Radiation Hazard for Deep Space Human Exploration

T.C. Slaba, M.S. Clowdsley

NASA Langley Research Center, Hampton, VA

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Exposure Analysis Overview

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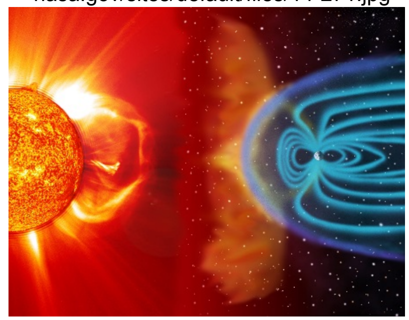
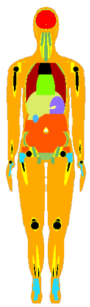
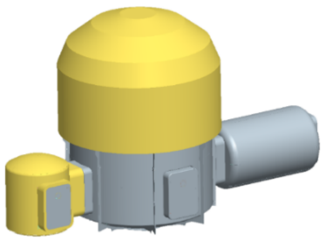
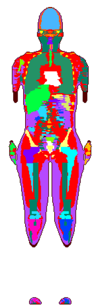
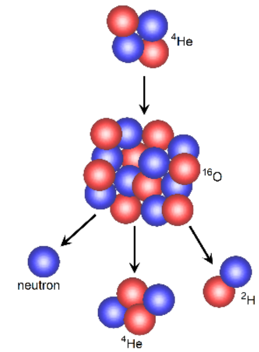










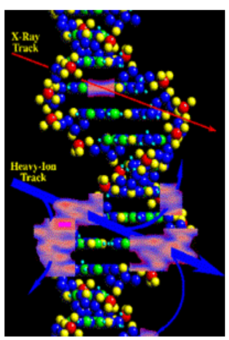
Shielding models

Environment models

Physics models

Radiation transport models

Exposure & Biological response



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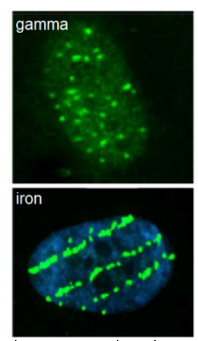
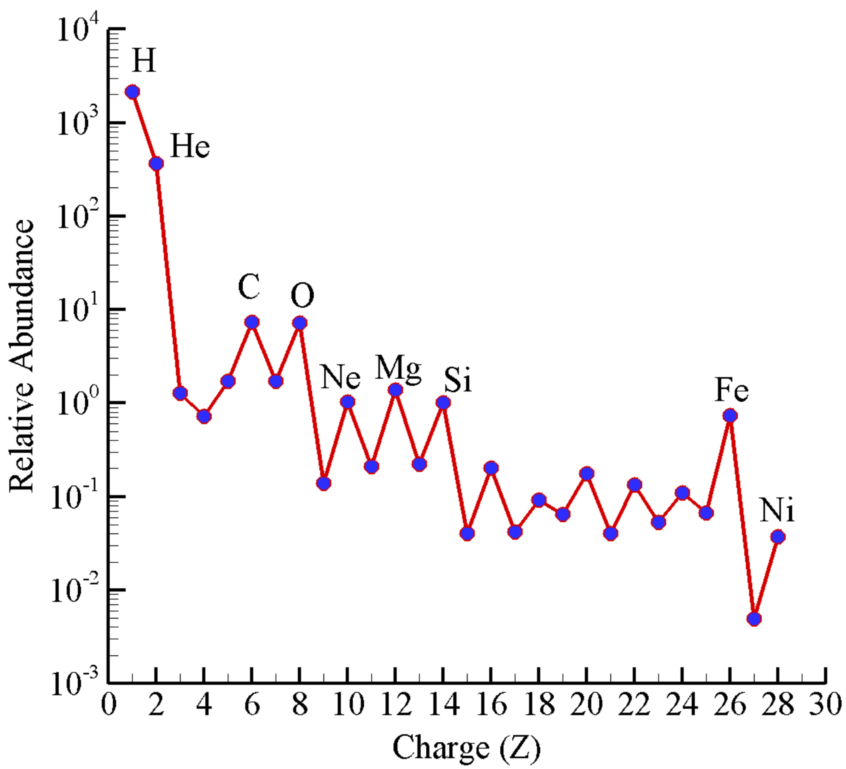
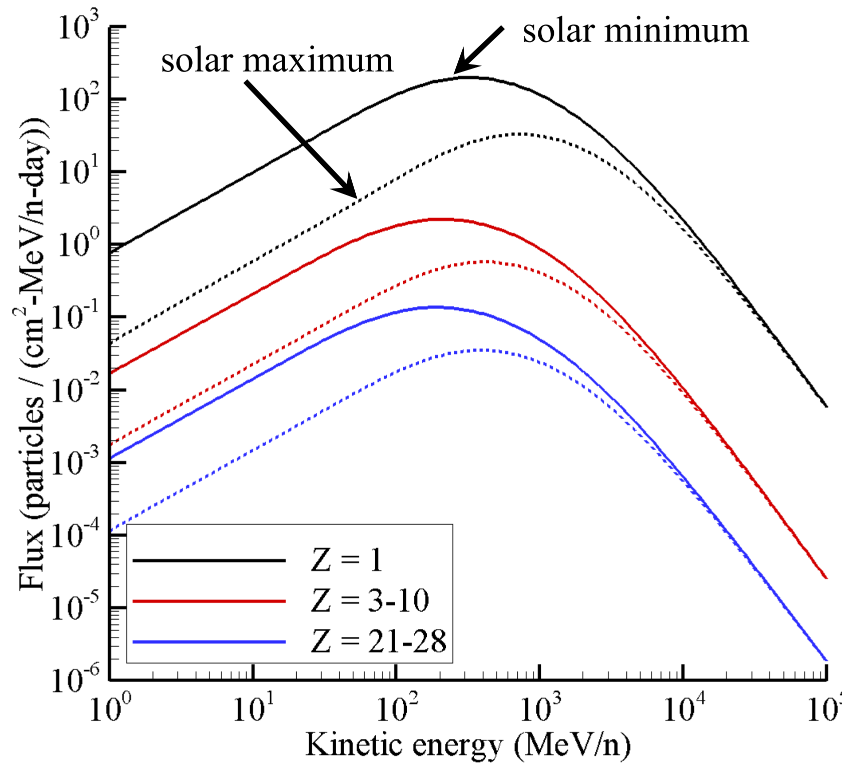


humanresearchroadmap.nasa.gov/evidence/reports/Carcinogenesis.pdf

Deep Space Radiation Environments

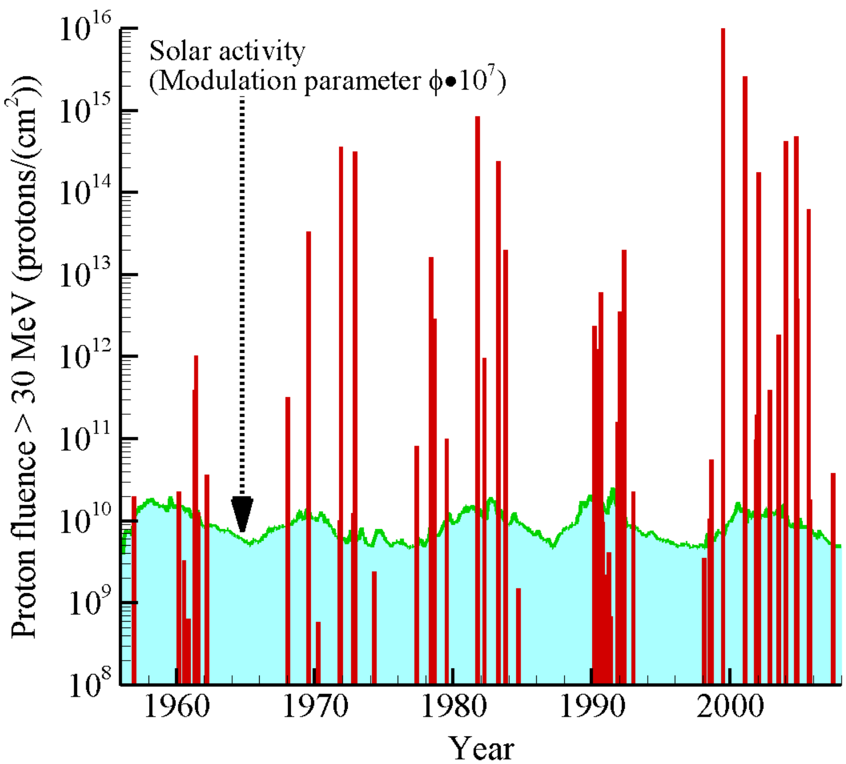
- The GCR environment is omnipresent in space and fluctuates between solar minimum and solar maximum on an approximate 11 year cycle
  - Exposures differ by approximately a factor of 2 between nominal solar extremes
  - Broad spectrum of particles (most of the periodic table) and energies (many orders of magnitude)
  - High energy and complexity of field make it difficult to shield against

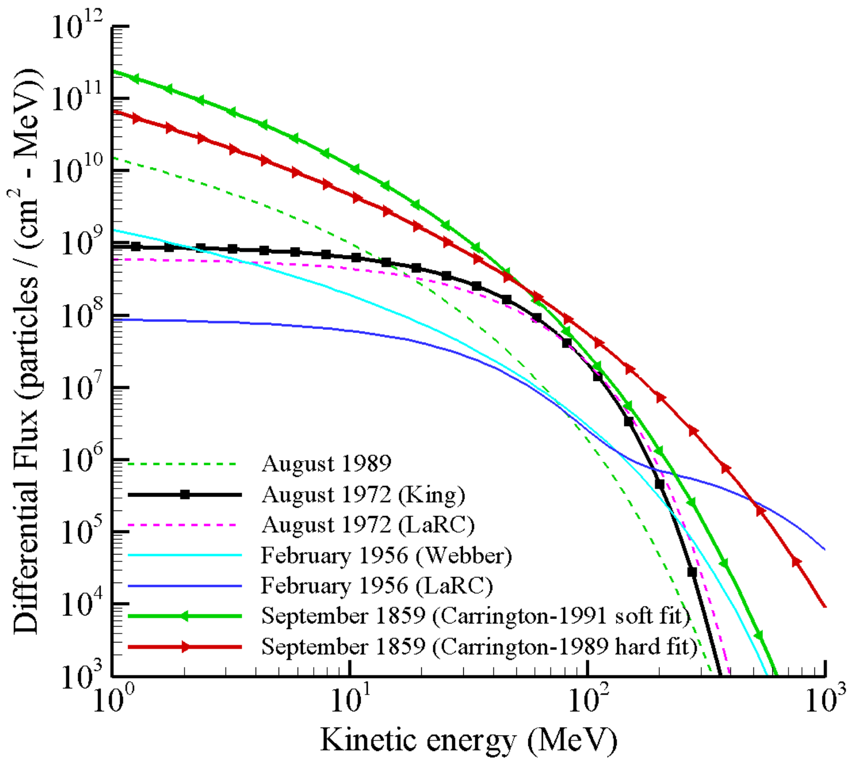




Deep Space Radiation Environments

- SPE/GLE are intense bursts of protons from the Sun
  - Difficult to predict occurrence, spectral shape, or magnitude
  - More likely to occur during periods of heightened solar activity (solar max)
  - Energies up to several hundred MeV (may extend up to GeV)
  - Presents serious acute risk to astronauts if not adequately shielded



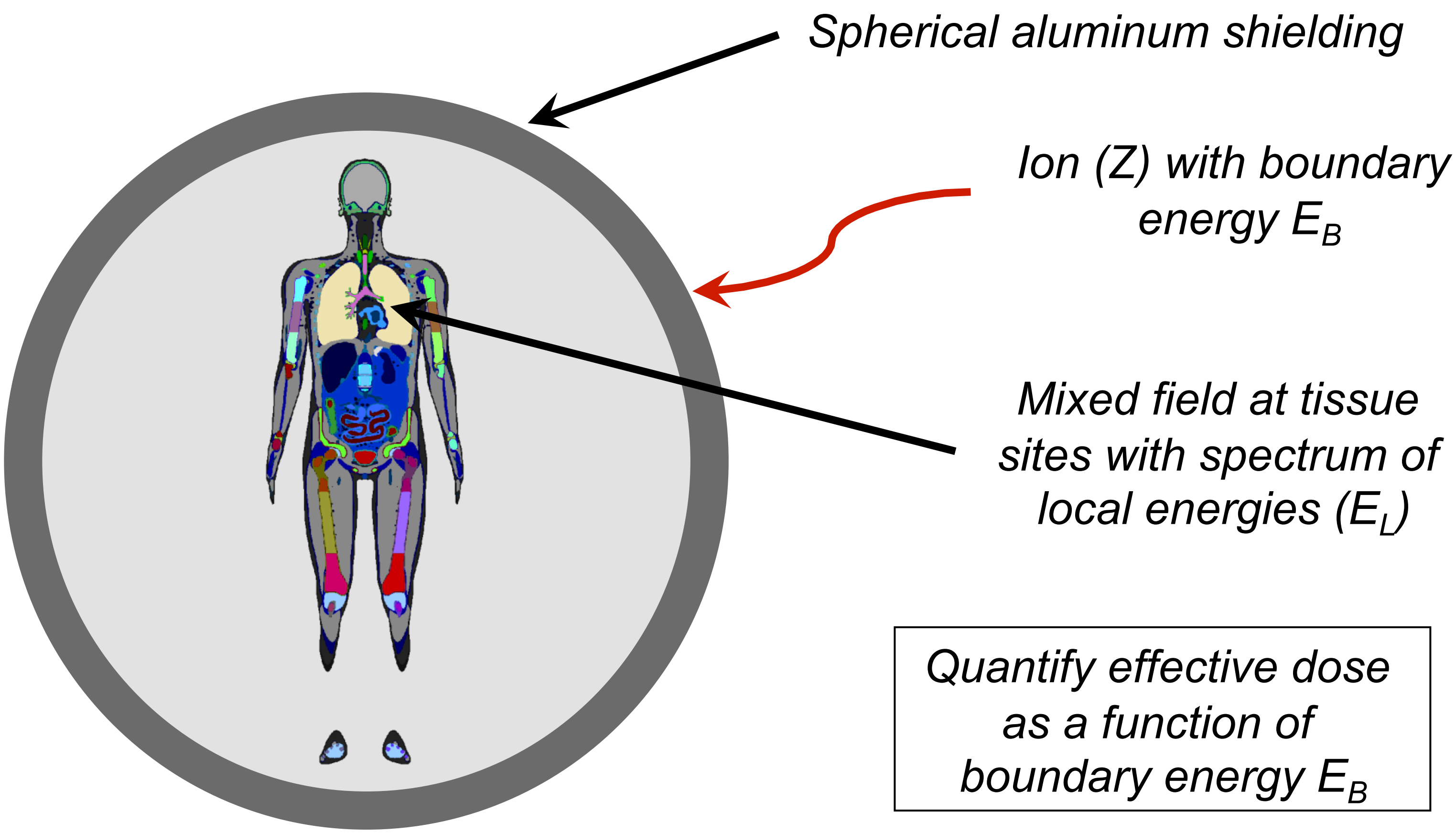


Exposure Quantities

- Two exposure quantities will be used here
- Dose equivalent (mSv)
  - Radiation quality factor is used to quantify increased biological effectiveness of high LET particles compared to gamma rays
- Effective dose (mSv)
  - Weighted sum of tissue averaged dose equivalent values
  - Tissue weights quantify relative radiosensitivity of individual tissues
  - Provides a measure of human mortality risk from radiation exposure
- Note: effective dose includes detailed human model and tissue self-shielding
  - Average human thickness is ~30 g/cm^2 of tissue

Sensitivity Studies

- Sensitivity analysis [1]
  - Quantify extent to which each SPE or GCR ion/energy contributes to exposure behind shielding
  - Identifies primary ions/energies that are most important from radiation shielding perspective



Quantify effective dose as a function of boundary energy E_B

Sensitivity Studies - GCR

- Energy/ion region measured by ACE/CRIS induces less than 5% of the exposure behind shielding
  - Region measured by ACE/CRIS (E < 500 MeV/n, Z = 5-28)

Relative contribution of each boundary ion/energy group to effective dose behind 20 g/cm^2 aluminum during solar minimum [1]. Note: a value of 0.0 indicates relative contribution < 0.1%

	Boundary energy interval (GeV/n)					
	< 0.25	[0.25, 0.5]	[0.5, 1.5]	[1.5, 4]	> 4	Total
Z = 1	1.2	5.4	18.2	18.4	14.8	58.1
Z = 2	1.2	2.2	4.1	2.9	1.7	12.2
Z = 3-10	0.0	3.3	3.8	1.3	0.8	9.1
Z = 11-20	0.0	0.2	6.6	2.0	1.1	10.0
Z = 21-28	0.0	0.0	4.7	3.8	2.1	10.6
Totals	2.5	11.1	37.4	28.4	20.5	100.0

Sensitivity Studies - GCR

- Z=1 with energies >500 MeV/n induce ~51% of the total exposure behind shielding
  - Energy region has been only sparsely measured with balloon and satellite instruments
  - The AMS-02 instrument should begin to fill this very important gap in the measurement database

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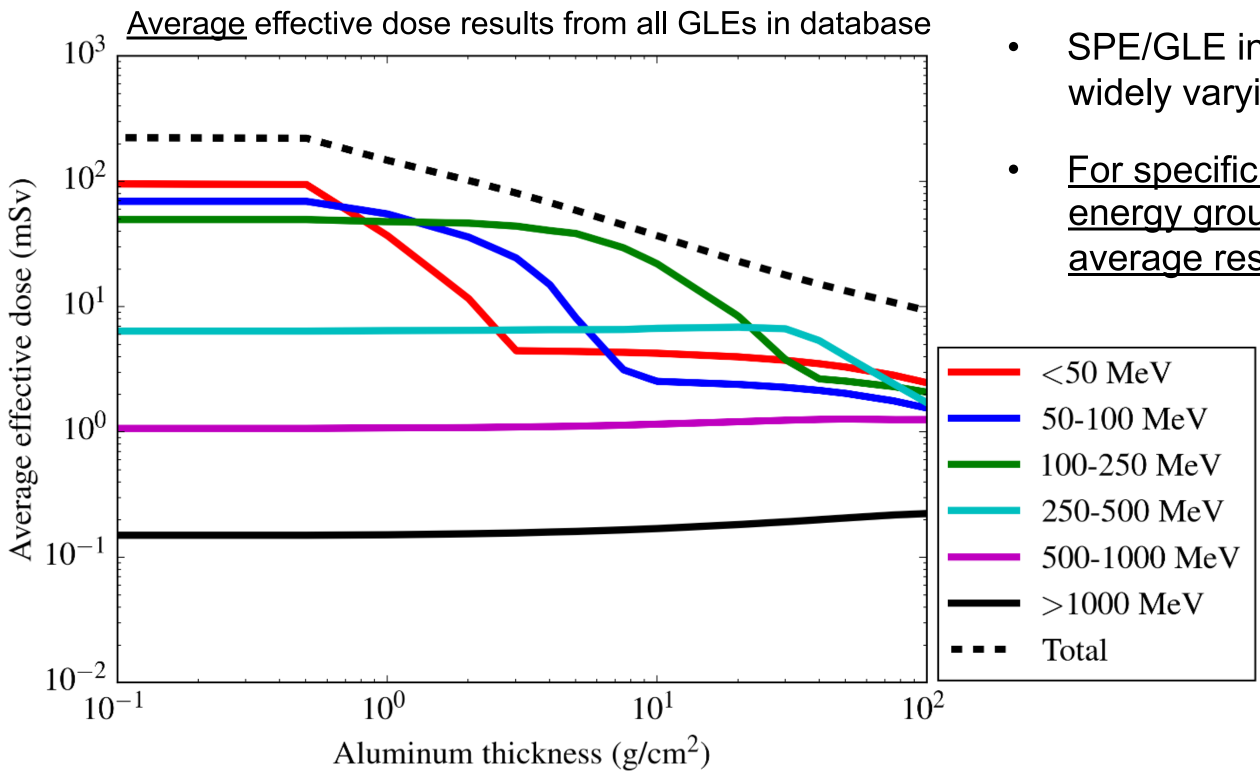
Sensitivity Studies - SPE

- Tylka et al. [2] analyzed historical GLEs from 1956-2006
  - Provided a database of Band function parameters for most of the events (58 in total)
- Tylka parameters used to quantify the contribution of various energy groups to effective dose behind shielding

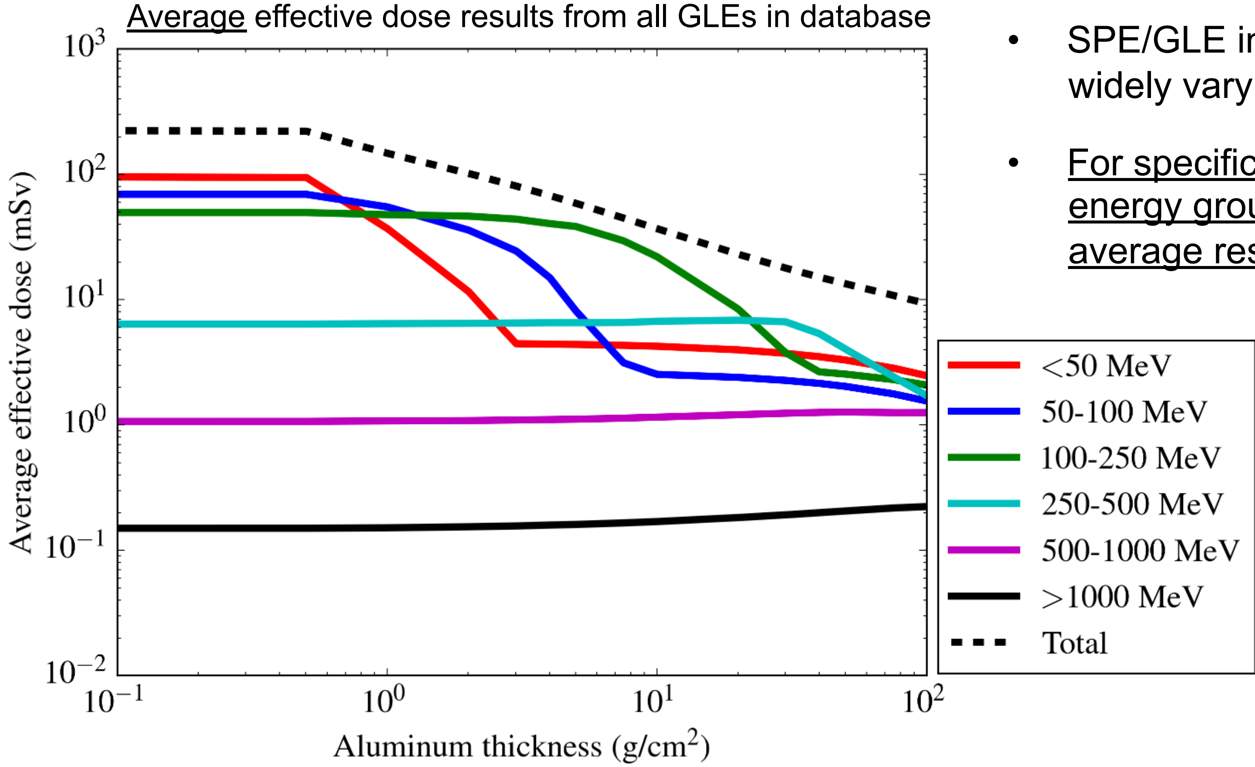


- SPE/GLE intensities and spectral shapes are widely varying
- <u>For specific events, relative contribution from energy groups may look very different than the average results</u>

Sensitivity Studies - SPE

- <u>On average</u>, it appears as though energy bins >500 MeV contribute very little to effective dose behind shielding
  - This turns out to be the case for most of the GLEs in the database
  - Feb 1956 (GLE5) and Sep 1989 (GLE42) are good examples of intense events with pronounced high energy tails that can make significant contributions to the total exposure

<u>Average</u> effective dose results from all GLEs in database



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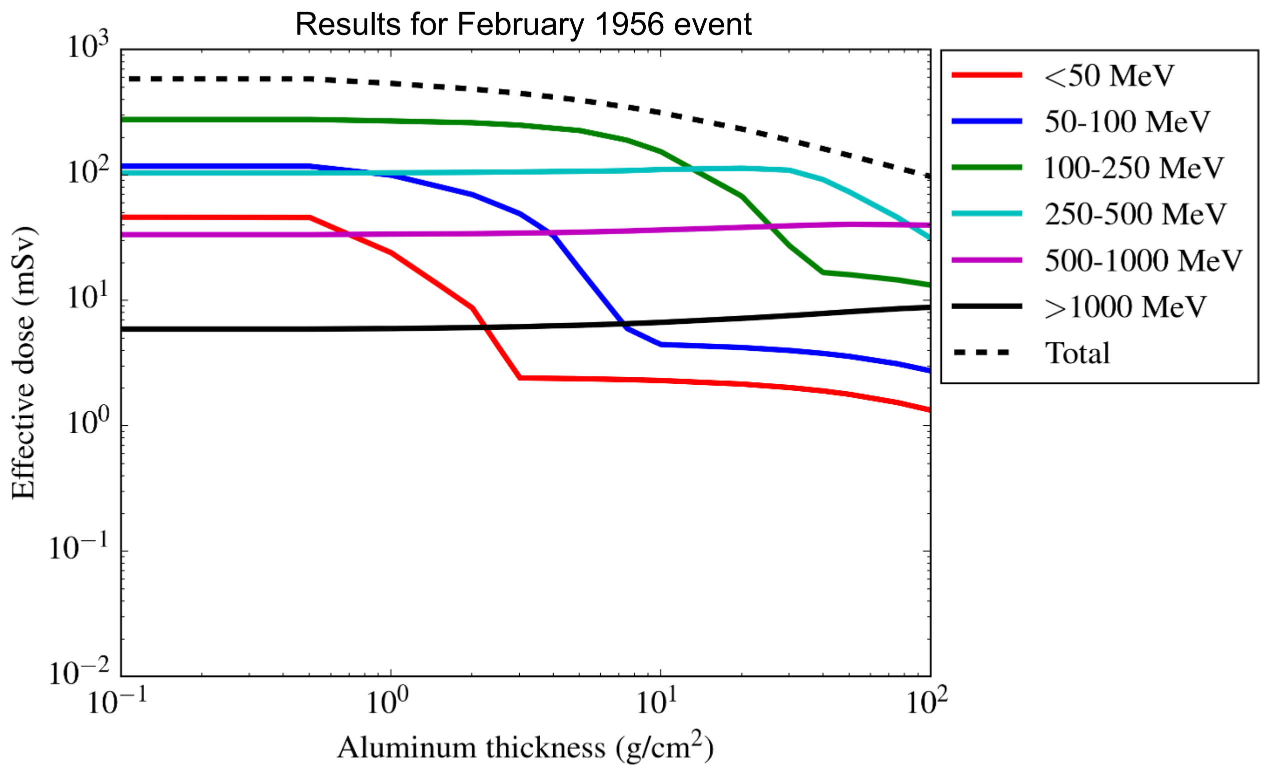
Sensitivity Studies - SPE

- For the Feb 1956 event (GLE5), the highest energies (> 500 MeV) make significant contributions to the total exposure beyond ~20 g/cm^2
  – Energy bin between 250-500 MeV still appears to dominate the exposure up to almost 100 g/cm^2
  – Energy bin >1000 MeV contributes less than 10% across all shielding thicknesses
  – Similar trends seen for Sep 1989 event (GLE42)
  – AMS-02 measurements could help constrain the high energy tails on future events



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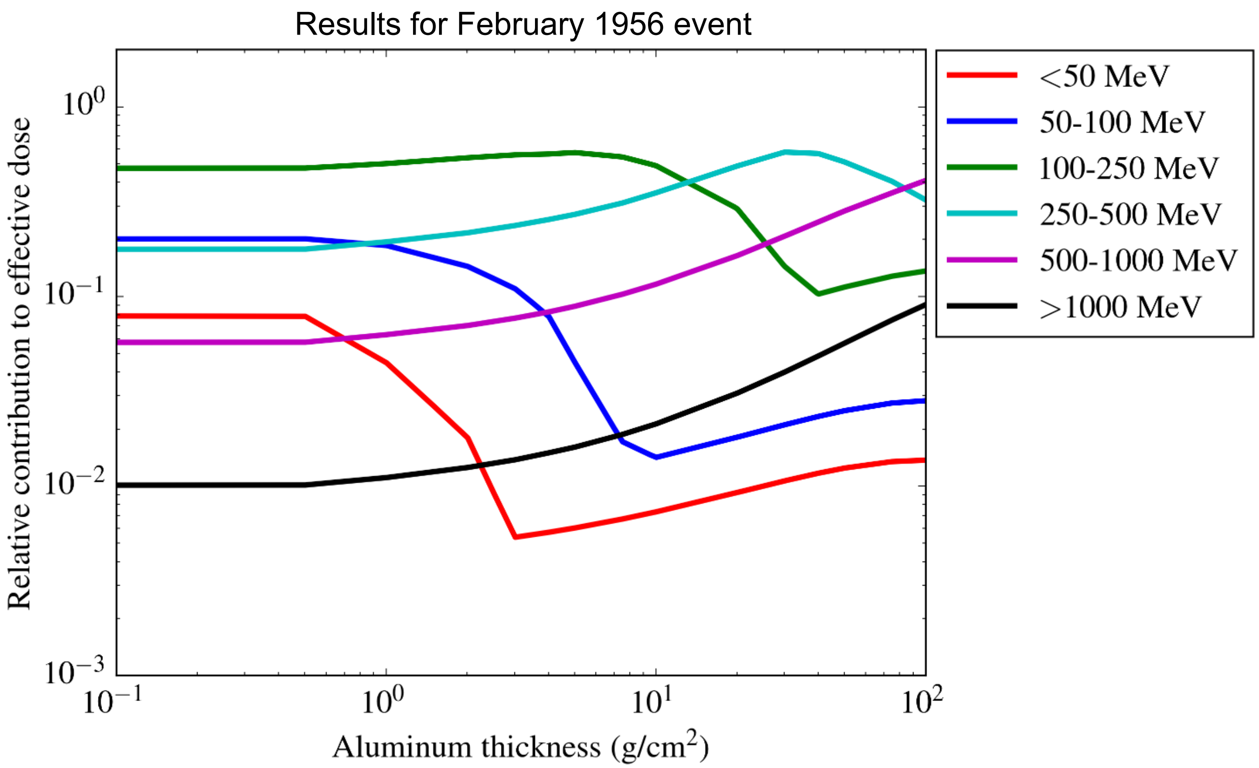
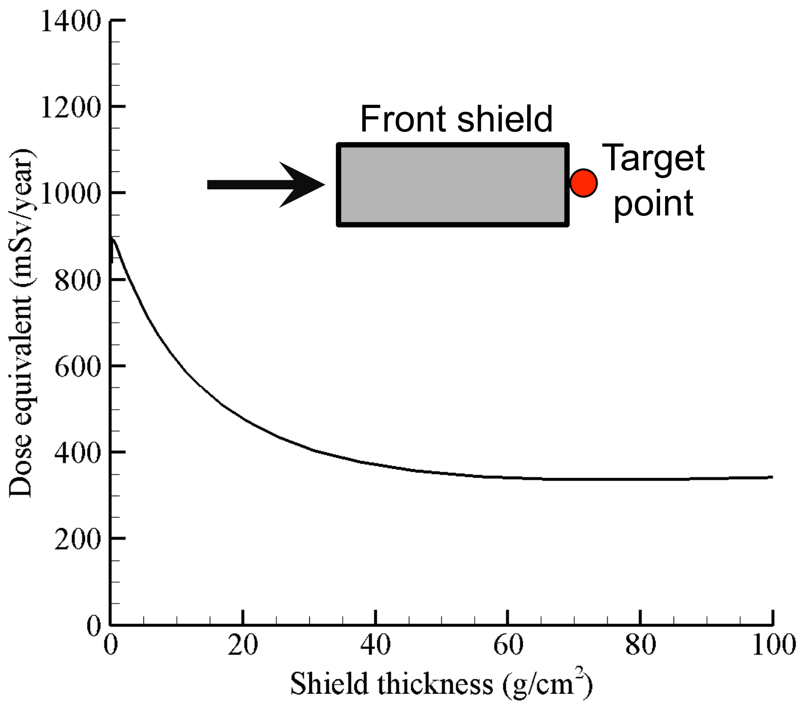


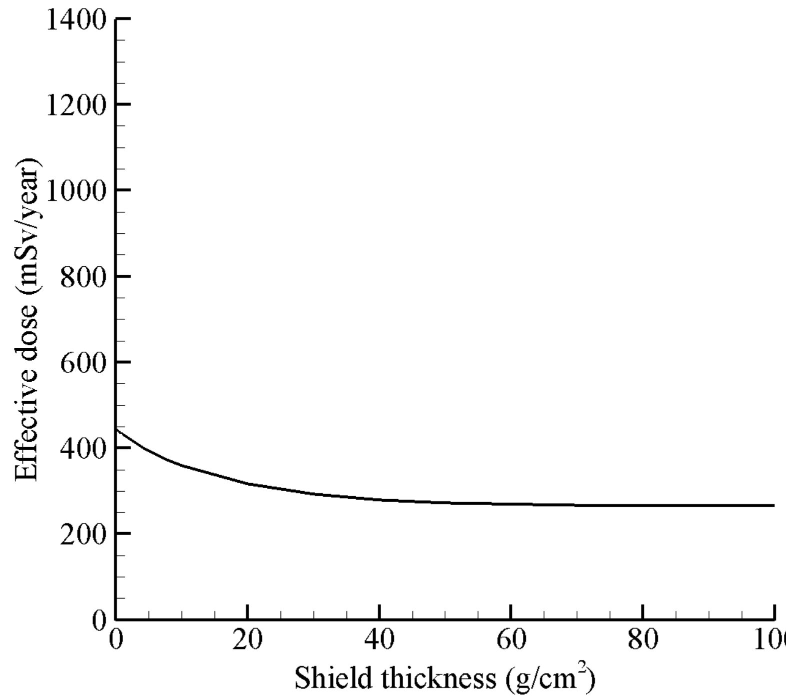
Shielding Design Strategies - GCR

- Previous design paradigm for GCR environment
  - Exposure and risk is not effectively mitigated with passive shielding [3]
  - Increased shielding (mass) only slightly decreases exposures beyond ~40 g/cm^2
  - Transport performed with HZETRN (straight ahead transport with no pion contributions)

Dose equivalent versus aluminum shield thickness



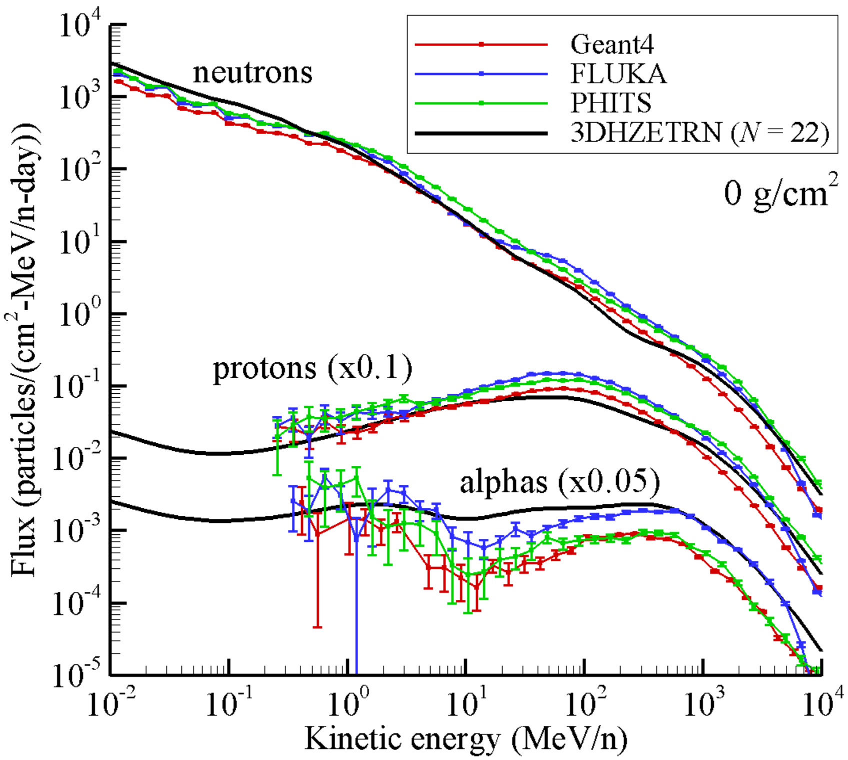
Effective dose versus aluminum shield thickness



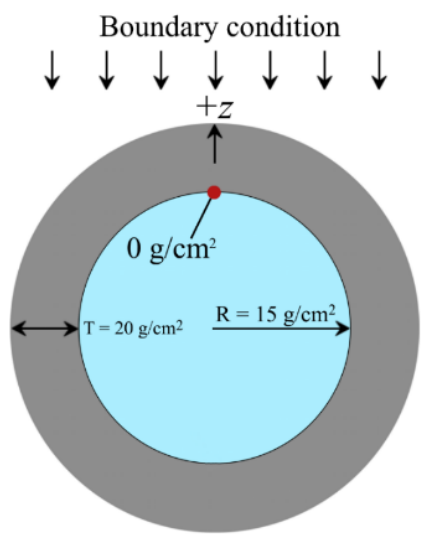
Note: Unless explicitly stated, all GCR results in subsequent slides are for 1977 solar minimum environment

Shielding Design Strategies - GCR

- Major updates to HZETRN transport code have recently been compared to Monte Carlo simulations
  - 3D corrections for neutrons and light ions [5,7,8]
  - Additional contributions from pions, muons and electromagnetic cascade [6]
  - Current effort underway to assess impact of transport code updates



56Fe solar minimum galactic cosmic ray spectrum

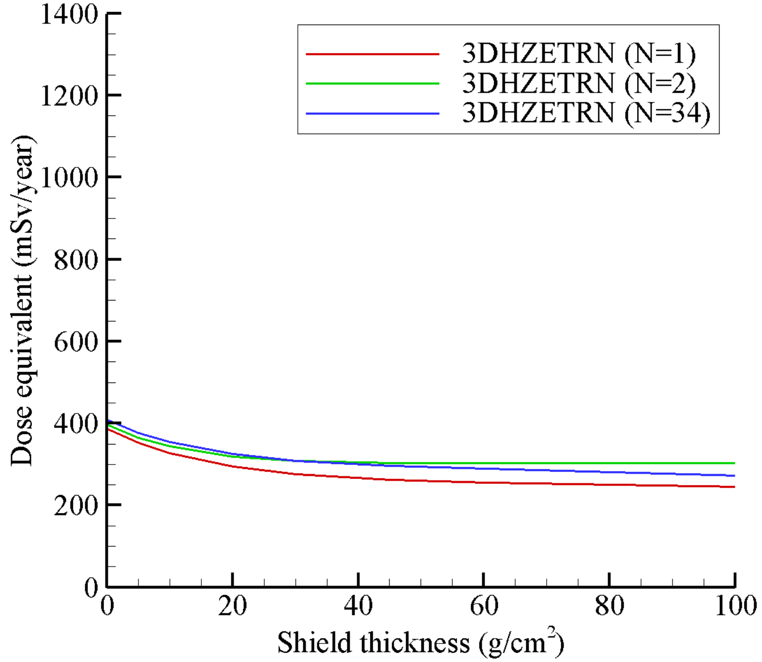


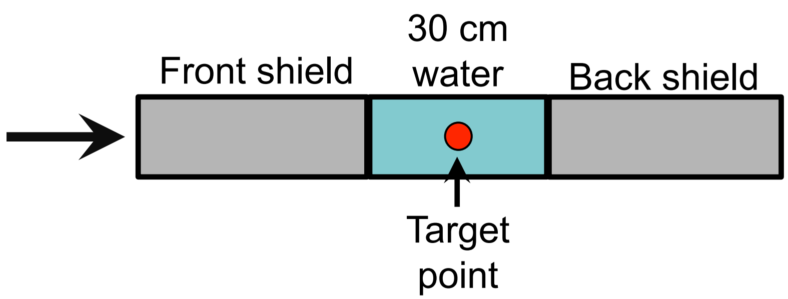
Tissue sphere with radius 15 g/cm² surrounded by 20 g/cm² of aluminum

Shielding Design Strategies - GCR

- Straight ahead (N=1) and bi-directional (N=2) compare reasonably well to full 3D solution (N=34) in this geometry
  - Effective dose (not dose equivalent) is used in vehicle and shield design but is more computationally intensive
  - Simplified geometry used here to provide quick comparison between transport code approximations
  - 30 cm water used to represent tissue self shielding
  - Crude geometry approximation gives results very close to effective dose values

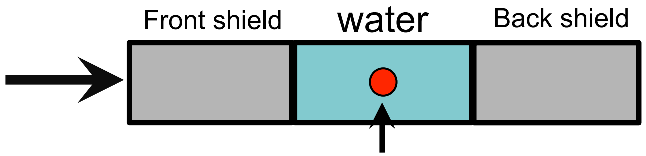
Dose equivalent versus aluminum shield thickness with 30 cm water absorber

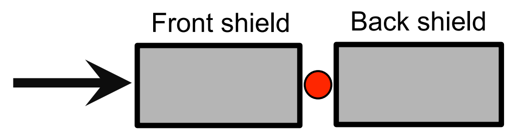




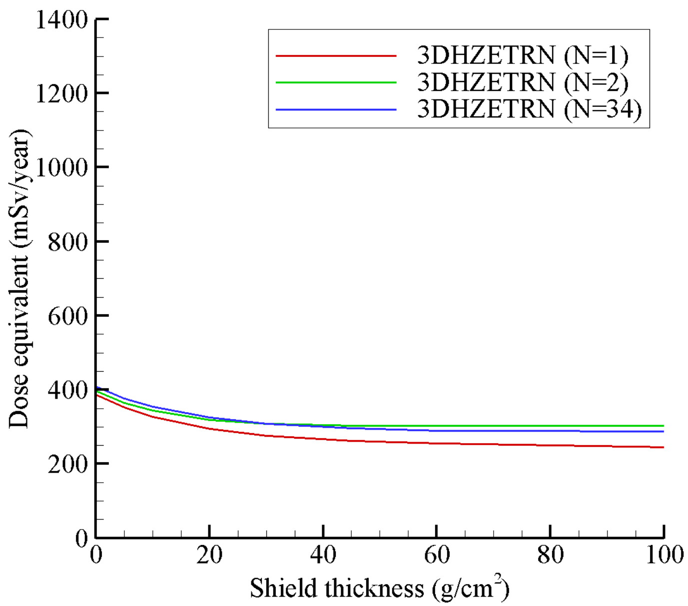
Shielding Design Strategies - GCR

- The absence of water shielding greatly alters exposure versus depth results
  - Increased shielding (mass) can amplify exposure
  - Material and design optimization may be more important than previously thought for GCR environments

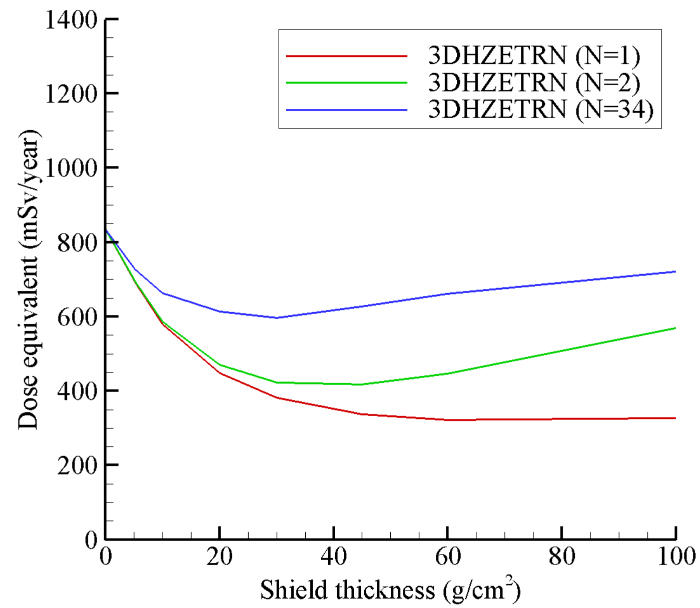




With 30 cm water absorber



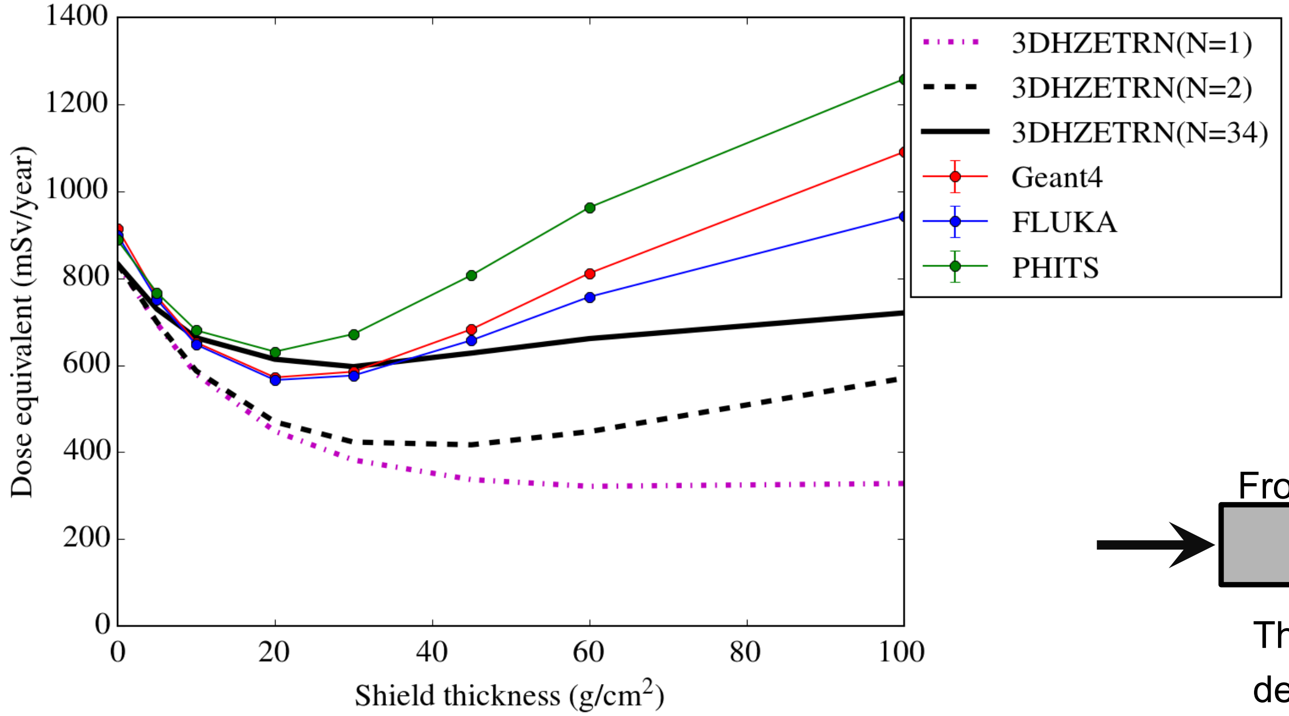
No water absorber

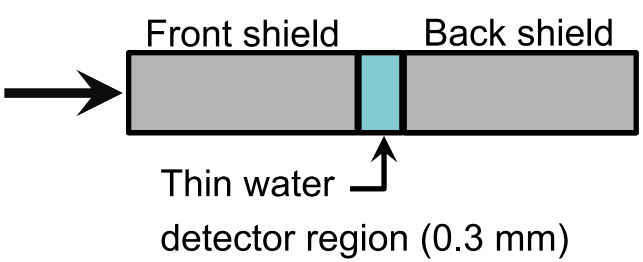


Shielding Design Strategies - GCR

- Benchmarks with Monte Carlo codes are verifying a minimum in the dose equivalent versus depth curves
  - Utilizing idealized geometry in Monte Carlo simulations to enable computational efficiency
  - Geometry setup makes the local minimum appear to be more dramatic than what would be expected in a realistic vehicle (infinite lateral dimensions)
  - Local minimum is not as pronounced if effective dose is considered due to additional tissue shielding which effectively attenuates neutron contributions [9]

Dose equivalent versus aluminum shield thickness

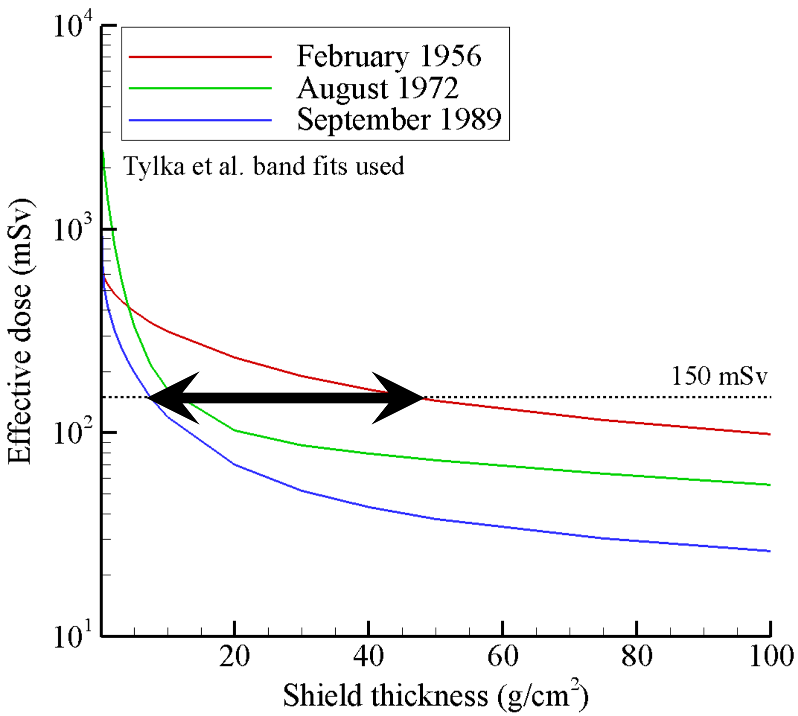




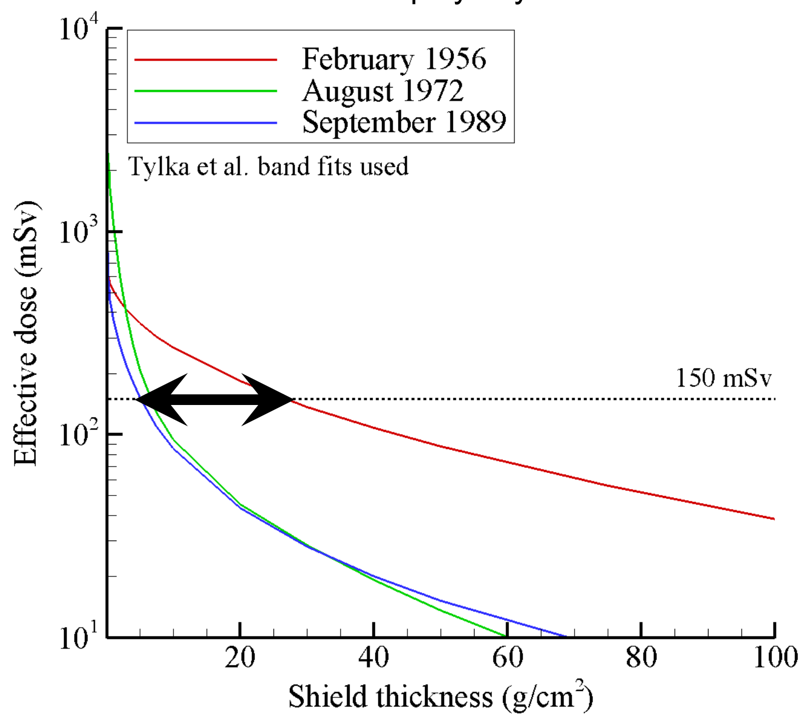
Shielding Design Strategies - SPE

- For SPE environments, shield requirements are highly sensitive to the vehicle design, mission duration, destination, and other factors
  - There are no simple rules that define an optimal or sufficient shield design
  - Even if limits are met, ALARA* principle requires design efforts to further reduce exposure
  - The SPE used as design environment can have a significant impact on determining shield requirements
  - For a given SPE, location in the vehicle and onboard equipment and supplies can also have a significant impact on SPE shield design

Effective dose versus aluminum shield thickness



Effective dose versus polyethylene shield thickness

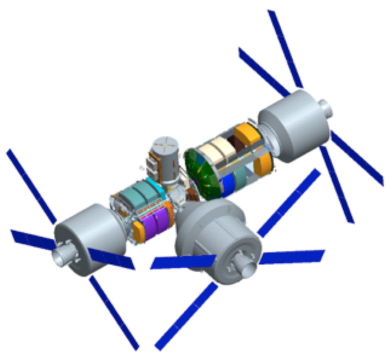


* ALARA: As Low As Reasonably Achievable

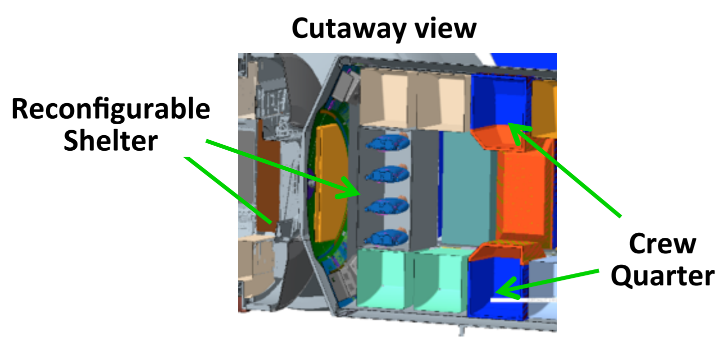
Shielding Design Strategies - SPE

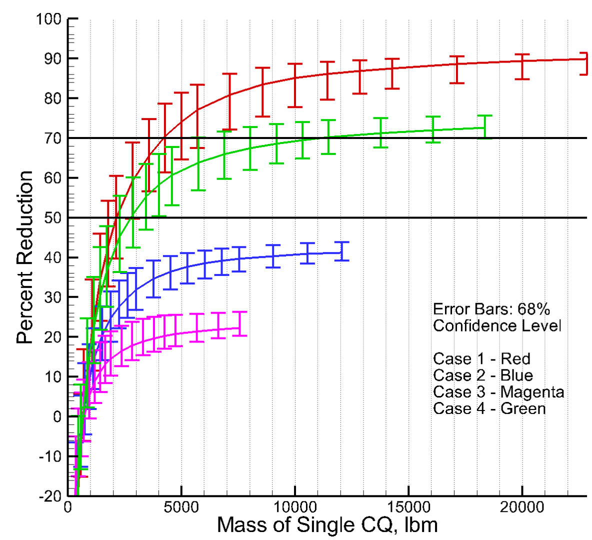
- Probabilistic approaches are being pursued for SPE shield design
  - Past efforts to design SPE protection concepts utilized either static, representative environments (e.g. King 1972 event) or a single energy spectrum representing a percentile flux based on a database of historical events (e.g. Xapsos model)
  - Difficult to decide which historical event or percentile flux to design against for a future mission

- New approaches are being developed that leverage computational efficiency of HZETRN transport code
  - Astronaut exposure is evaluated for each SPE in a historical database and exposure results are analyzed probabilistically [10]
  - This approach makes it possible to optimize shield design no matter the spectral shape or magnitude of the SPE



Cislunar vehicle





Summary

- For human missions beyond low Earth orbit, exposure from SPE and GCR are a primary concern
- Sensitivity studies have been performed to quantify which energies in the primary SPE and GCR environments are most import to exposure quantities behind shielding
  - These studies have helped identify areas where new measurements are needed to reduce environmental modeling uncertainties (AMS-02 should be helpful in both cases)
- General shielding strategies for SPE and GCR environments
  - **For SPE:** passive shielding and design optimization are effective in mitigating the exposure and risk in most cases
  - In cases where limits are satisfied, the ALARA principle still requires designers to seek optimal shielding strategies and reduced exposures
  - **For GCR:** transport code updates and benchmarks have revealed a minimum in the dose equivalent versus depth curve for aluminum shielding near ~20 g/cm^2
  - Material optimization may be more important than previously thought, and simply adding more mass to the vehicle design can actually make the problem worse

References

[1] Slaba, T.C. and Blattnig, S.R., GCR Environmental Models I: Sensitivity Analysis for GCR Environments. Space Weather, Volume 12, pp. 217-224 (2014).

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