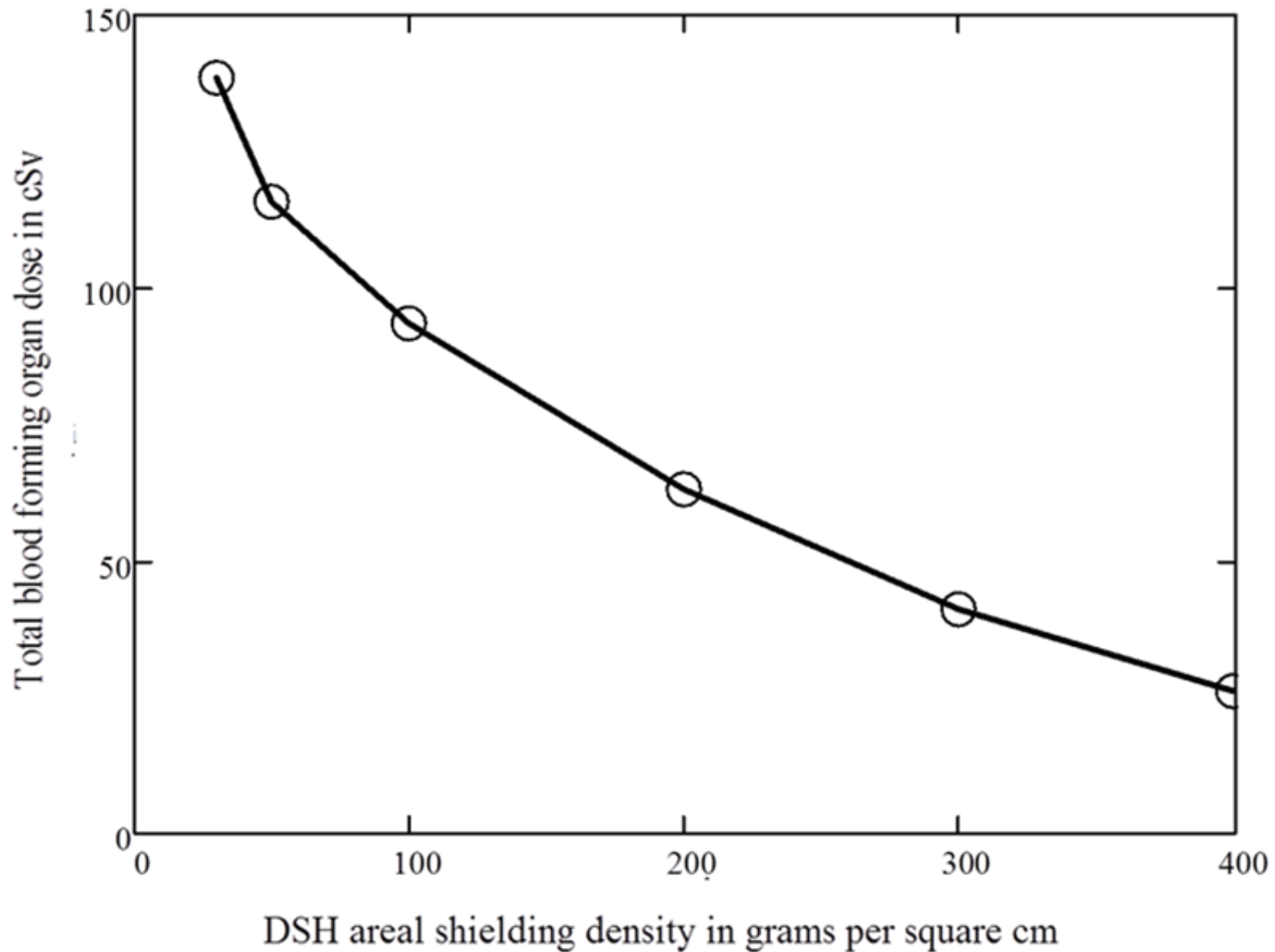
Total BFO dose equivalent as a function of areal density of water shielding mass for a worst-case, three-year interplanetary mission (solar minimum GCR and three October 1989 SPEs).
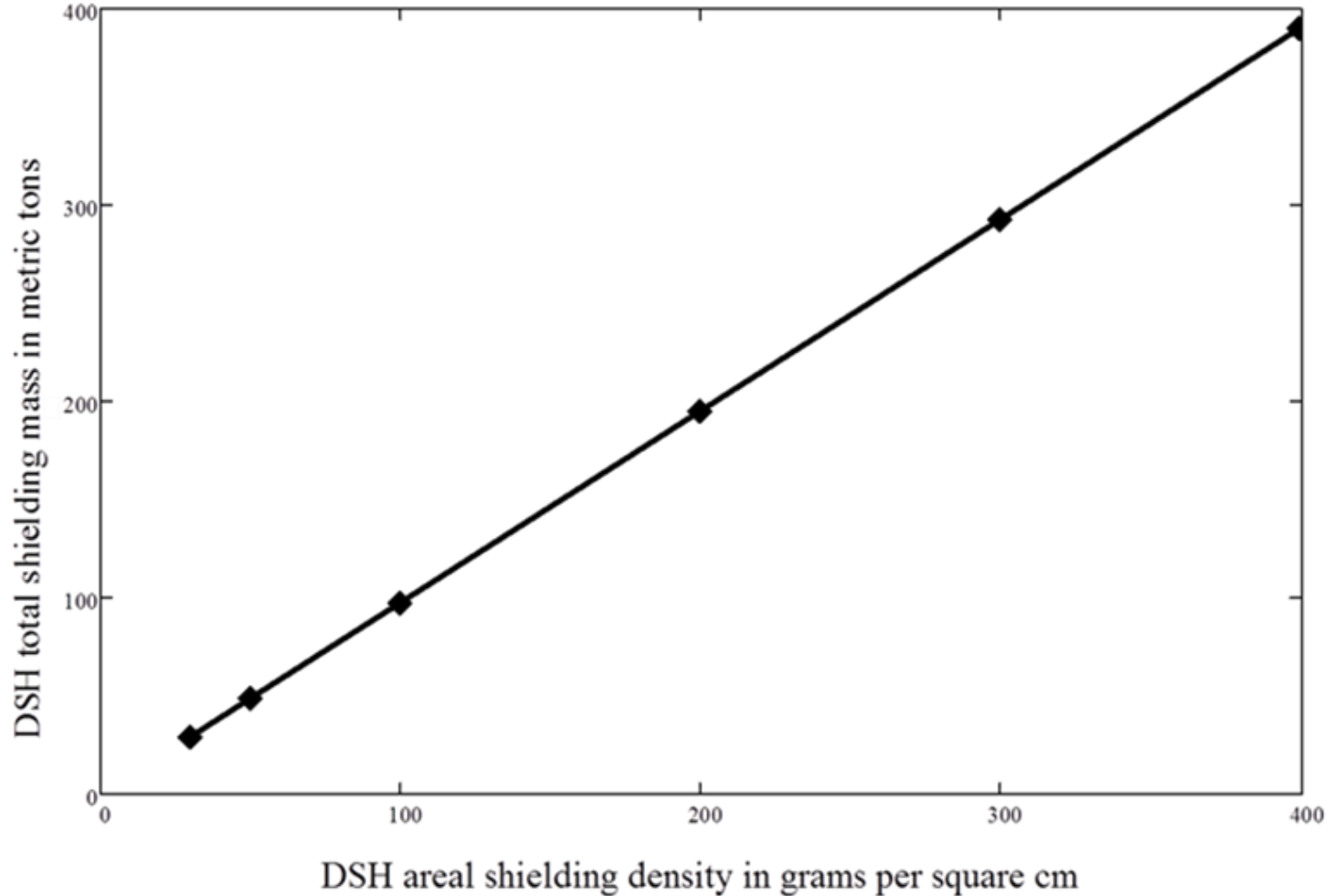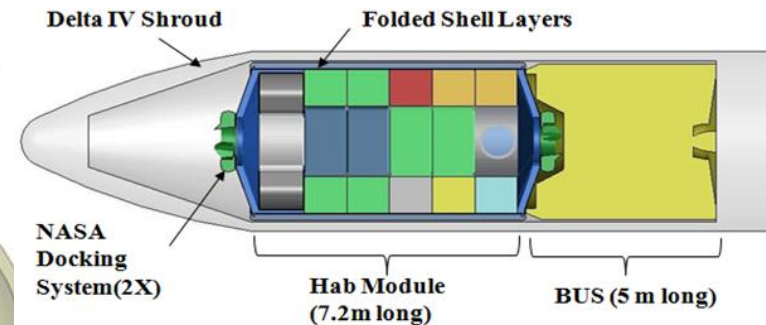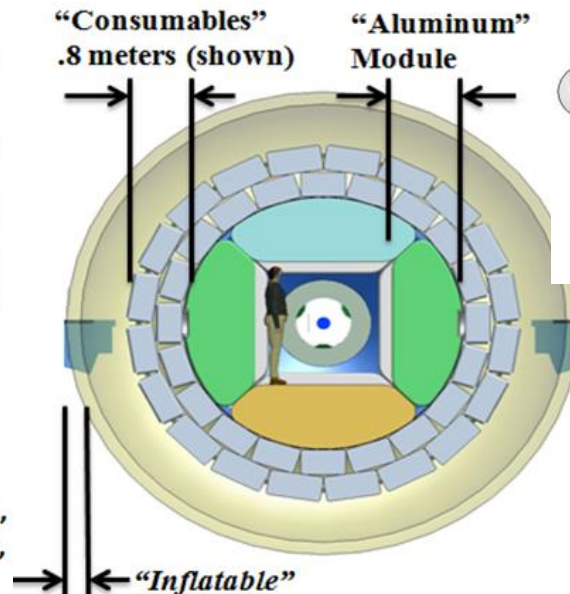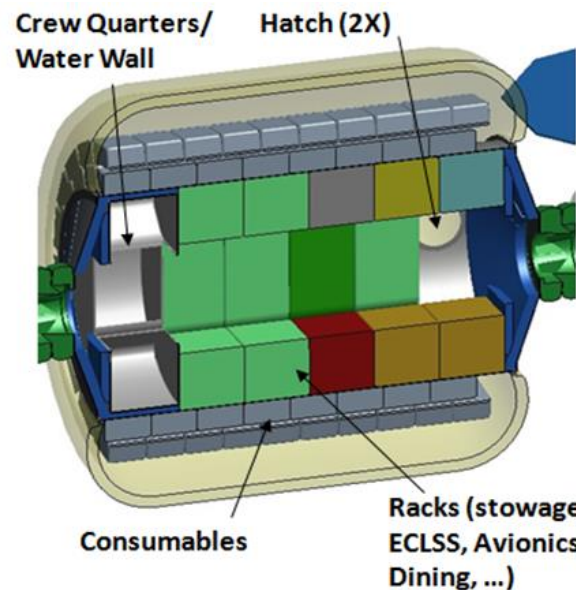
Total Hybrid DSH shielding mass (metric tons of water) corresponding as a function of shielding areal density.   Depending on the crew IR dose requirement the total habitat shielding mass can range from less than 50 to nearly 400 metric tons.
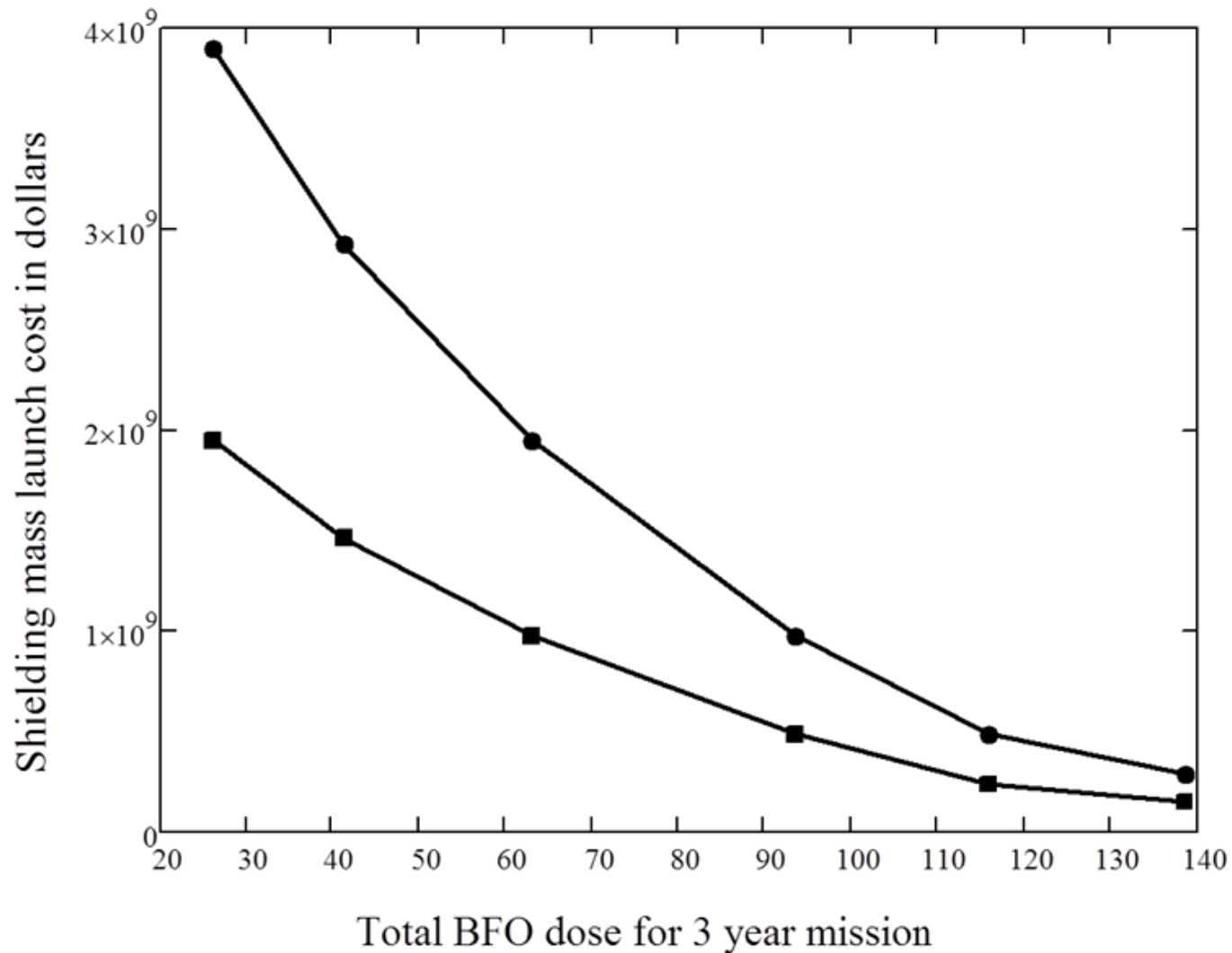
Total DSH shielding launch costs (dollars) as a function of the three-year BFO dose equivalent (solar minimum GCR and three Oct. 1989 SPEs). Costs are plotted for direct launch to GTO (-●-) and launch to LEO (-■-). A reusable solar electric tug can move bulk cargo from LEO to GTO at lower cost that direct launch to GTO

V. The Hybrid Inflatable Deep Space Habitat

- Provides a flexible architecture capable of providing radiation protection on initial launch
- Consist of a metal or composite core surrounded by an inflatable shell
- Launched in the folded configuration with racks and consumables prepositioned inside the central core
- Post-inflation consumables moved from inside through one of the two hatches to the outside of the core
- Additional consumables and generated waste (radiation protection) can be added throughout and on supplemental missions
- Water wall surrounding crew quarters provides additional radiation protection during SPE's
- NASA Docking System (NDS) located on the forward and aft sides of the module
- A Service Module is required to provide power, propulsion, and GN&C as required (not shown)
- A Propulsion Bus is included to slow the module down post-insertion and Service Module mating
- Can be launched on an Expendable Launch Vehicle (ELV).

Crew Quarters/ Water Wall — Hatch (2X)

Consumables

Racks (stowage, ECLSS, Avionics, Dining, ...)

"Consumables" .8 meters (shown)

"Aluminum" Module

"Inflatable"

Delta IV Shroud — Folded Shell Layers

NASA Docking System (2X)

Hab Module (7.2m long) — BUS (5 m long)

- Hybrid inflatable supports a one-year mission meeting a 40 cSv guideline (see Figure page 22)

V. The Hybrid Inflatable Deep Space Habitat

- For a three year mission with a 40 cSv guideline, a 310 cm (10 ft) equivalent water wall is required (see Figure page 22)

- An alternate embodiment of a Hybrid Inflatable Module, including supplemental inflatable water bags is shown below

- Air and water bags are compartmentalized so that water can be added incrementally over time

- External inflatable water bags require their own passive thermal and micrometeoroid protection layers

Air
H_2O
Air H_2O
H_2O Air
Air H_2O
H_2O Air
H_2O
Air
3.35
2.75
Ø10.6
Ø1.4 Ø7.5 Ø13
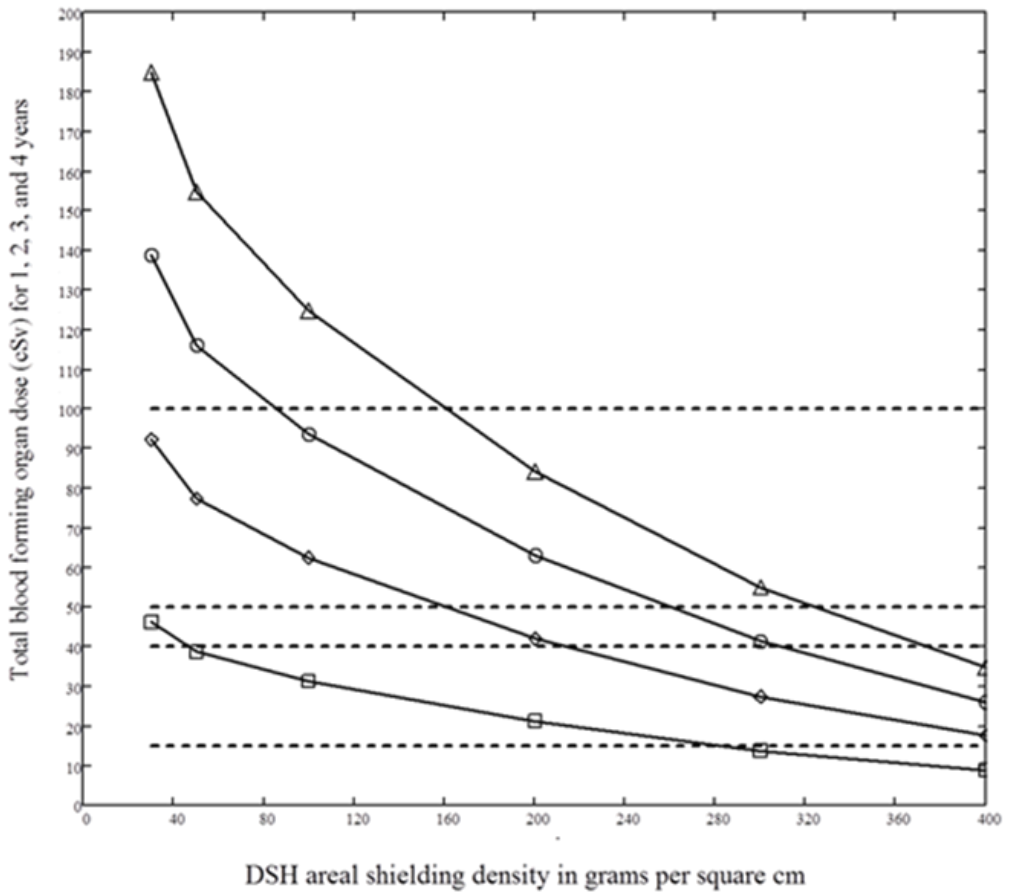3.5
8
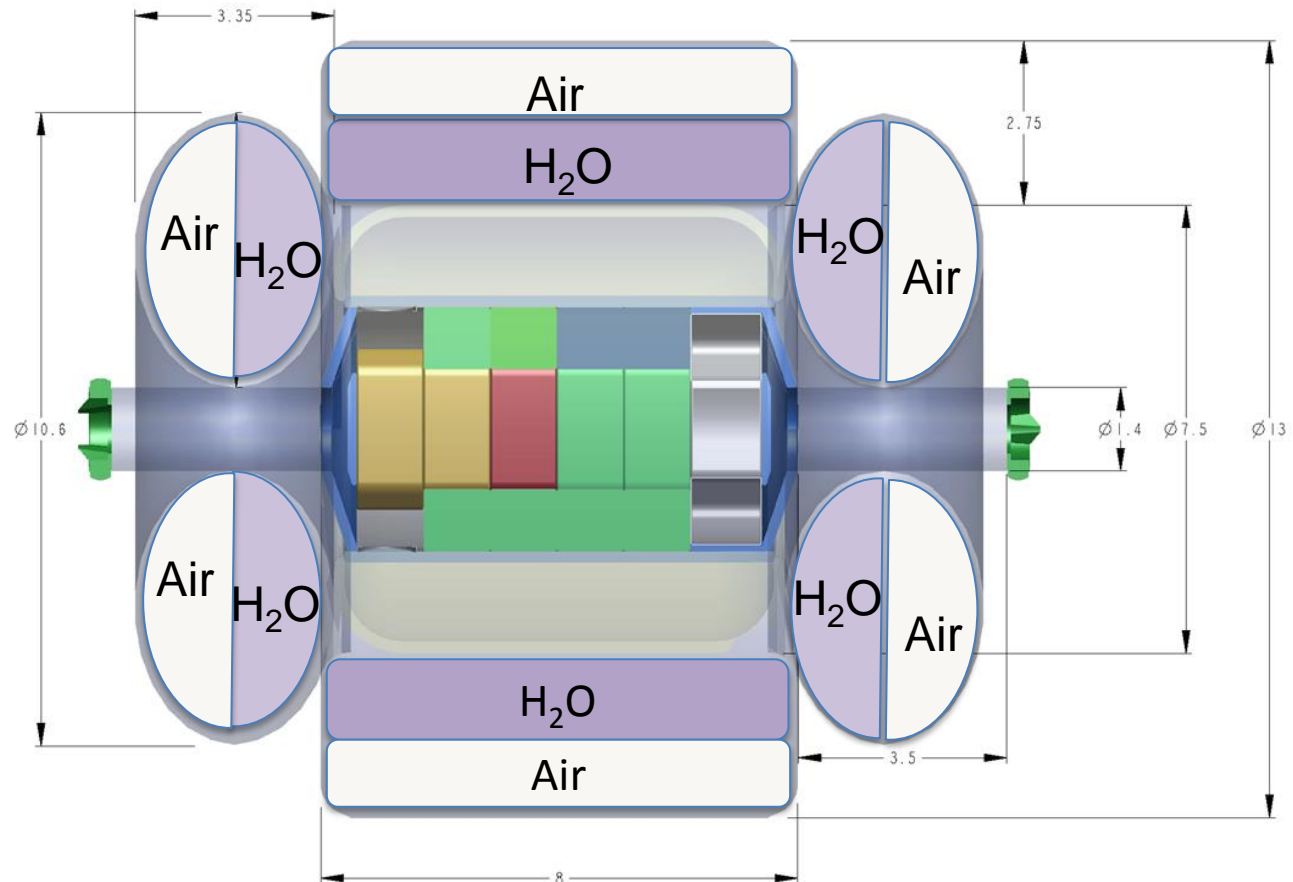
* Dimensions in meters

A graphical spacecraft shielding estimator for mission durations of one (-□-), two (-◇-), three (-○-), and four (-Δ-) years. The dashed horizontal lines represent various possible crew dose limits (in cSv): 15, 40, 50, and 100.

To estimate the shielding thickness (water) needed for a particular mission time and crew dose limit combination, select a dose limit and draw a horizontal line at that point.

The areal density (thickness) for a particular mission duration is the X coordinate corresponding the intersection point of the dose line and the areal density curve for that mission duration.

Some examples are shown in the table above the graph.

Mission duration in Years	15 cSv (cm)	15 cSv (ft)	40 cSv (cm)	40 cSv (ft)	50 cSv (cm)	50 cSv (ft)	100 cSv (cm)	100 cSv (ft)
1	290	9.4	50	1.6	< 30	< 1	< 30	< 1
2	> 400	>13	220	6.9	160	5.2	< 30	<1
3	> 400	> 13	310	10	260	8.5	85	2.8
4	> 400	> 13	> 400	12	325	10	160	5.2

DSH areal shielding density in grams per square cm

VI. How the Hybrid Inflatable Deep Space Habitat Enables Affordable Multi-mission Architectures

- Affordability and cost control are necessarily high priority objectives for any new manned space flight initiative.
- Controlling the space radiation dose to the flight crew to during long duration missions is one of NASA's highest priorities.
  - Current space radiation dose limits are based on worst case analysis and are expected to increase in future as space biomedical research progresses
- The engineering community is faced with the challenge of designing an interplanetary transport without a stable crew radiation dose limit for design and verification purposes.
- The Hybrid Inflatable DSH offers a simple solution to the changing dose requirements problem
  - A single DSH design can accommodate a wide range of crew dose requirements
    - Simply changing the water shielding mass in the inflatable external shielding mass containers
  - One core habitat design can meet the needs of a variety of missions and mission dose requirements without costly redesign or re-work.
  - External water tanks can be used to augment the basic core habitat shielding as needed for specific missions
    - The mass of water can be reduced when crew dose limits are increased or flight opportunities at solar maximum appear unexpectedly.
- **One DSH design that the agency can use for a variety of manned interplanetary flights over many years reduces or eliminates the costs associated with multiple mission-specific designs or periodic mission-specific re-design and re-work.**

VII. Summary & Conclusions

The Hybrid Inflatable DSH combined with electric propulsion and high power solar-electric power systems offer a near TRL-now solution to the space radiation crew dose problem that is an inevitable aspect of long term manned interplanetary flight.

Spreading program development and launch costs over several years can lead to a spending plan that fits with NASA's current and future budgetary limitations, enabling early manned interplanetary operations with space radiation dose control, in the near future while biomedical research, nuclear electric propulsion and active shielding research and development proceed in parallel.

Furthermore, future work should encompass laboratory validation of HZETRN calculations, as previous laboratory investigations have not considered large shielding thicknesses and the calculations presented at these thicknesses are currently performed via extrapolation.

Questions?
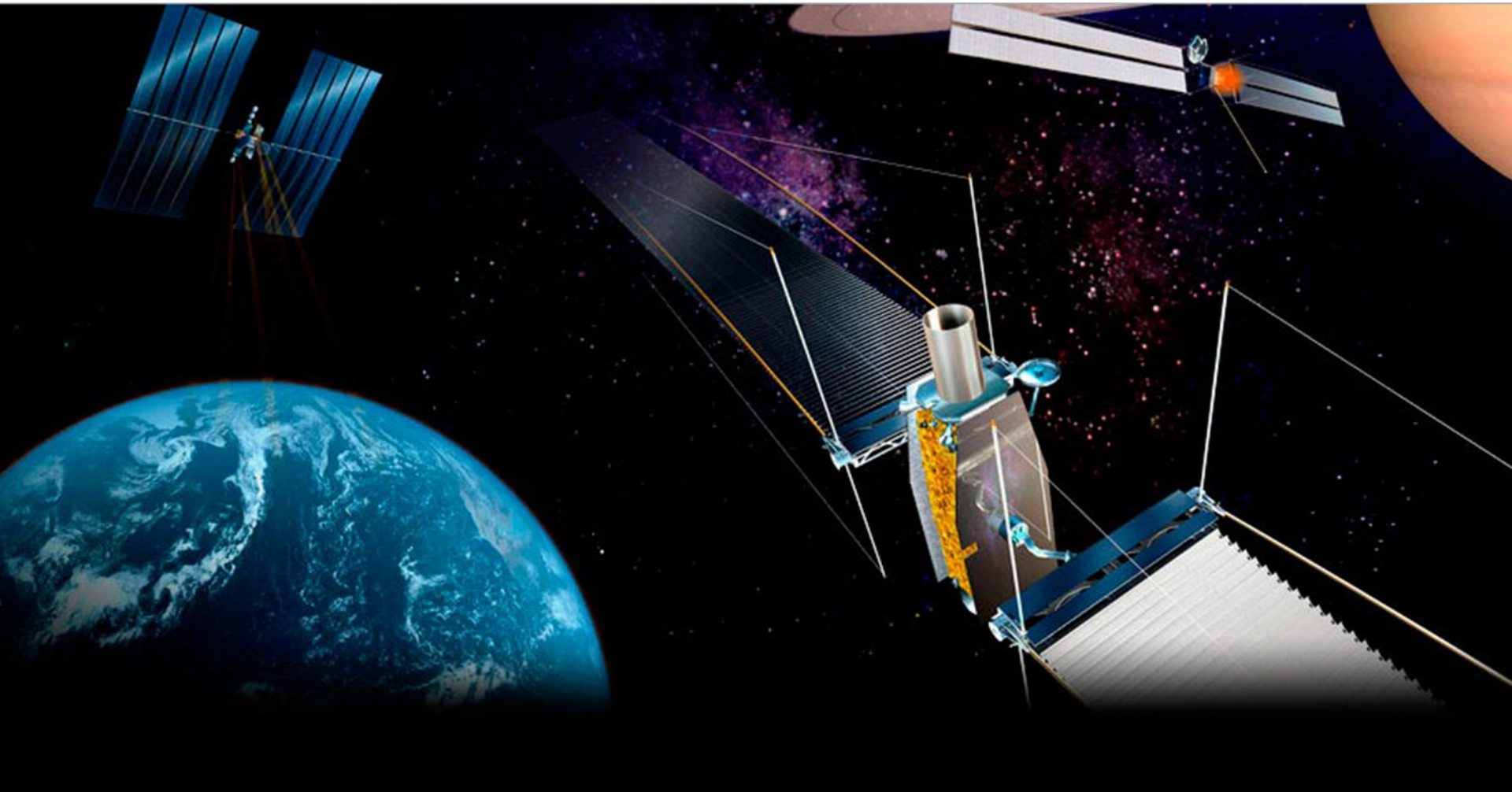
http://www.boeing.com/advertising/space/advancedsystems/solar_elec_prop.html

BACKUP

Energetic charged particle interactions with matter (including human tissue): Three Basic Processes

1. Energy loss (dE/dx) by direct ionization/excitation of material along the particle track
- Direct ionization effects – linear energy transfer (LET) – "slowing down"
- Primary cause of single event effects (SEE) in susceptible electronic devices
- Primary cause of total ionizing dose effects in susceptible electronic devices
- Primary cause of human health effects and degraded function of avionics systems

2. High energy collisions (inelastic/hadronic) triggering nuclear reactions
- Nuclear hadronic reactions initiate secondary particle showers in the target mass
- Further collisions of secondary particles with target nuclei lead to expansion and propagation of the secondary particle shower
- Secondary particles can produce direct ionization and more nuclear reactions

3. Collisions with material nuclei that produce displacement damage
- Displacement of target atoms so as to disrupt crystal structure (solids only – not considered further here, but important for some spacecraft optoelectronics)

Direct ionization & excitation of target substance

- **High speed charged particles decelerate by loosing energy to target substance electrons during columbic collisions leaving an ionization/excitation damage track**
  - ◆ Nuclear collisions make little contribution to deceleration except at the lowest kinetic energies near end of track.
  - ◆ http://pdg.lbl.gov/2010/reviews/rpp2010-rev-passage-particles-matter.pdf
- **dE/dx is the rate of energy transfer: keV/micron or MeV-cm^2/mg in a particular target substance**
  - ◆ Linear and nearly constant over most of the particle range - hence the term linear energy transfer (LET)
  - ◆ Nonlinear near end of track – most of the energy is deposited near the end of track in the "Brag Peak"; basis of accelerator hadron therapy for certain cancers
- **Quantified by the relativistic Bethe-Bloch equation**

$$-\frac{dE}{dx} = \frac{4\pi}{m_e c^2} \cdot \frac{n z^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \cdot \left[\ln\left(\frac{2 m_e c^2 \beta^2}{I \cdot (1 - \beta^2)}\right) - \beta^2\right]$$

Projectile (cosmic ray particle) dependencies

$\beta = v/c$; v = velocity of the particle; E = energy of the particle; x = distance travelled by the particle in the target; c = speed of light; z = particle charge; ε_0 = vacuum permittivity

Target substance dependencies

I = mean excitation potential of the target = $10 eV(Z)$, n = electron density of the target = $(N_A Z \rho)/A M_\mu$; ρ = density of the target; Z = target atomic number; A = target atomic mass number; N_A = Avogadro number; and M_u = Molar mass constant = 1 in Si units; e = charge of the electron; m_e = rest mass of the electron
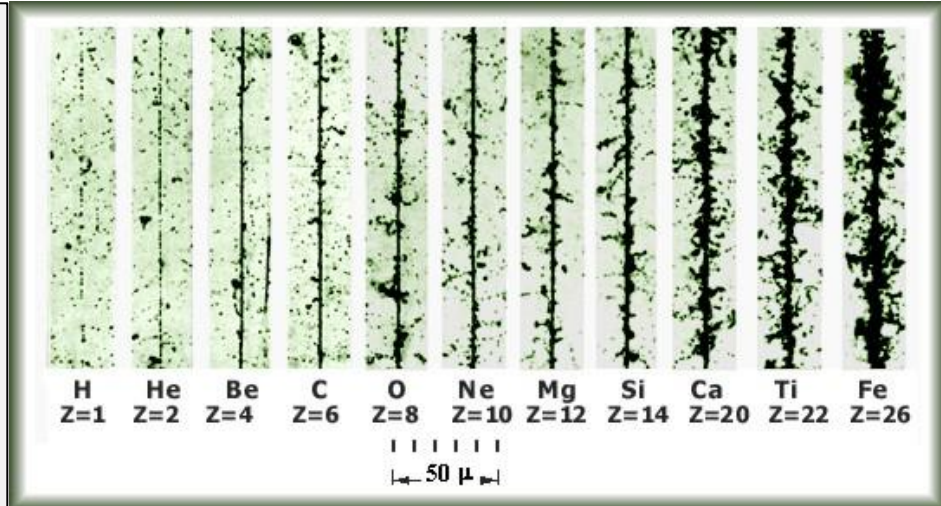

Photographic/nuclear emulsion tracks - Image Credit - PROF. P. FOWLER, UNIVERSITY OF BRISTOL
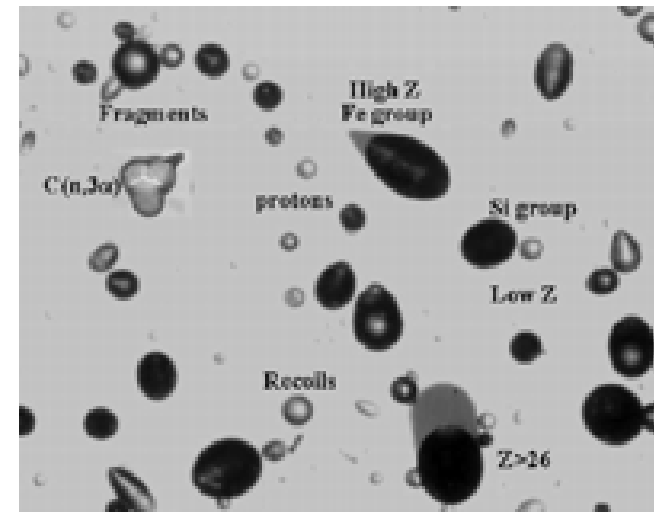
CR-39 (polycarbonate thin plastic sheet) solid state nuclear track detector SSNTD – ISS Tracks are revealed by etching the plastic post flight

Nuclear Reactions and Secondary Particle Showers

- **Inelastic collisions attenuate the primary flux exponentially and generate secondary particle showers via nuclear reactions**
  - **$N(l) = N(0) \exp(-l/\lambda)$**
    - λ = inelastic collision length (grams/cm^2)
    - l = thickness in g/cm^2
  - **http://pdg.lbl.gov/2010/reviews/rpp2010-rev-atomic-nuclear-prop.pdf**
    - λ ranges from **42 g/cm^2 to 118 g/cm^2 for protons in various materials**
    - At fixed target mass, number of collisions decreases with increasing atomic weight (i.e. fewer target nuclei per gram)
    - λ Scales as **(projectile atomic number)$^{0.77}$**
    - λ increases with target atomic number
- **$\langle n_{event} \rangle$ = average number of secondary particles per collision event**
- **$\langle n_{collision} \rangle$ is proportional to A(projectile) x A(target) x (average nuclear thickness function)**
- **$\langle n_{shower} \rangle$ is proportional to primary projectile energy**
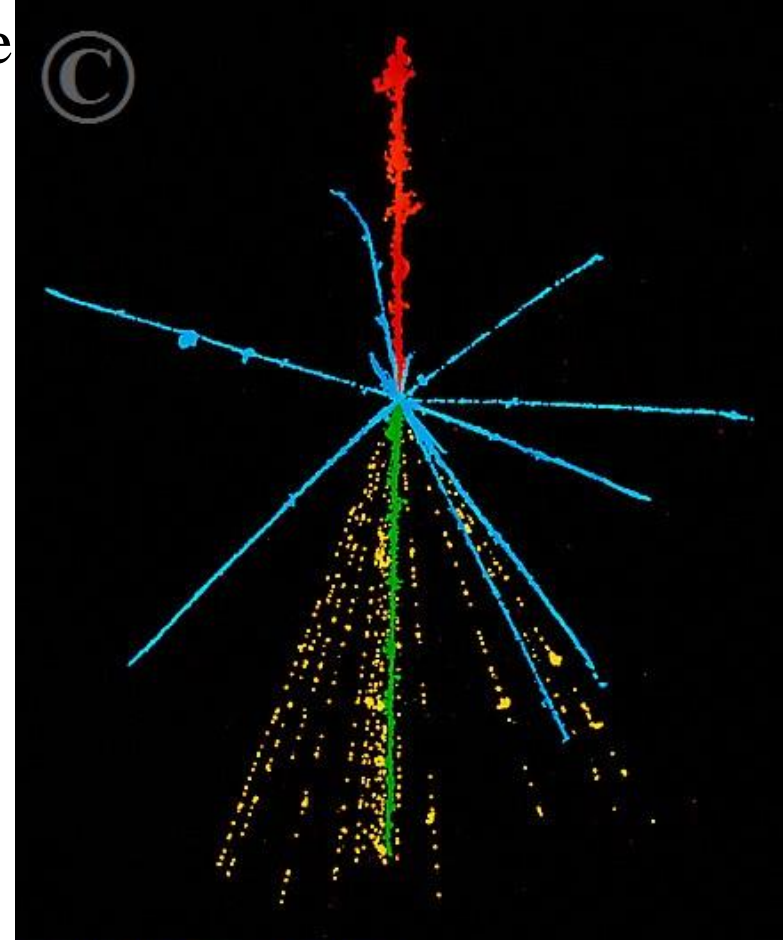
a134005 [RM] © www.visualphotos.com

False- color emulsion photo of a cosmic ray sulfur nucleus (red) colliding with a nucleus in the emulsion. The collision produces a spray of other particles: a fluorine nucleus (green), other nuclear fragments (blue) & 16 pions (yellow). The length of the sulfur track is 0. 11 mm. The curlicues which adorn the track of the sulfur nucleus are electrons which it has knocked out of atoms in passing. The photograph was taken in 1950 by Cecil Powell, the English physicist who pioneered the use of photographic emulsions to record the tracks of electrically charged particles.

Radiation Hazard to Astronauts