Materials for Radiation Protection

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Introduction

Units:

1 Gray (Gy) = 1 joule/kg (= 10^4 erg/g = 100 rads)
1 Sievert (Sv) = W_R * Gray (= 100 rem)
Note: $0.8 < W_R < 20$

Exposure Limits for Astronauts:

0.2 Sv to the blood forming organs (BFO)/year
Note: Was 0.5 Sv/yr until recently

Sources of Radiation in Space:

Galactic Cosmic Rays:

- Always present, varies with Solar Cycle and weakly with distance from the Sun
- Very energetic particles, partial shielding from the earth's magnetic field
- Comprised of electrons and the nuclei of all the known elements
- Typical dose on MIR missions: 0.5 mSv/day (Cucinotta, 1999)
- Deep Space Dose in 1997: 1.1 Sv/year behind 5 g/cm of Al (Wilson et al, 1998)
- Model accuracy: 15-25% (Badhwar, 1997)

Trapped Radiation:

- Always present but only in earth orbit, episodes of enhancement
- Varies with orbital altitude and inclination and in LEO with solar cycle
- Consists mainly of protons and electrons
- Typical dose on MIR missions 0.3 mSv/day (Cucinotta, 1999)
- Typical model accuracy for Shuttle Missions: 5%* (Wilson et al, 1999)

*Except during episodes of enhancement (can be higher 50% on Shuttle)

Anomalous Cosmic Rays:

- Always present
- Varies with strongly Solar Cycle and with distance from the Sun
- Comprised of certain elements, He, O, Ne, etc.
- Significant doses only in the outer heliosphere

Solar Energetic Particles (SEPs):

- Present in outbursts called SEP events
- Events cannot be predicted in advance
- Event rate varies with solar cycle and event size
- Varies with radial distance from the sun and solar longitude
- Comprised of electrons and the nuclei of all the known elements
- Shielding from the earth's magnetic field
- Sept. 29, 1989 dose on MIR: 0.03 Sv (Shurshakov, et al., 1999)
- Worst-case Deep Space Dose: 3.5 Sv (pressure vessel)*, 4.2 Sv (Spacesuit)*

*Wilson, et al, Intl. Conf. on Environmental Systems (1999)

Radiation Transport Through Shielding:

Methods:

- Slab Method
  (Used for interpretation of cosmic ray data – NRL, U of Minn., etc)
  (Used for space radiation shielding – NASA LaRC and JSC)
- Monte Carlo Method
  (Used for reactor and accelerator shielding – ORNL)

Slab Method:

- Use continuous slowing down approximation for electronic energy loss (dE/dx)
- dE/dx is scaled from proton dE/dx by Z^2/A
- Neglect straggling and multiple scattering
- Use straight ahead approximation for nuclear interactions and decays
- Secondaries are assumed to have the same velocities as their progenitors
- Divide the shield into slabs so thin that two interactions within a slab are very improbable
- Corrections:
  1) Schimmerling's method for multiple scattering corrections
  2) Neutron Transport Algorithm (Heinbokel, Clowdsley and Wilson, 2000)
- Disadvantage – approximations
- Advantage – Speed
- Current research – Cucinotta et al.

Monte Carlo Method:

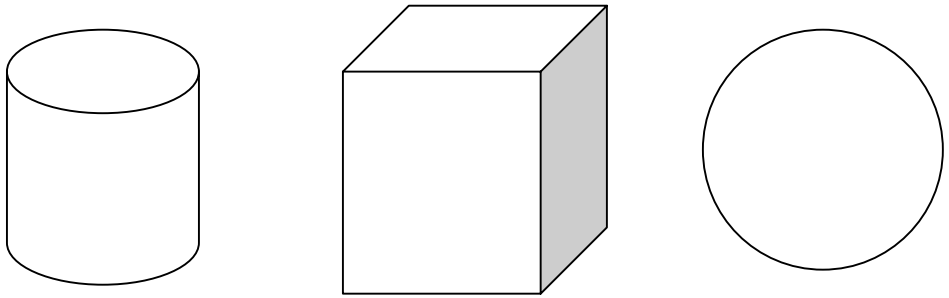
- Follows individual particles as they do what physics dictates
- Fully three dimensional transport
- Advantage – very few approximations
- Disadvantage – does not do heavy ions
- Disadvantage – speed
- Current Research – Pinsky et al. and Townsend et al.
  1) "Development of a Space Radiation Monte-Carlo Computer Simulation Based on the FLUKA and ROOT Codes", Pinsky et al.

Nuclear Cross Sections:

- Primary Projectile nuclei ~68 (neglecting elements heavier than Ni)
- Unstable secondary Projectile nuclei ~160 nuclei
- Common target nuclei ~10
- Projectile-fragment-target combinations $\Rightarrow$ ~260,000 cross sections
- Energy range of interest: 10 MeV/nuc – 100 GeV/nuc
- Use theoretical models for these cross sections
  1) NRL Semi-empirical method (Silberberg and Tsao)
  2) LaRC Cross section models (e.g. NUFRG2, Wilson et al., 1995)
- Measure a small % of these cross sections as 'anchors' and 'checks'
- Theory and measurements are still an active area of research:
  1) "Integration of QMSFRG Database into the HZETRN Code" – Cucinotta et al.
  2) "Measurement of Charged Particle Interactions in Spacecraft and Planetary Habitat Shielding Materials" Zeitlin et al.

Combinatorial Geometry

Up to now the only way to describe the only way to describe the detailed three-dimensional design of a space vehicle to a radiation transport program was to begin from the engineering drawings and materials lists and build a three dimensional model using combinatorial geometry. This involves representing every part of the vehicle as a combination of solid shapes and/or Boolean combinations of these shapes. It is huge and tedious task that is very prone to error.



Plan:
Combine the radiation transport code with a combinatorial geometry package to insure that the package can accept configuration data exported by 3-D AUTOCAD packages that comply with ISO 10303 (Standard for the Exchange of Product [STEP] Model Data)

HETC geometry package is AUTOCAD compatible but supports only ray-tracing.

CADRays, An AutoCAD geometry application for radiation analysis being developed by SAIC (John Kern).

Energetic Particle Shielding and Interaction Tools activity of ESA to introduce an ISO 10303-compatible software package into GEANT4 that will import the 3-D geometry.

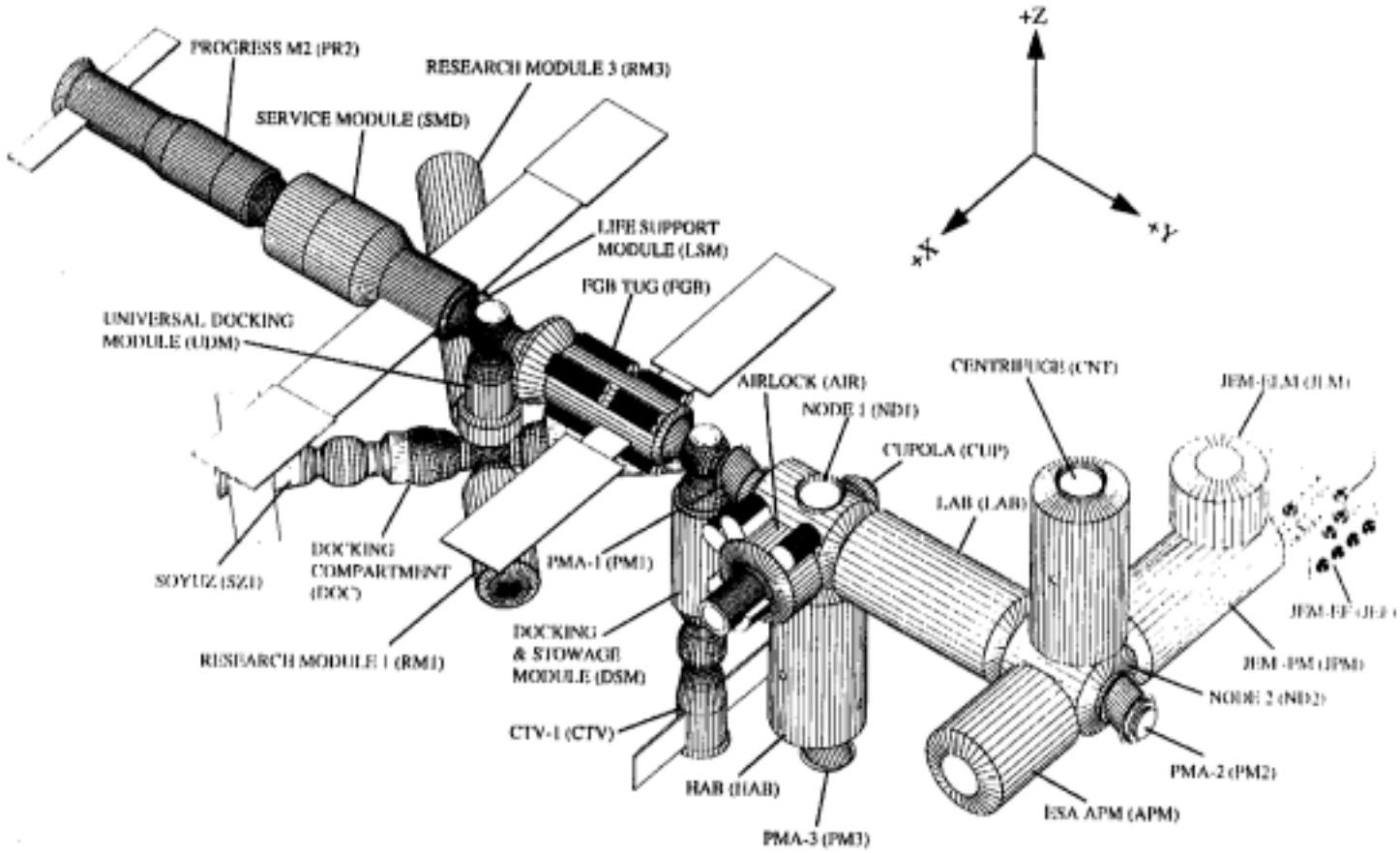
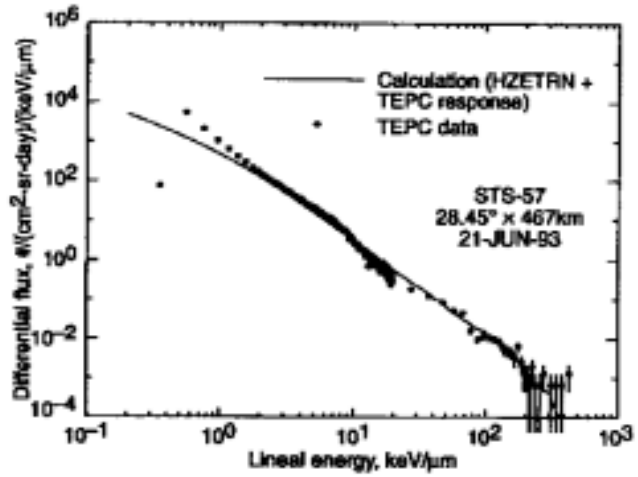


Fig. 3. Current version of CADrays 3-D mass model of International Space Station for radiation analyses (trusses not shown).

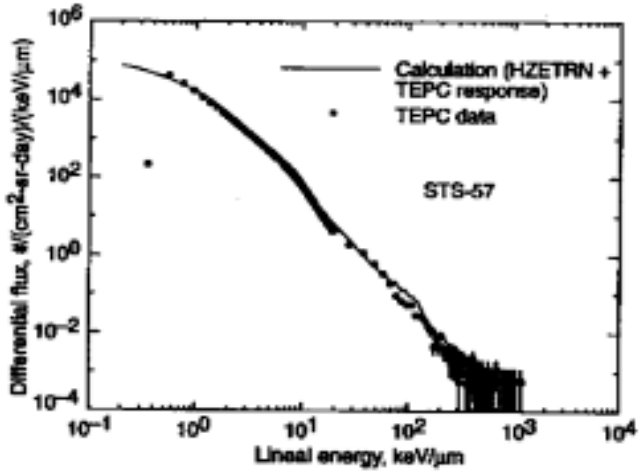
From Armstrong and Colborn, 1998

In-Flight Validation:

- Numerous in-flight measurement have been to validate shielding calculations
- Instrumented human phantoms have been flown
- Currently a neutron detector package is under development – Maurer
  1) "Development of a Neutron Spectrometer to Assess Biological Radiation Damage Behind Spacecraft Materials" – Maurer et al.



(a) GCR contribution



(b) Trapped protons

Figure 6. Comparison of differential lineal energy spectra with TEPC data for a 28-degree Shuttle flight.

From Shinn et al., 1999

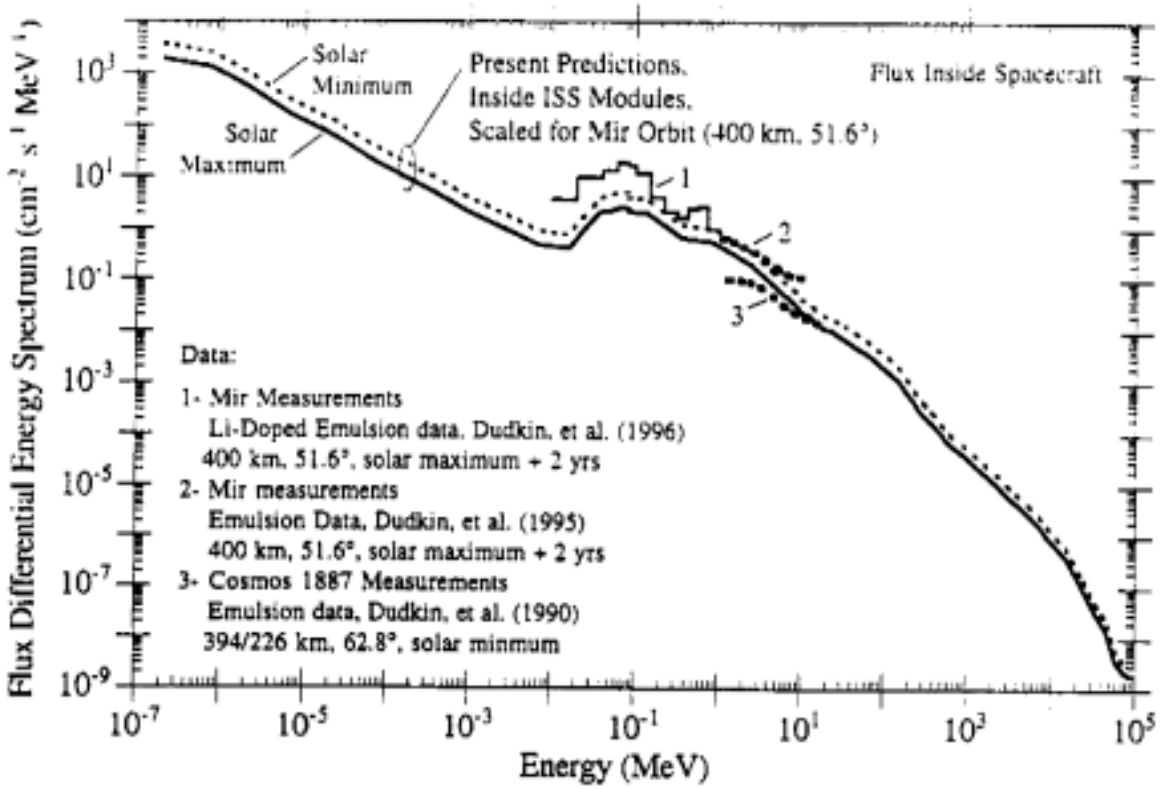


Fig. 28. Comparison of ISS predicted neutron spectra with measurements inside the Mir space station [30] and Cosmos 1887 spacecraft [31].

From Armstrong & Colborn, 1998

So, What About Shielding?

Historically the method was to use the shielding provided by the spacecraft, its equipment and cargo.

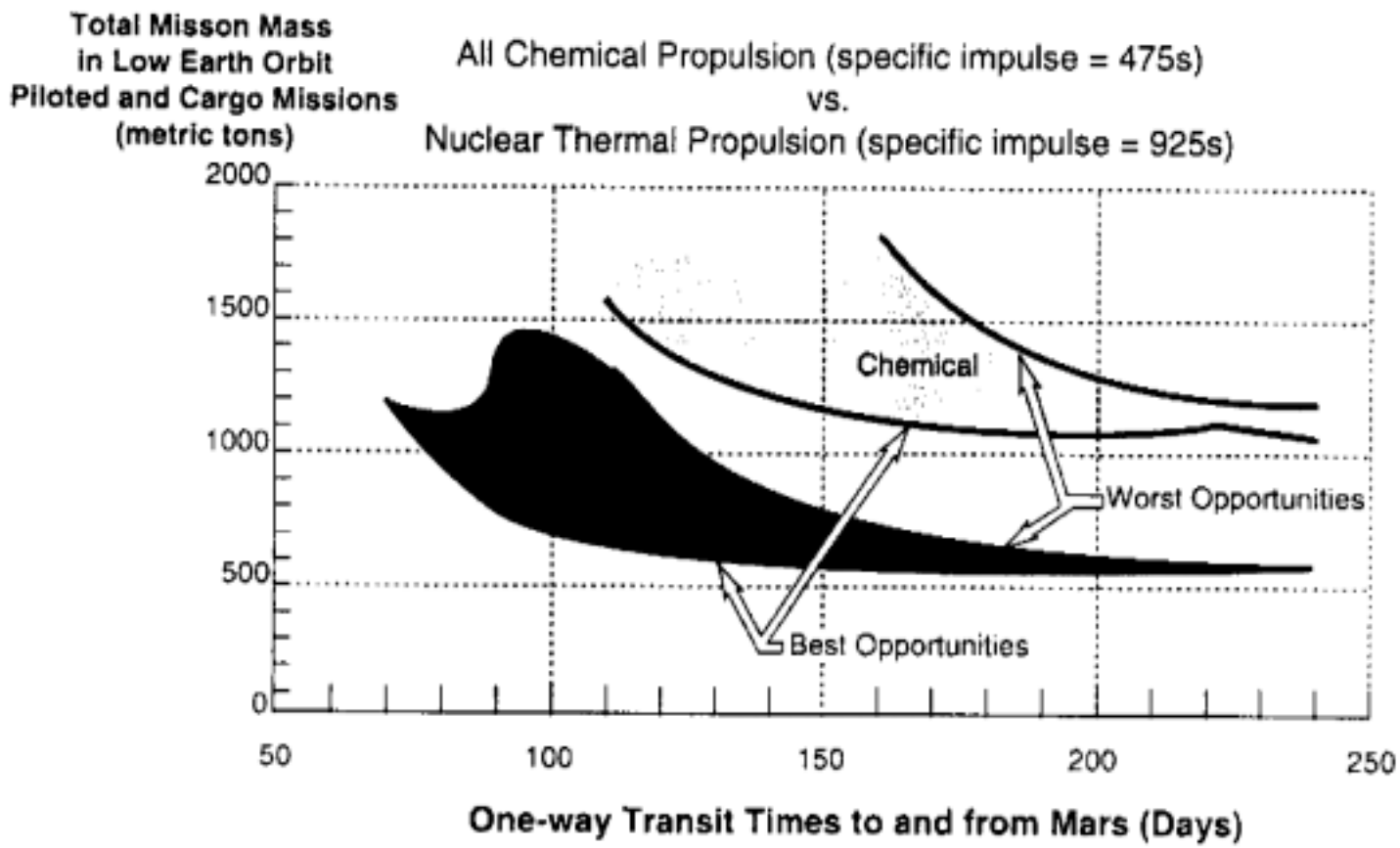
Because the dose for typical missions on the Shuttle and MIR (.5 to 5 mSv) were much lower than the dose limits (0.5 Sv), Only the ALARA principle applied.

NASA's radiation health program used the existing shielding (sometimes with a little added in thin spots) to make the radiation exposure 'As Low As Reasonably Achievable' (ALARA).

That is changing!

- Deep space missions would exceed the dose limit if nothing more was done.
- The dose limit was lowered (0.5 Sv $\Rightarrow$ 0.2 Sv), now even the ISS needs better shielding

TRANSIT TIMES FOR MARS LONG DURATION MISSIONS



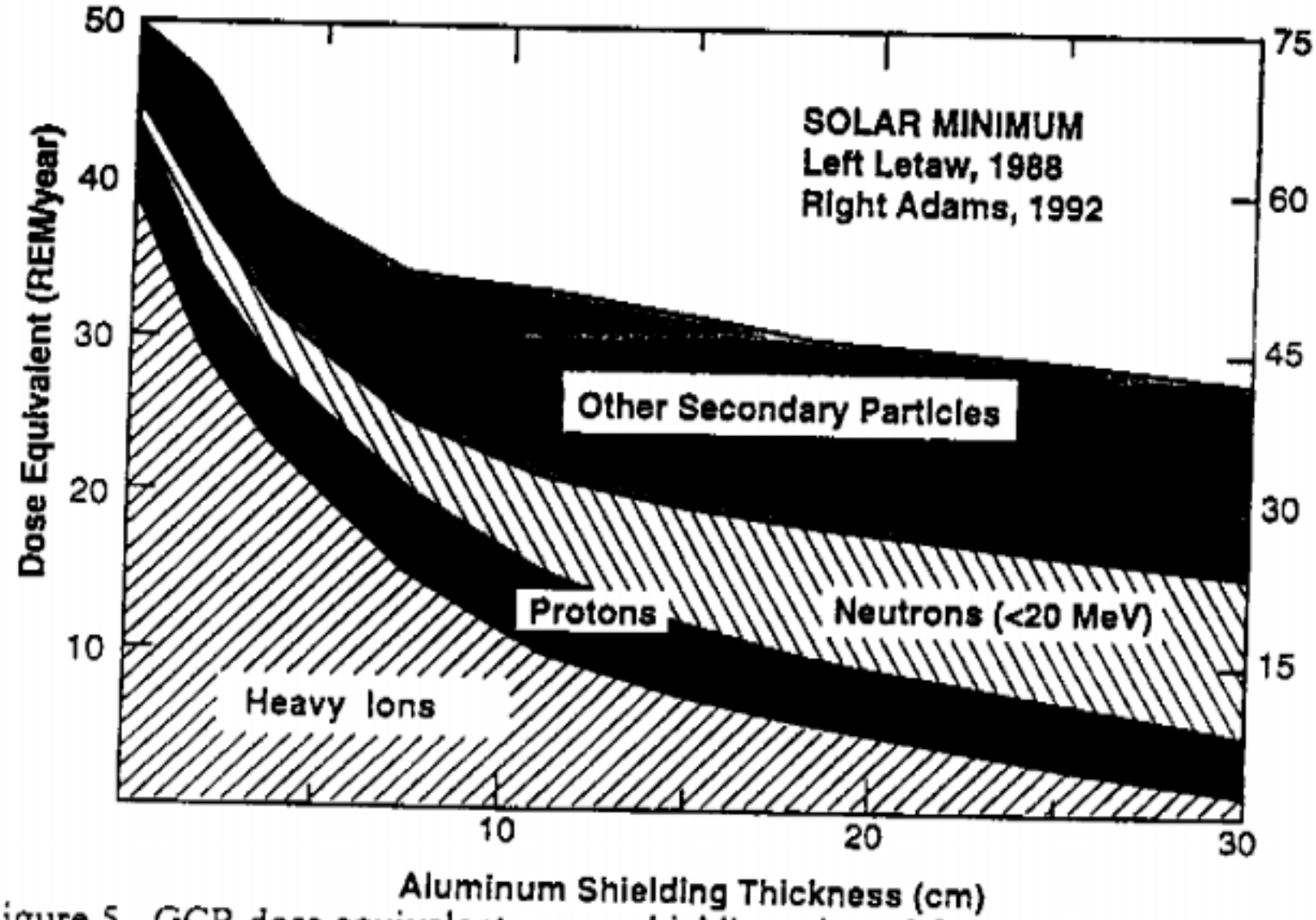


Figure 5. GCR dose equivalent versus shielding adapted from (Adams 1992; Letaw 1988). The left scale are dose values for nominal solar minimum (Letaw 1988) and the right scale are dose values for the 1977 solar minimum fluxes (Adams 1992). The largest doses are at solar minimum.

And That’s Where Material Science Gets Involved,

We need to select materials for manned spacecraft with shielding effectiveness in mind.

Good shielding materials are:

- Hydrogenous
- Thermalize and absorb neutrons
- Emit few target fragments

Existing Materials:

- Borated polyethylene
- Metal hydrides
- Boron or gadolinium coatings
- Food and water

New Materials:

- Palladium-silver alloy loaded with hydrogen
- Hydrogen-filled carbon nanotubes or bucky balls
- Composites of new and existing materials

In-Situ Materials:

- Lunar or martian regolith
- Composites of regolith and hydrogenous binders
- Current Research:
  1) “Radiation Transmission Properties of In-Situ Materials” – Heilbronn et al.
  2) “Radiation Transport Properties of Potential In Situ-developed Regolith-Epoxy Materials for Martian Habitats” – Miller et al.
  3) Measurements of Charged Particle Interactions in Spacecraft and Planetary Habitat Shielding Materials – Zeitlin et al.

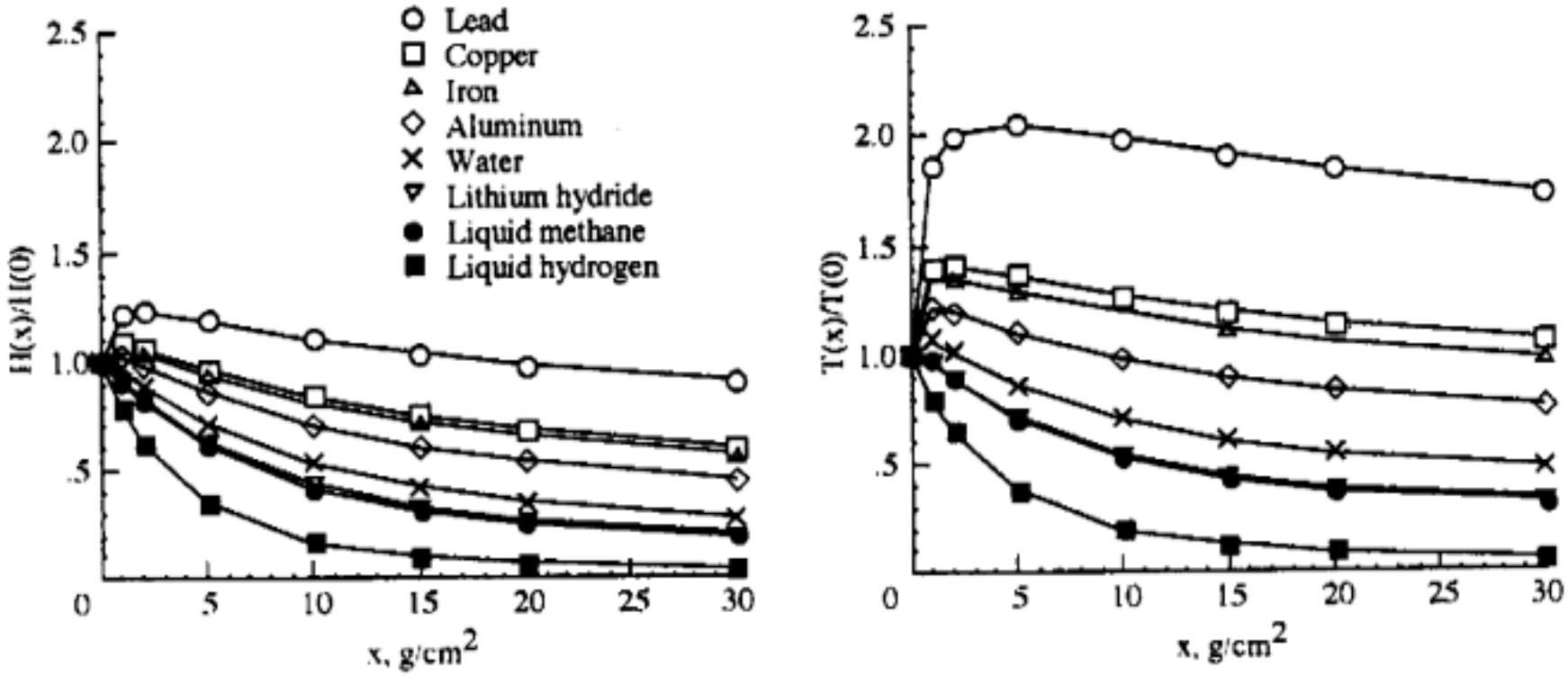
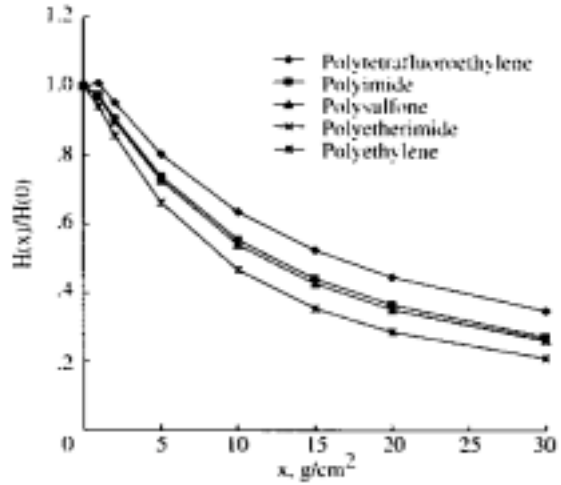


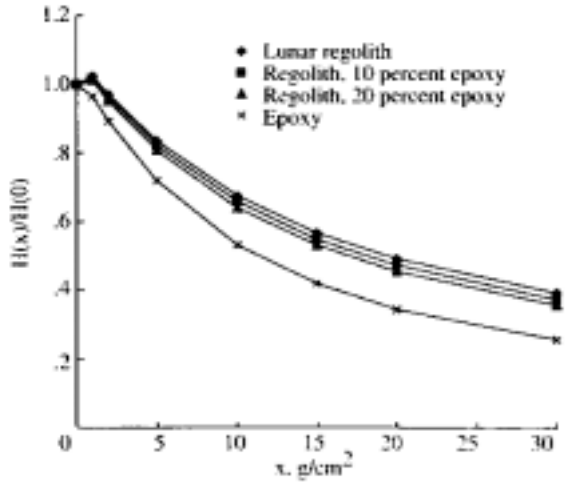
Figure 7. Attenuation of dose equivalent and cell transformation for a one-year GCR exposure at solar minimum behind various shield materials.

Wilson et al, 1998

Thibeault et al., 1997



(a) Polymeric shields.



(b) Lunar construction materials.

Figure 6. Attenuation of dose equivalent behind several shield materials as a function of shield thickness.

Where are Headed?

- New materials and composites for manned spacecraft that emphasize radiation-shielding effectiveness.
- Accelerator testing
- In-flight validation