Use of Superconducting Magnet Technology for Astronaut Radiation Protection

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Presentation

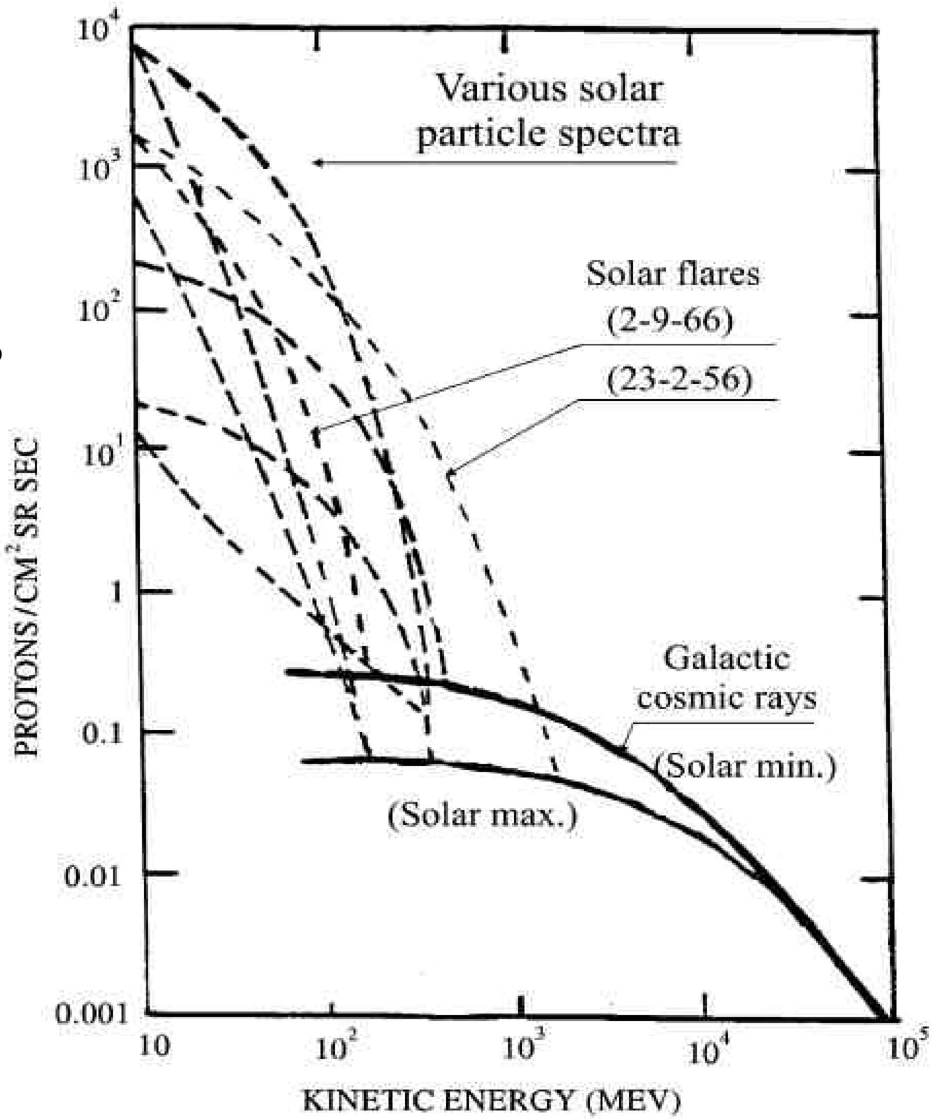
- The Radiation Problem
- Methods of Shielding
- Details of Electromagnetic Shielding
- Future Work

Nature of Space Radiation

(outside the Earth's radiation belts)

- Solar Radiation
  - Flares
  - Coronal Mass Ejections

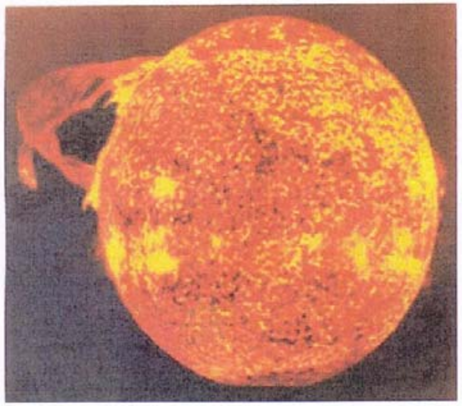
- Galactic Cosmic Radiation



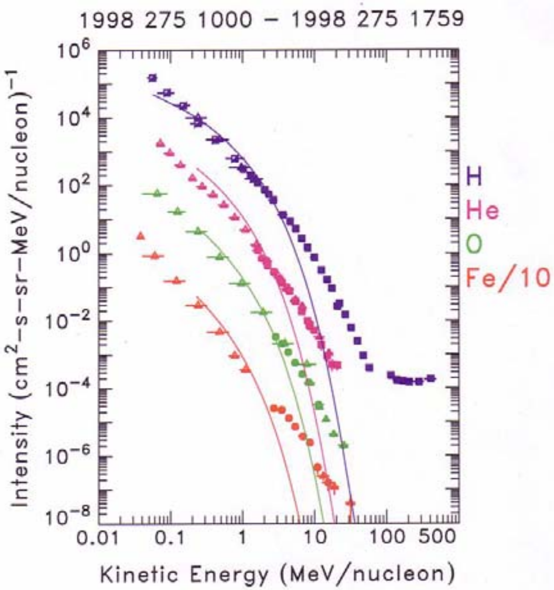
Solar and cosmic proton energy spectra
[Spillantini, et al., 2000]

Particle Sources

(2) Solar flares



The Sun, photographed by astronauts on NASA's Skylab 4 mission (Nov.16, 1973 – Feb. 8, 1974). This image shows a spectacular solar flare, with a base more than 591,000 km (367,000 miles) across.



Spectra of H, He, O, and Fe in the 1998 Sep 30 Event, 48 hours after onset.. Data are compiled from the missions: Wind (filled circles), ACE/SIS (filled triangles), IMP8 (filled squares), ACE/EPAM (half-filled squares), ACE/ULEIS(half-filled triangles). The curves are computed from the model.

Ref. for this Figure: C. K. Ng, D. V. Reames, and A. J. Tylka "Evolution of Abundances and spectra in the large solar energetic particle events of 1998 Sep 30 and 2000 Apr 4" Proceedings of ICRC 2001: 3140.

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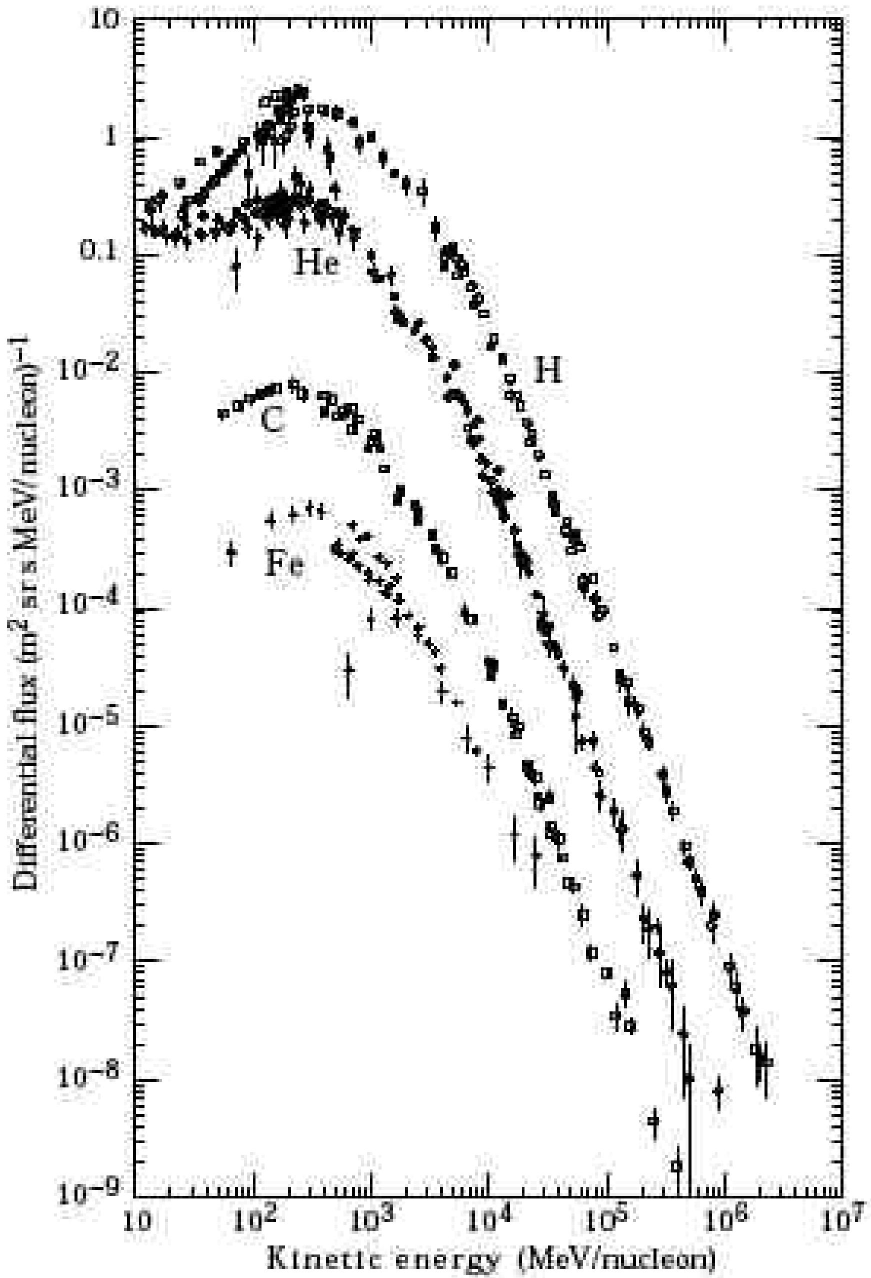
Galactic Cosmic Ray Spectrum

Simpson (1983)



Radiation

- Terminology:
  - RAD (Radiation Absorbed Dose; cgs) = 100 ergs/gm
  - GRAY or Gy (SI unit) = 1 joule/kg = 100 rads
  - REM (cgs) or SIEVERT or Sv (SI) Dose Equivalent Units

    Rad or Gray dosage multiplied by a quality factor (QF)
- Quality Factors:
  - X-rays, Gamma Rays, 0.1-1.0 MeV electrons : QF = 1
  - Thermal Neutrons (<.005 MeV) : QF ~ 2.5
  - 1 MeV Neutrons, 0.1-1.0 MeV Protons : QF ~ 10
  - Alpha Particles and Heavy Nuclei : QF up to 20

Effects of acute doses received by homogeneous irradiation of the whole body (1):

0 to 250 mGy (1-25 rad): no biological or medical effect, immediate or long-term, has been observed in children or adults. This is the domain of low doses.

250 to 1000 mGy (25-100 rad): some nausea may appear along with a slight decrease in the number of white blood cells.

Note that **for doses higher than 250 mGy (25 rad)**, long-term effects (risk of cancer increasing with the dose) have also been observed.

1000 to 2500 mGy (100-250 rad): vomiting, change in the blood count, but satisfactory recovery or complete cure assured.

- The most sensitive cells are rapidly dividing cells such as stomach lining and intestinal cells (and hair cells).
- >200 rad affects blood cell count and ability to fight infection.
- The next to go are sperm cells and bone marrow.

Effects of acute doses received by homogeneous irradiation of the whole body (2):

Lethal Doses

- **2 Gy (200 rad)** can be a fatal dose in some circumstances
- **2.5to 5 Gy (250-500 rad)**: consequences on health become serious; hospitalization is mandatory.
- **4 Gy (450 rad)** 50% will die in ~6 weeks with no treatment.
- >**5Gy (>500 rad)**: death is almost certain.
- **8 Gy (800 rad)** 100% will die at with no treatment.
- Up to **20 Gy (2000 rad)** have been survived with exceptional treatment and luck

Long-Term Effects of Radiation

- 4×10^{-4} fatal cancers/REM with long latency
- i.e. 1000 REM total body dose gives a ~40% chance of cancer over the "long term"
- Hardiest tissues are nerve cells and egg cells
- Long-term effects of radiation received in <1 week ~ 2X more dangerous than equivalent amount received over the long term

Allowable Radiation Doses

- Legal Limits based on annual exposure (radiation workers)
  - 5 REM/year in USA with guideline of <10 REM/5 years
  - 2 REM/year in Europe
- Epidemiological studies cannot track risk at <5 REM (acute) or <10 REM (lifetime)
- Actual Doses:
  - Sea Level Background Exposure 0.005 rad/year (.05 in brick houses)
  - Round Trip Cross-Country Airplane Trip 0.004 rad
  - Living in Denver ("Mile-High City") 0.20 rad/year
  - Chest X-ray 0.05 rad
  - Dental X-ray 1.0 rad (mainly limited to mouth)
  - Typical Shuttle Flight 0.05 rad (HST flights up to ~2 rad)
  - Apollo Moon Landings 0.2-1.1 rad
  - Skylab 2,3,4 (1,2,3 months) 2.4, 6.0, 7.4 rad
  - ISS ~1mSv (0.1 rem)/day
  - Estimated Mars trip (no large solar flares) ~100-150 rem

Radiation Exposure Limits (radiation workers and astronauts):

Constraints in REM	Bone 5 cm	Skin 0.1 mm	Eye 3 mm	Testes 3 cm
1 yr average daily rate	0.2	0.5	0.3	0.1
30 day max	25	75	37	13
Quarterly max	35	105	52	18
Yearly max	75	225	112	38
Career Limit	400	1200	600	200

(Double the statistical chance of leukemia in 20 years from 1 in 50,000 to 2 in 50,000)

Lots of uncertainty still exists, requiring experimental data!

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

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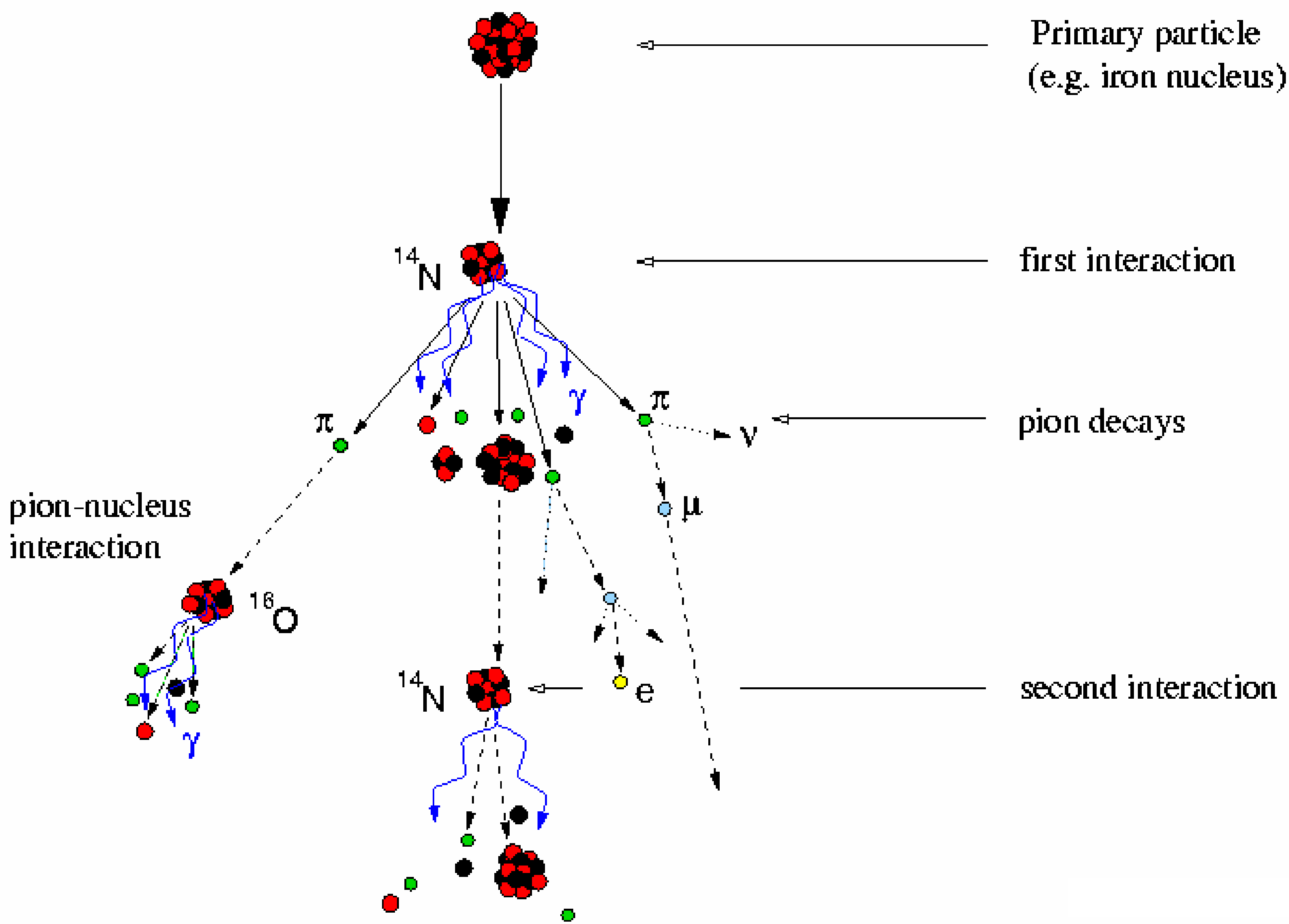
TIFF (Uncompressed) decompressor
are needed to see this picture.

Passive Shielding against Radiation:

- **Electrons, photons, low-energy protons (SPEs)**:
  - No nuclear reactions
  - Stopped mainly by interactions with electrons
  - Maximize number of electrons per unit mass (Pb)

- **High-energy protons, neutrons, and cosmic rays**:
  - Interact with nuclei to create showers
  - Maximize ratio of electrons per nucleon
  - Hydrogen ratio = 1
  - Light elements ratio ~0.5
  - Heavy elements ratio <0.5

Development of cosmic-ray air showers



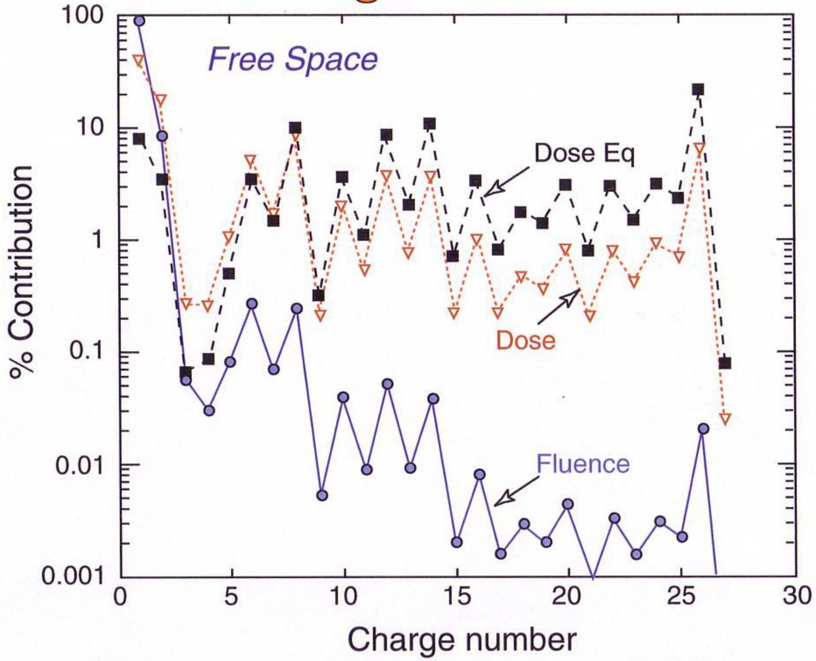
Radiation Effects and Protection for Moon and Mars Missions

Thomas A. Parnell , John W. Watts, Jr. and Tony W. Armstrong

Particle Sources

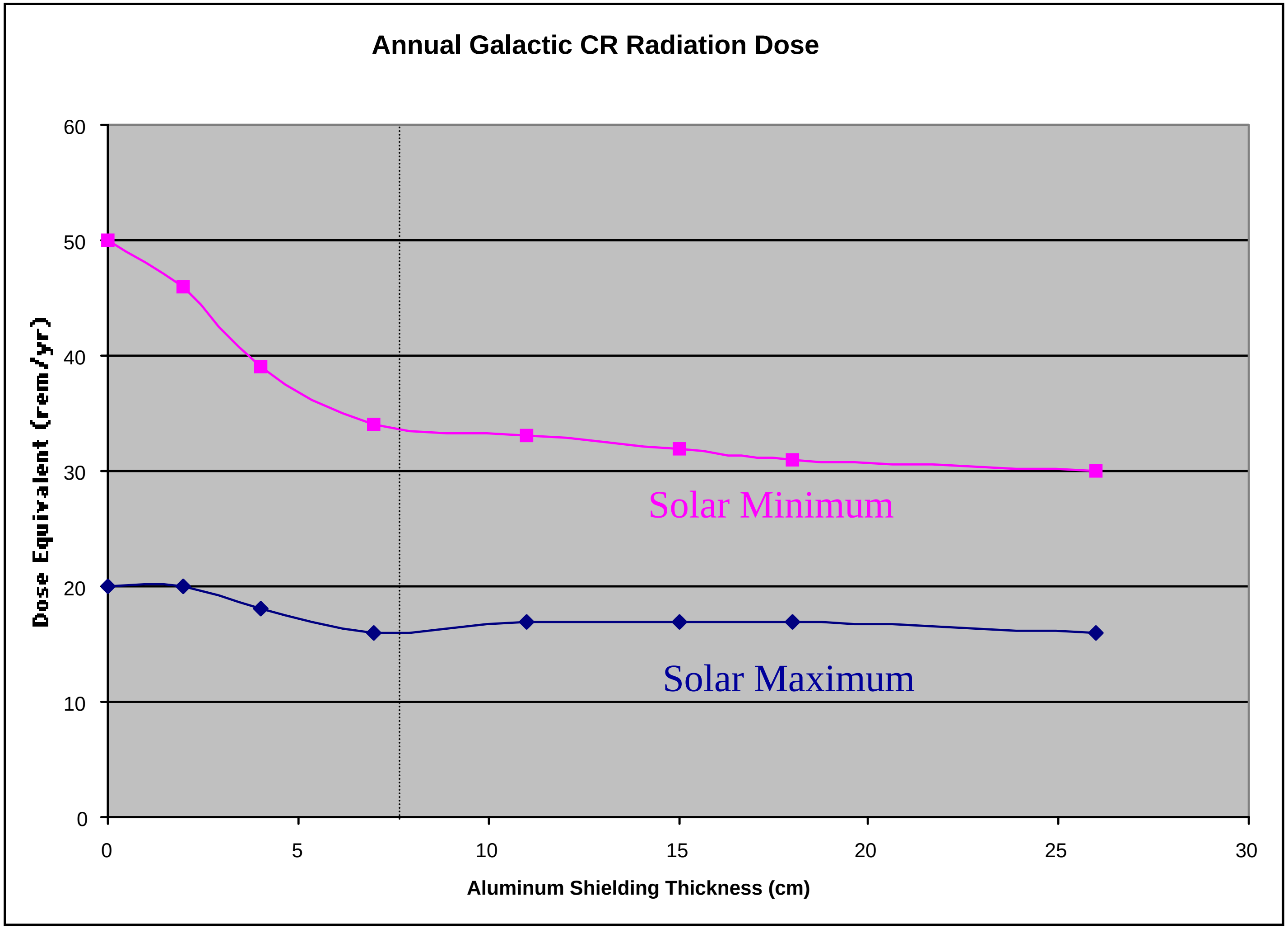
(1) Galactic Cosmic Rays (GCR) consist of atomic nuclei with about 85% protons, 14% alpha particles, and 1% heavier nuclei (Wiebel 1994). The effects of heavy nuclei far outweigh their number because their energy deposition is proportional to atomic charge squared.

GCR Charge Contributions



NASA - JSC, Francis A. Cucinotta

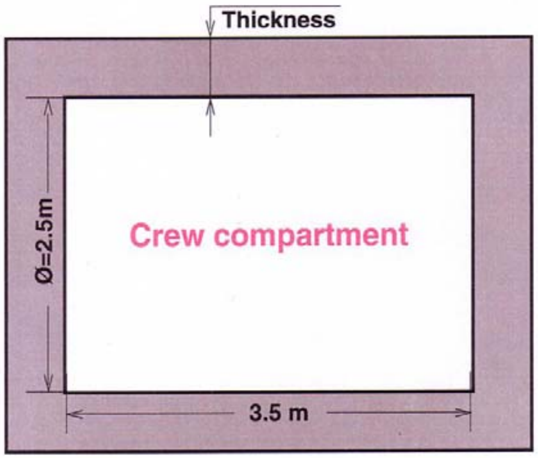
y04K171a Cucinotta



Solar Flare of August 1972 would have exposed unshielded astronauts to 960 rem.

With 9 cm of Aluminum shielding, the dose equivalent would have been 40 rem.

Solar Min GCR 1 Year Dose Rad/Rem



Weight t	Shielding Al (cm)	p	He	Z>2	Total Rad/Rem
2.3	2.2	13.5/24.1	4.8/15.6	2.7/63.7	21/103.4
10.4	9.6	16.6/30.3	5.4/14.9	1.9/17.8	23.9/63
24.6	21.1	19.3/36.2	5.8/14.2	1.6/6.4	26.7/56.8
54.8	41.1	20.2/39.7	5.6/13	1.5/3.8	27.3/54.4
138.2	81.1	17.2/36.4	4.8/10.9	1.3/3.1	23.3/50.4
257.9	121.1	13.9/27.8	3.9/8.1	1.0/2.3	18.8/38
353.2	145.9	10.5/20.5	2.9/6.0	0.6/1.5	14/28

Note:
Dose changes from 38 Rem to 28 Rem (30%)
The weight changes from 257.9 tons to 353.2 tons (37%)

Weight t	Shielding LH_2 (cm)	p	He	Z>2	Total Rad/Rem
58.0	371.4	15.2/27.1	4.2/9.2	1.2/3.7	20.6/40.0
382.7	814.3	14.5/25.2	3.7/6.8	1.1/2.1	19.3/34.1

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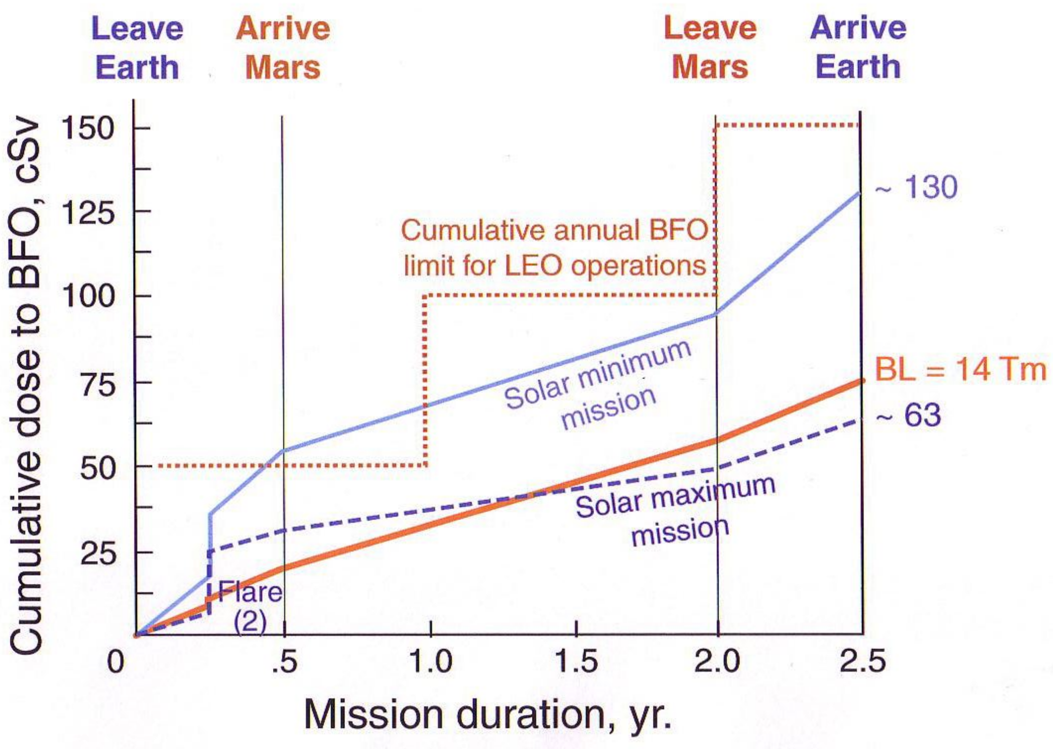
Mars Reference Design Mission

- Used by NASA for design studies of costs and necessary technologies and science
- Model predictions using HZETRN and Nominal Shields of 30 ton



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Real limits on radiation are statistical, based on small percentage increase in long-term cancer risk, with much uncertainty.

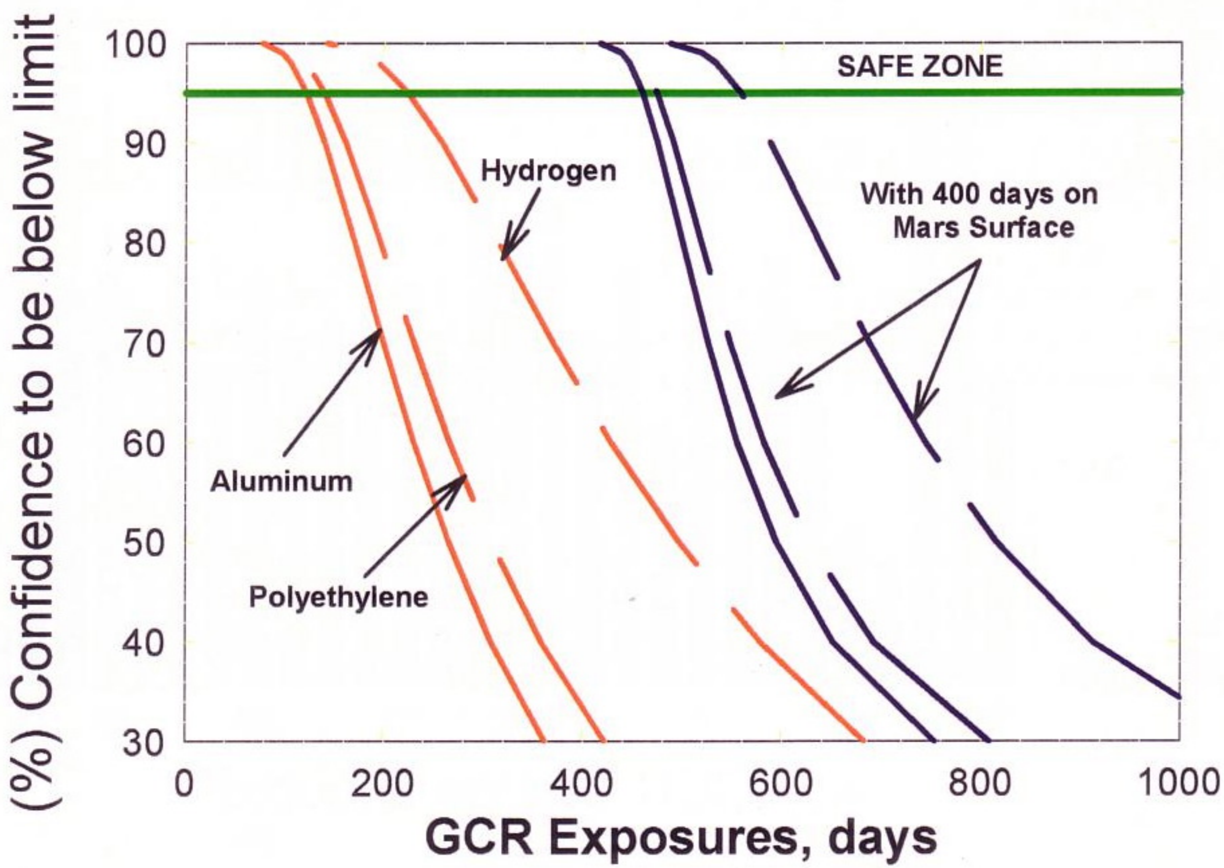
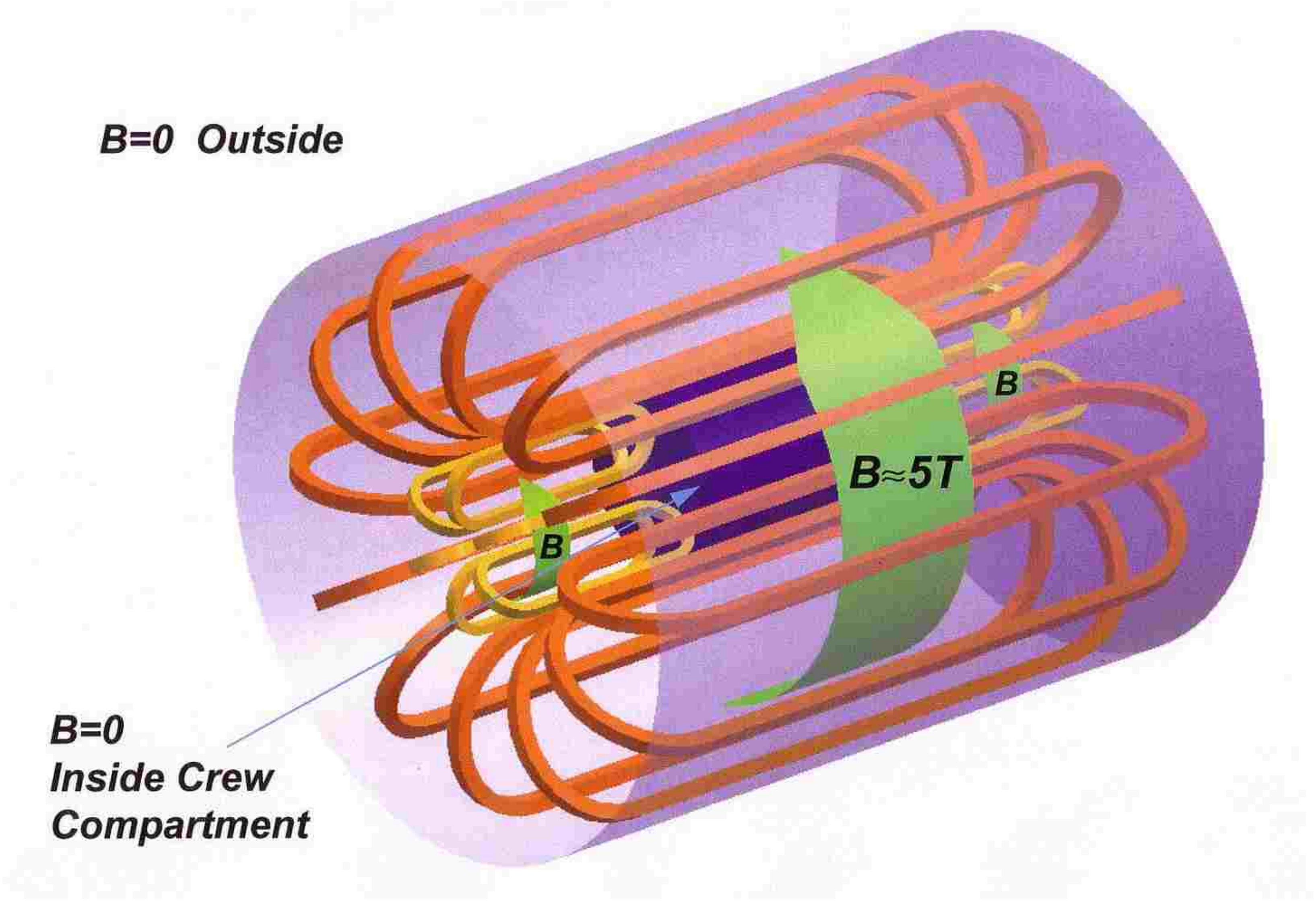


Figure 15: Confidence levels to stay below a 3% excess fatal cancer risk versus the number of days in free space or with 400 days on Mars surface for 45-year-old males.

Magnetic Shield (conceptual)



Magnetic Shielding - basic concepts

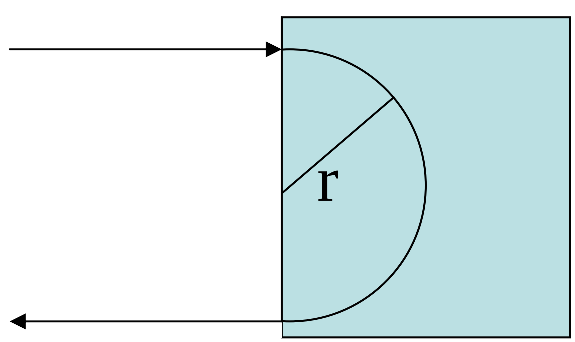
- Lorentz force on charged particle:

$$\vec{F} = q\left(\vec{v} \times \vec{B}\right)/c = qvB\sin\theta/c$$

- Force is perpendicular to motion, does no work
- For relativistic particle moving perpendicular to field, motion is circular, with radius:

$$\rho = m\gamma v/\kappa B$$, where $$\kappa = 0.3\,\mathrm{GeV/T{-}m}$$

- e.g. T = 9 Tesla, 2 GeV ⇨ radius = 1.1m



(desired thickness of magnetic shielding region = 2r)

Magnetic Shielding - Details

- Baseline - Toroidal Magnetic Field

  9 Tesla; 1.5m thick (both are variable)
- Habitable Volume 7m diameter x 7m height (116 m^3 volume)
- Overall size 10m diameter x 10m height

Simulation Method - basic

- Monte Carlo Integration
- 100,000 test particles at each of 28 energy bins
- Particles impact outside of shield isotropically
- Trajectories calculated in 0.5 cm steps
- Keep track of particles entering habitable volume
- Calculated with and without B-field, to show reduction factor R:

  R = (number entering no field)/(number entering with field)
- Calculations repeated for different field strengths and thicknesses

Simulation Method -
more "realistic" field geometry

- Include radial dependence of magnetic field,

$$\vec{B} = B_o \left(r_o / r \right) \hat{\varphi}$$

such that $\left\langle BL^2 \right\rangle = \int_{r_{in}}^{r_{out}} B\left(r\right) r dr = 20.25\ T - m^2$

(For a uniform field B of thickness L, bending is BL^2.)

- Assume 50 cm radius zero field at each end of cylinder to account for inner coil discontinuities.

Simulation Results

- Use simulations with and without B-field at different energies to produce R(E).
- Use input spectrum $\Phi_i = F_i E^{-2.7}$ for species i.

  (F_i given in stand-alone table.)

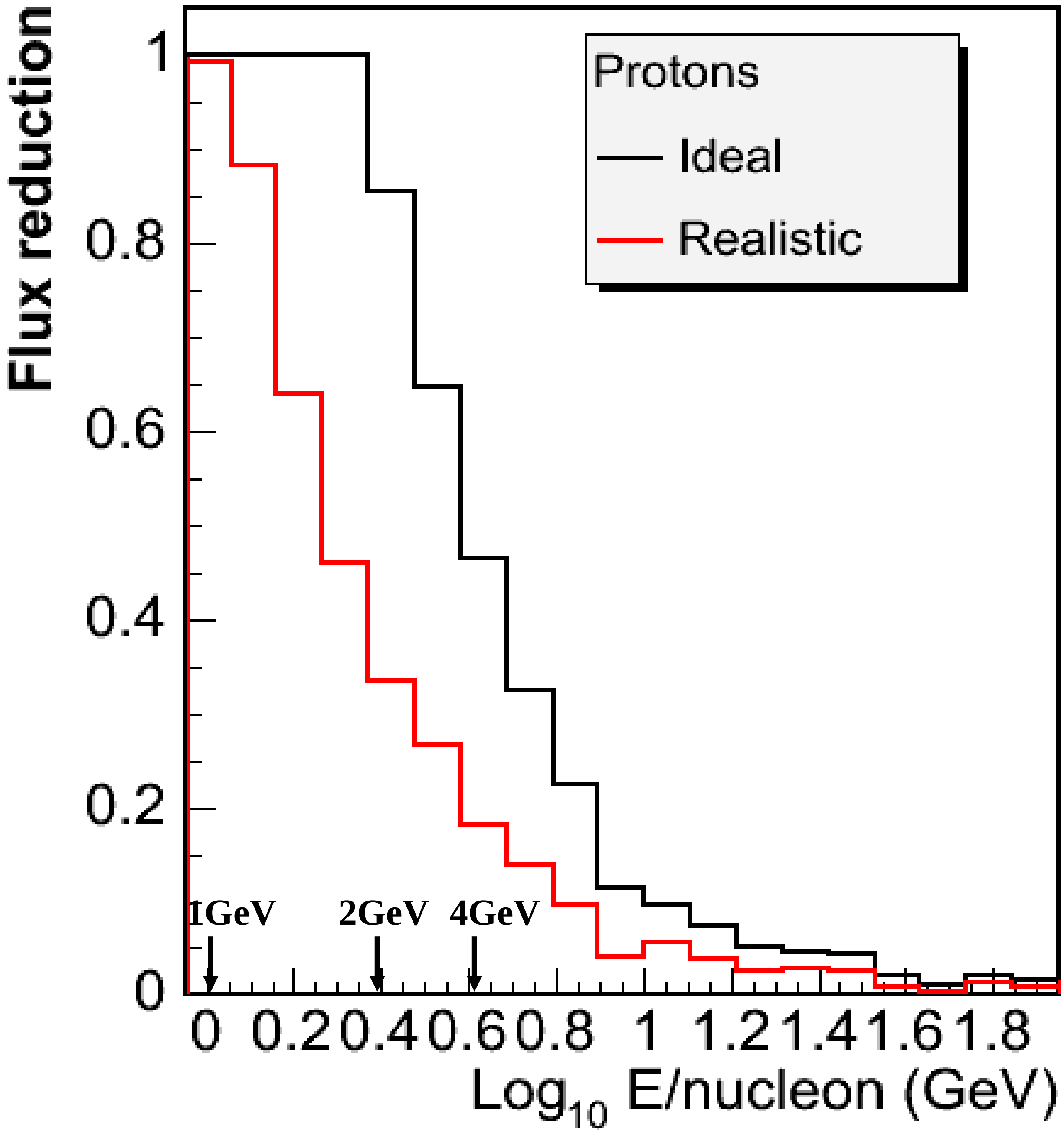
- Flux inside habitat is given by:

$$\Phi_{i,inside}(E) = \Phi_i(E)/R(E)$$

- All protons below 2 GeV are rejected.
- 50% of protons at 3 GeV are rejected.
- Curves for heavier elements similar but slightly less rejection because of lower Z/A.

Z	M	F	%dose	Z	M	F	%dose
1	1	485	71	15	31	0.005	0.012
2	4	26	6.4	16	32	0.03	0.074
3	7	0.121	0.033	17	35.45	0.005	0.0012
4	9	0.087	0.023	18	40	0.009	0.024
5	10.8	0.192	0.049	19	39	0.006	0.015
6	12	0.986	0.24	20	40	0.018	0.045
7	14	0.218	0.054	21	45	0.003	0.00077
8	16	1	0.25	22	47.867	0.01	0.0026
9	19	0.015	0.0038	23	51	0.005	0.0013
10	20	0.152	0.0065	24	52	0.011	0.029
11	23	0.026	0.049	25	55	0.009	0.024
12	24.3	0.197	0.0077	26	55.485	0.110	0.028
13	27	0.031	0.040	27	59	0.001	0.0026
14	28	0.163	0.012	28	58.69	0.007	0.0017

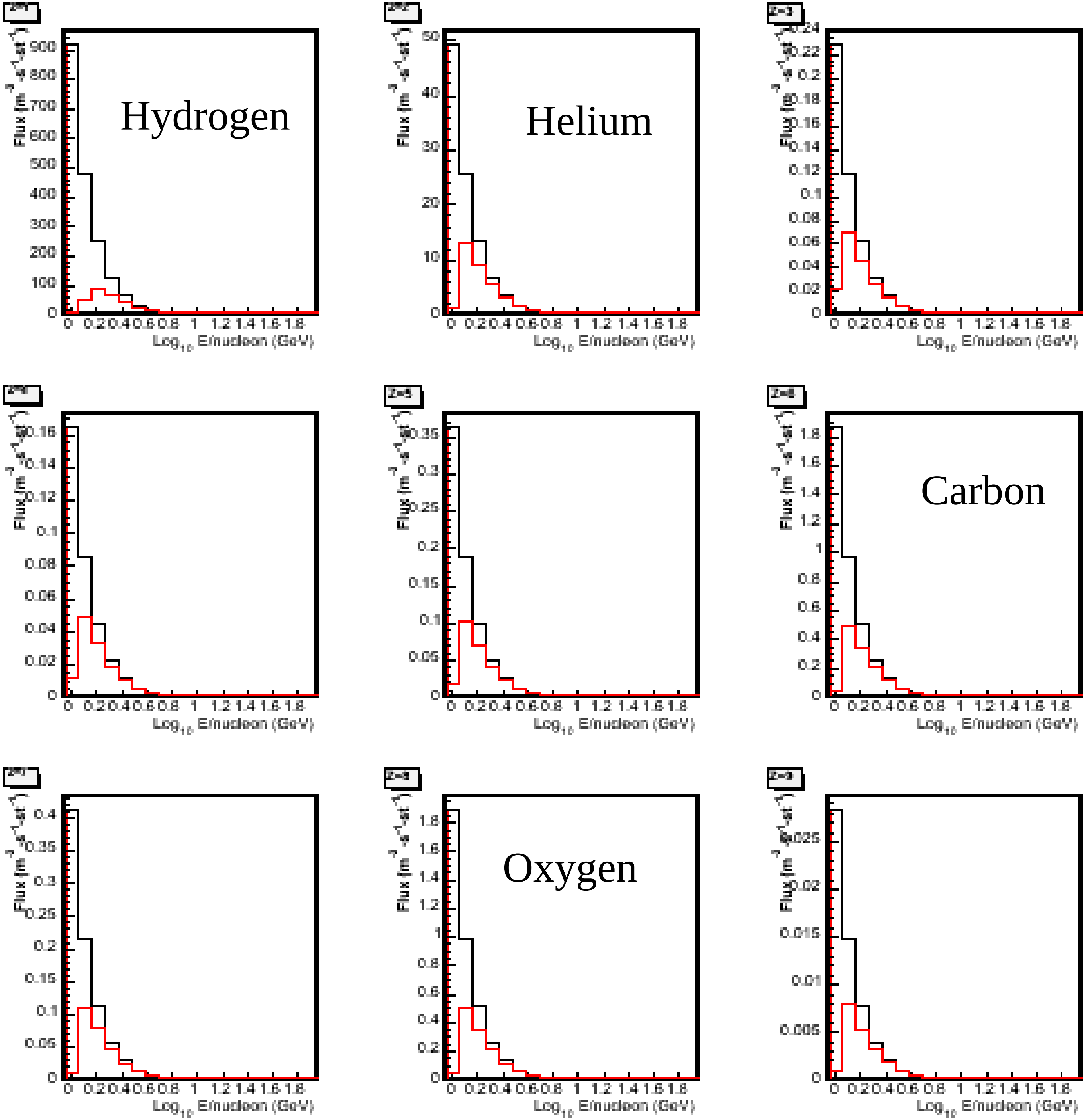
Table 1 - Abundance and contribution to dose inside habitat for ideal case for each element.



Comparison of "Ideal" and "More Realistic" magnetic field configurations

"Ideal" too optimistic.
"More realistic" too pessimistic.

Overall difference in flux for the two cases is ~3.3

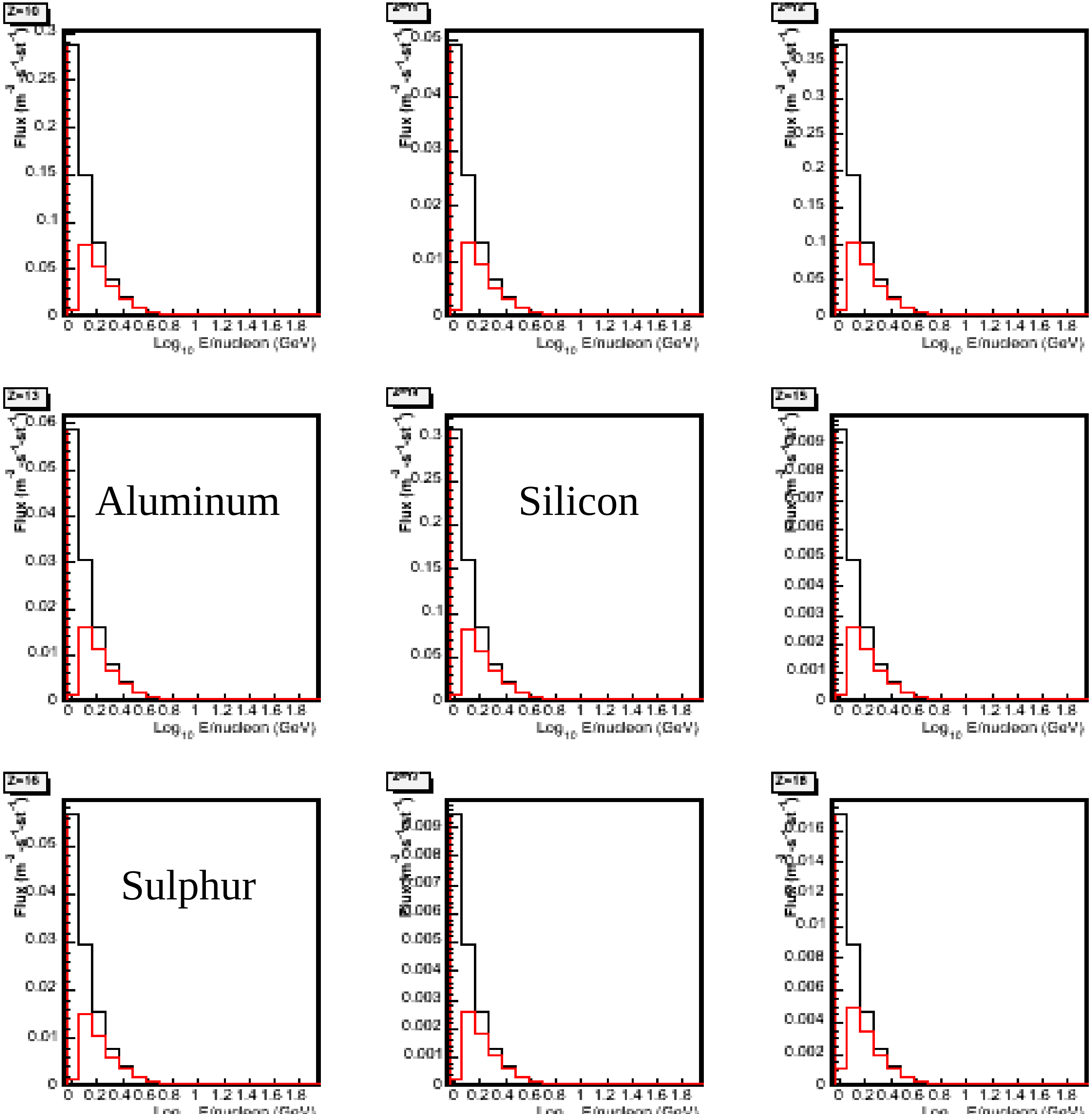


Comparison of flux inside habitat with and without <u>ideal</u> magnetic field

No B-field

"Ideal" 9 Tesla B-field

Elements
Z = 1-9

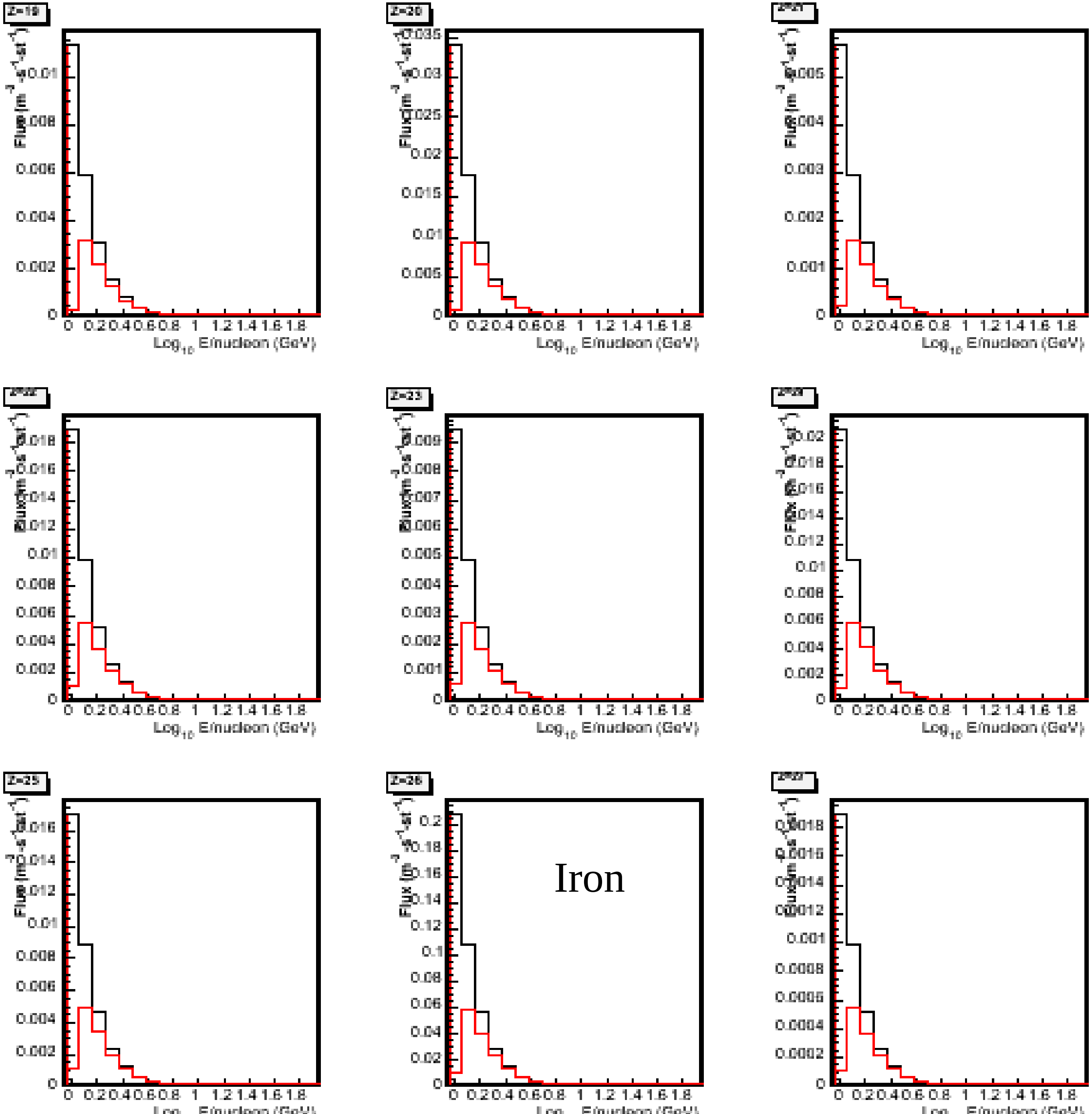


Comparison of flux inside habitat with and without <u>ideal</u> magnetic field

No B-field

“Ideal” 9 Tesla B-field

Elements
Z = 10-18

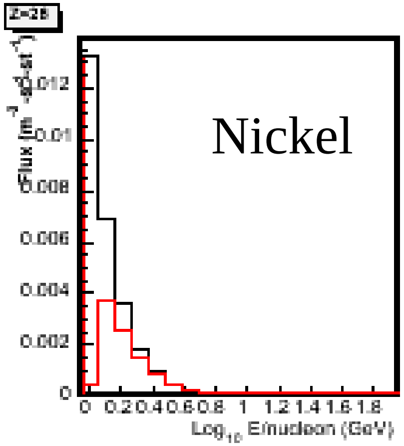


Comparison of flux inside habitat with and without ideal magnetic field

No B-field

“Ideal” 9 Tesla B-field

Elements
Z = 19-27



Comparison of flux inside habitat with and without ideal magnetic field

No B-field

“Ideal” 9 Tesla B-field

Element Z = 28

Special Considerations for High-Energy Cosmic Rays

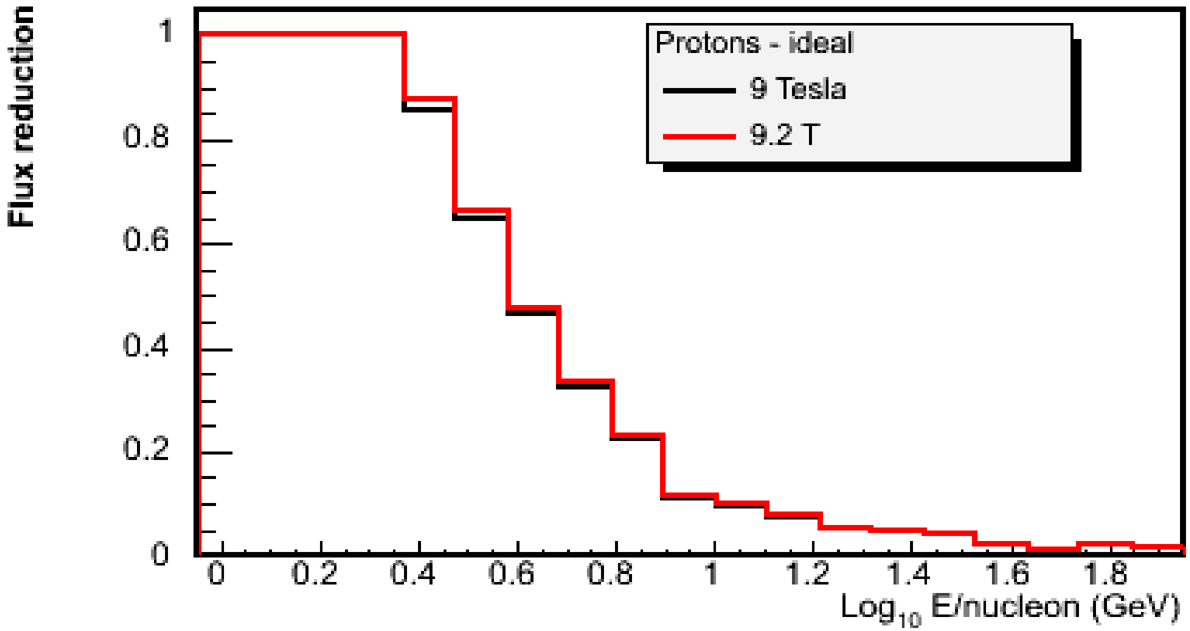
- Magnetic shielding becomes less effective at higher energies.
- Above ~4 GeV/nucleon, particles lose energy at a ~constant rate (which is lower than for lower energy particles).
- e.g., an alpha particle loses ~120 MeV passing through the human body whether its energy is 10 or 100 GeV/nucleon
- Below ~1 GeV/nucleon, energy loss ~$1/v^2$, so an alpha particle with 500 MeV/nucleon deposits *all* its energy (2 GeV) into the human body, ~16X higher than a 10-100 GeV/nucleon alpha.
- Passive shielding increases the number of lower-energy particles due to energy losses and secondary production.
- Magnetic shielding does not reduce the energy of particles and creates fewer secondary particles than secondary shielding.

Summing over all Energies

- Total flux reduced by ~10.7
- Radiation in free space reduced from

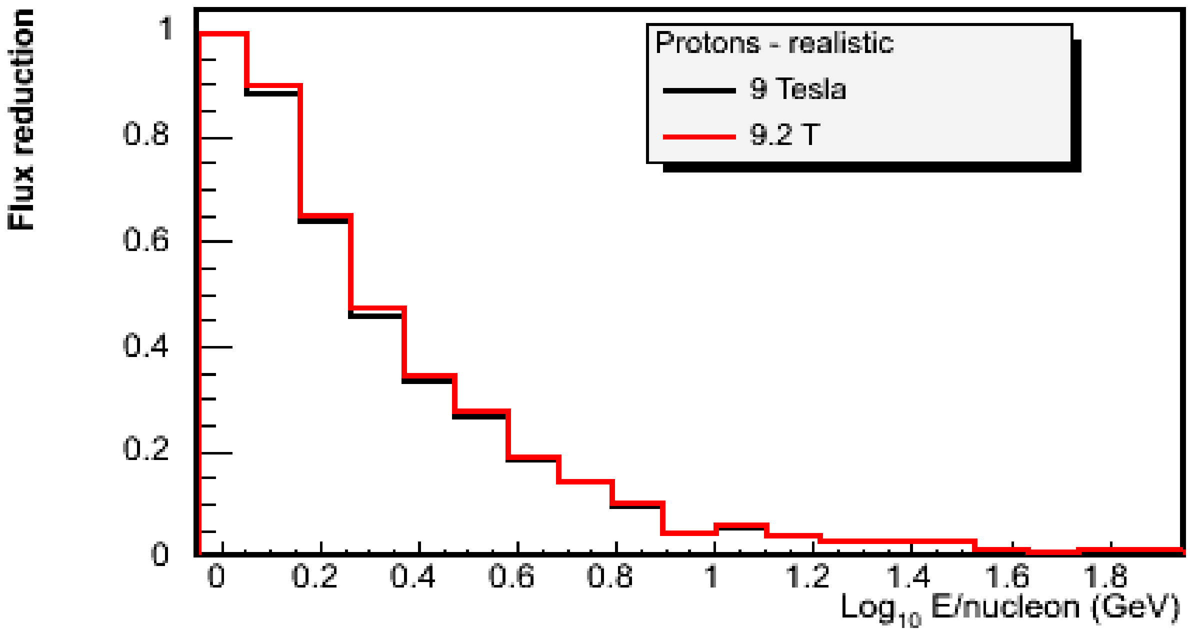
  ~90 rem/year to ~8.4 rem/year

  (~300 rem considered lethal)
- “Linear” treatment justified because in the energy range not blocked by the magnetic shield, the energy deposition rate is ~constant.

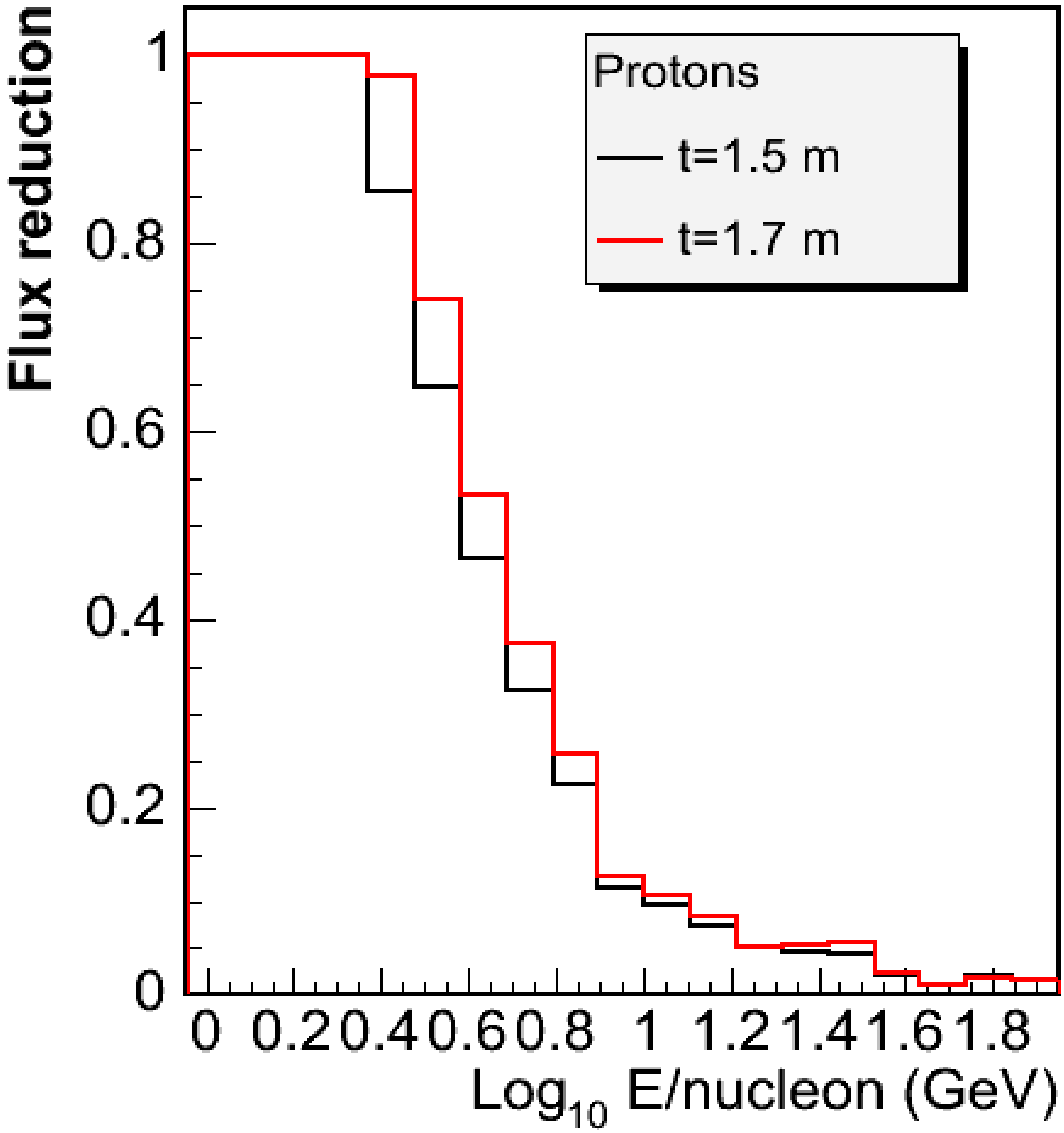


Vary magnetic field **strength** from 9 to 9.2 Tesla.

Overall flux reduction increases to ~11.1



i.e., ~20% increase in field strength leads to ~20% reduction in flux.



Vary **thickness** of magnetic field region from 1.5m to 1.7m.

Overall flux reduction Increases to ~13.1

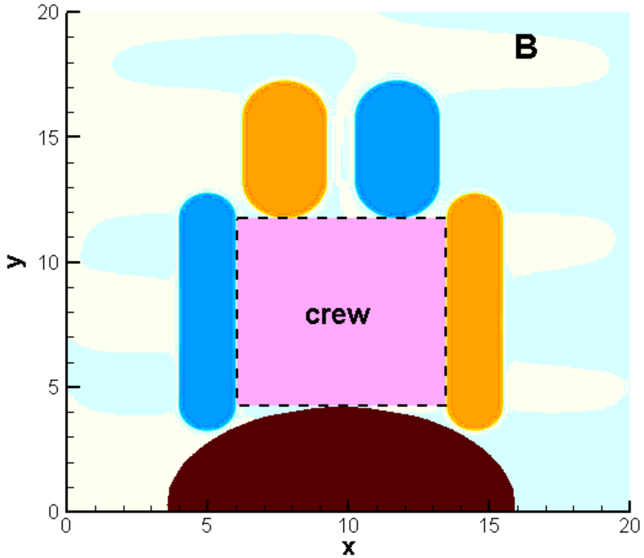
i.e. ~20% increase in field thickness leads to ~30% decrease in flux.

Bending Power α BL^2

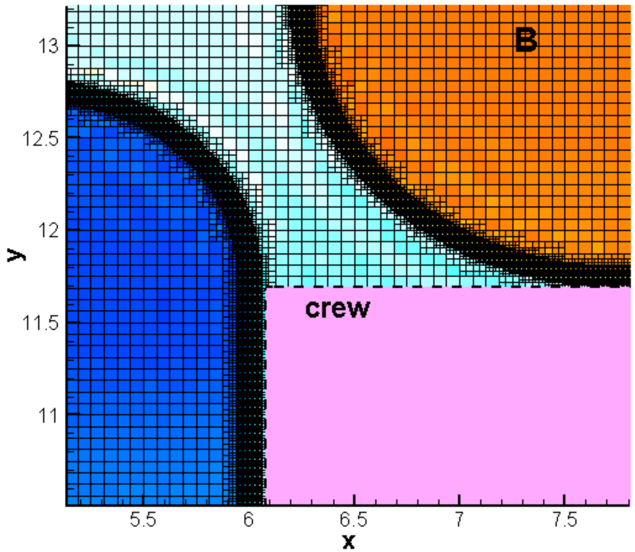
Analytic Study

- We develop a detailed transfer model of cosmic radiation through a combined region containing matter and a strong magnetic field. The goal of this calculation is to model the radiation penetrating the habitable volume.
- Physiological effects of the penetrating radiation are considered separately. It will be based on the comparison of the total dose calculations with existing NASA biomedical data and approved standard radiation requirements.
- Detailed space systems engineering design work will then produce a believable mass model associated with the assumed magnetic field.

Analytic Study - 2D



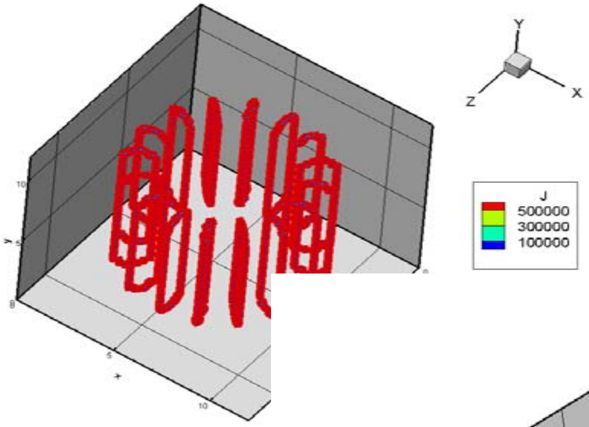
Contours of the calculated magnetic field created by a system of 4 coils. Dark region at the bottom resembles space craft, to which the habitat is attached.

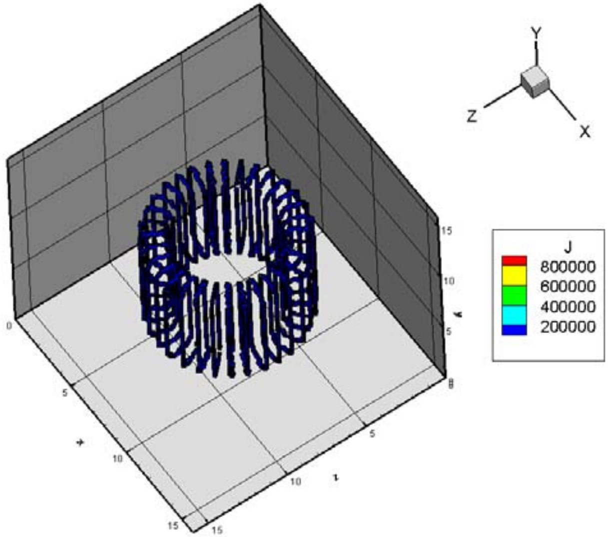


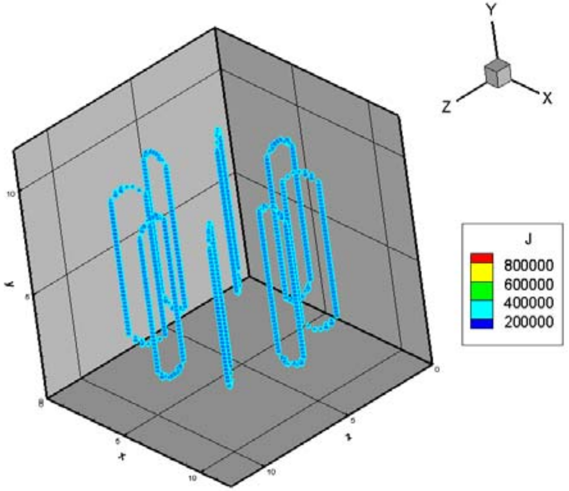
Zoomed portion of the domain, showing non-uniform grid spacing.

We are also running a full 3D calculation.

Radial coil configuration

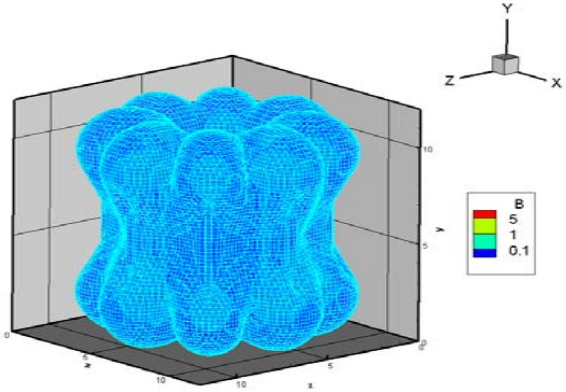


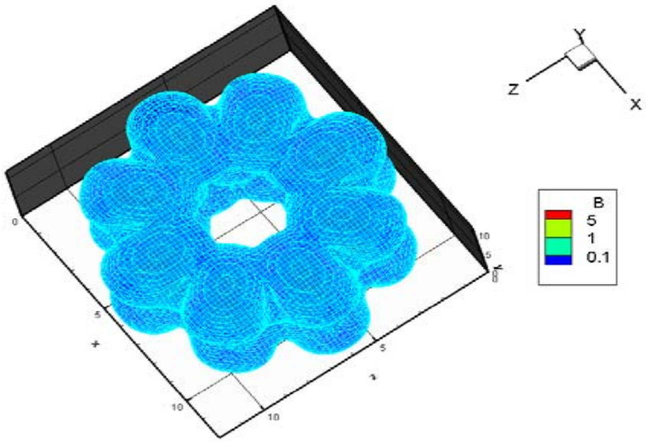




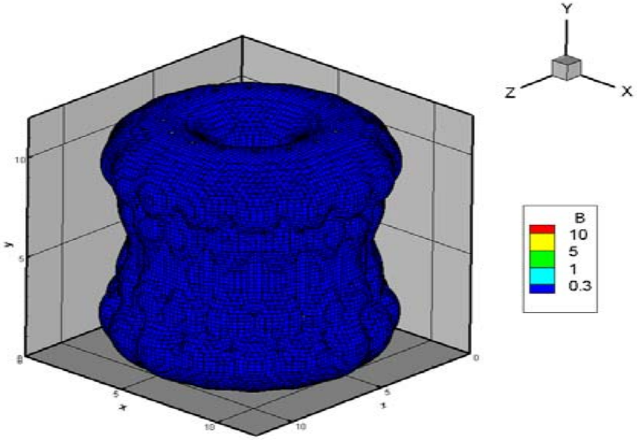
8, 16, 32 coils

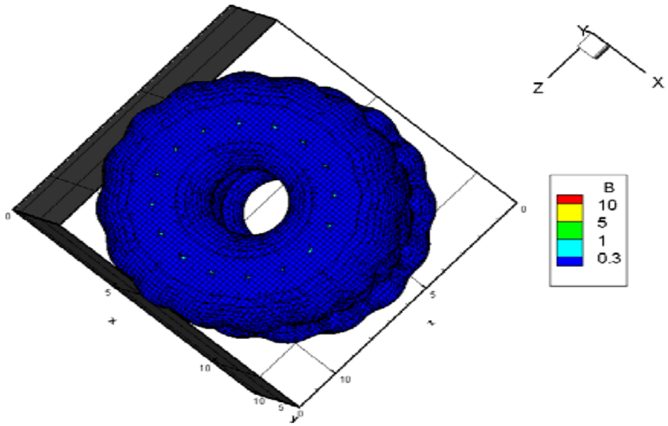
Magnetic field – 8 coils



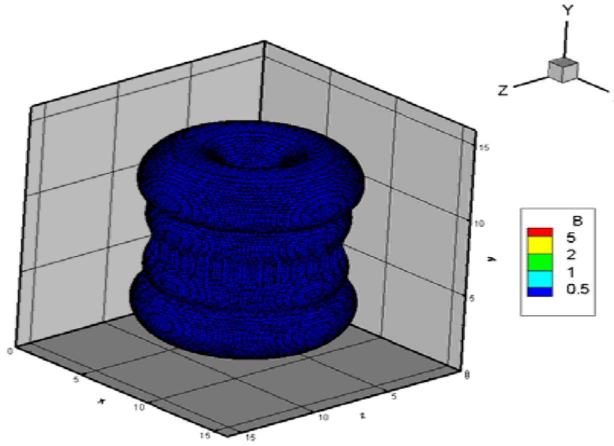


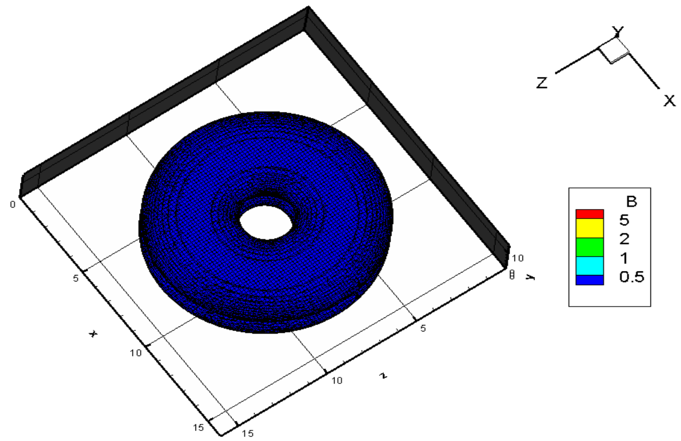
Magnetic field – 16 coils





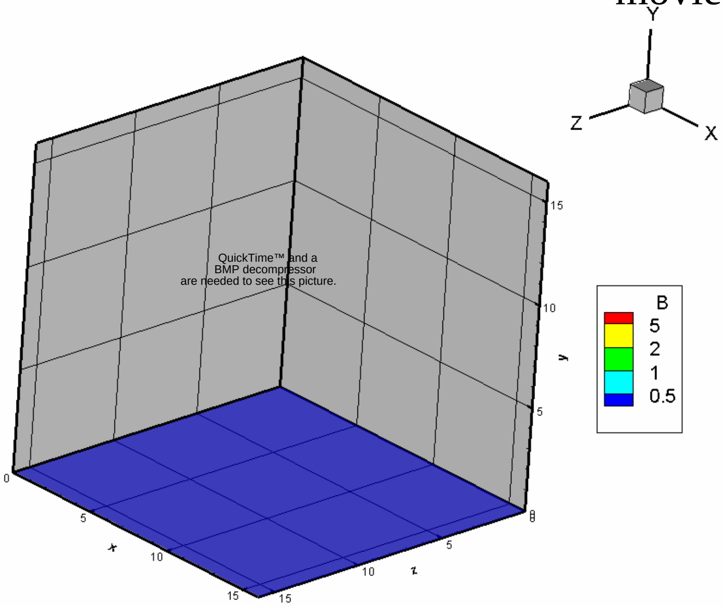
Magnetic field – 32 coils

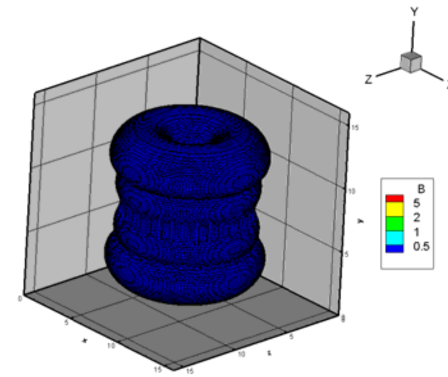


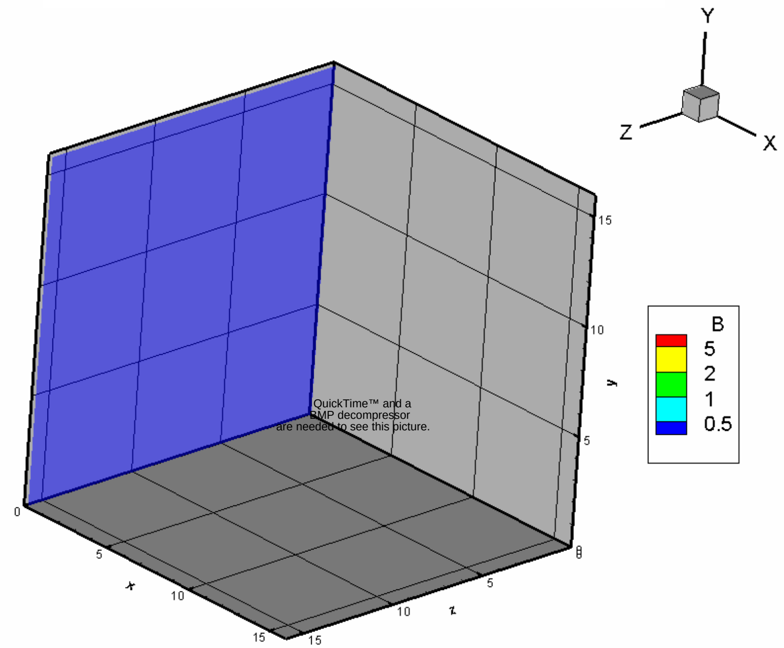


Magnetic field – 32 coils

movie







Kinetic Modeling

- The most detailed evolution of charged and neutral particles is given by the numerical solution of collisionally-coupled kinetic equations for charged and neutral species:

$$\begin{cases} \dfrac{\partial f_i}{\partial t} + \vec{v}\dfrac{\partial f_i}{\partial \vec{r}} + q_i\left(\vec{E} + \dfrac{\vec{v}\times\vec{B}}{c}\right)\dfrac{\partial f_i}{\partial \vec{p}} = C_i, \quad i = p, He^+, \ldots \\ \dfrac{\partial f_N}{\partial t} + \vec{v}\dfrac{\partial f_N}{\partial \vec{r}} = C_N, \quad N = n, \ldots \end{cases}$$

- As the particle density is low, these equations are coupled through sinks/sources, which occur as a result of particle interaction with elements of infrastructure. Particle tracing in the fixed non-uniform magnetic field is being presently developed.

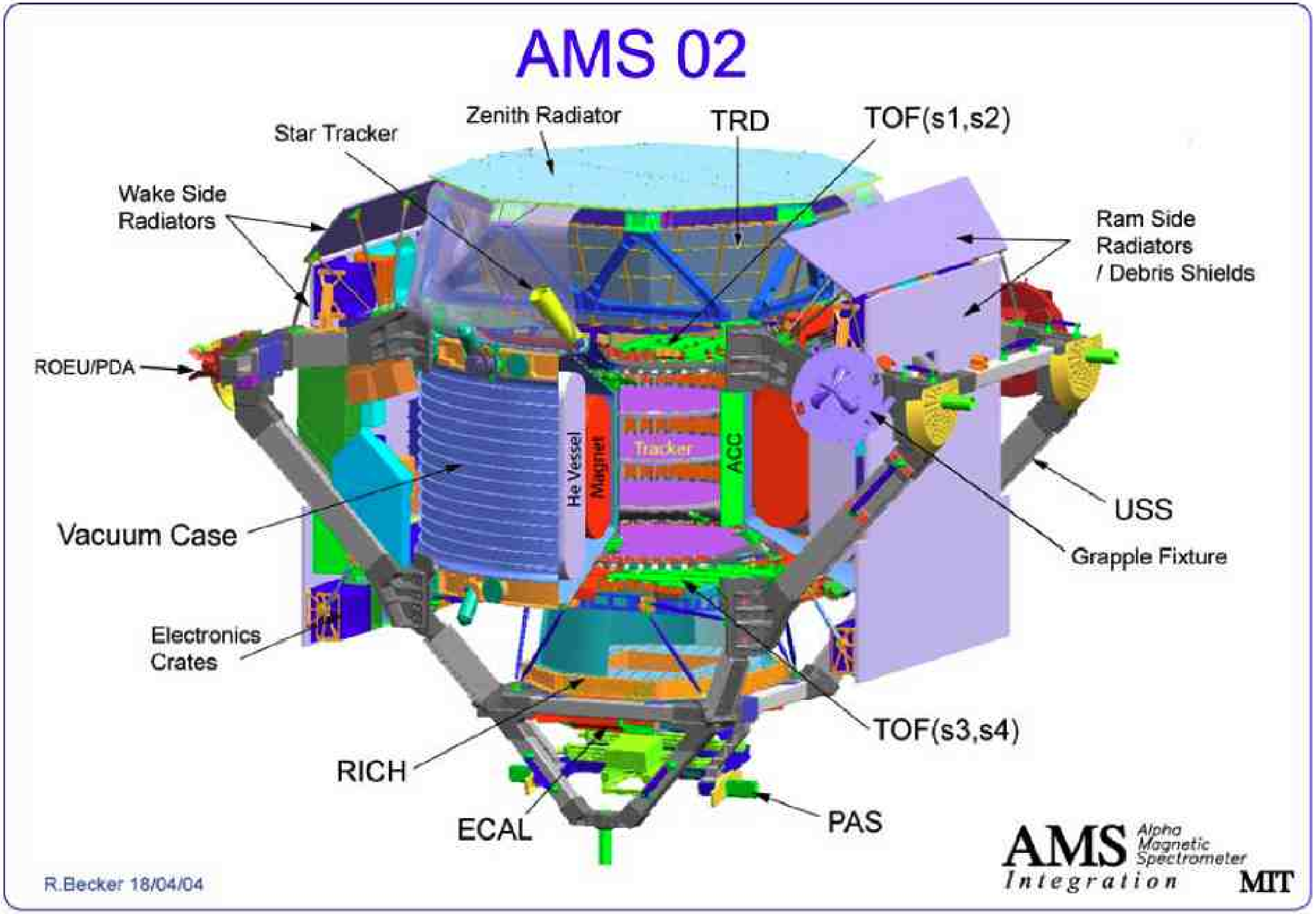
Design Considerations

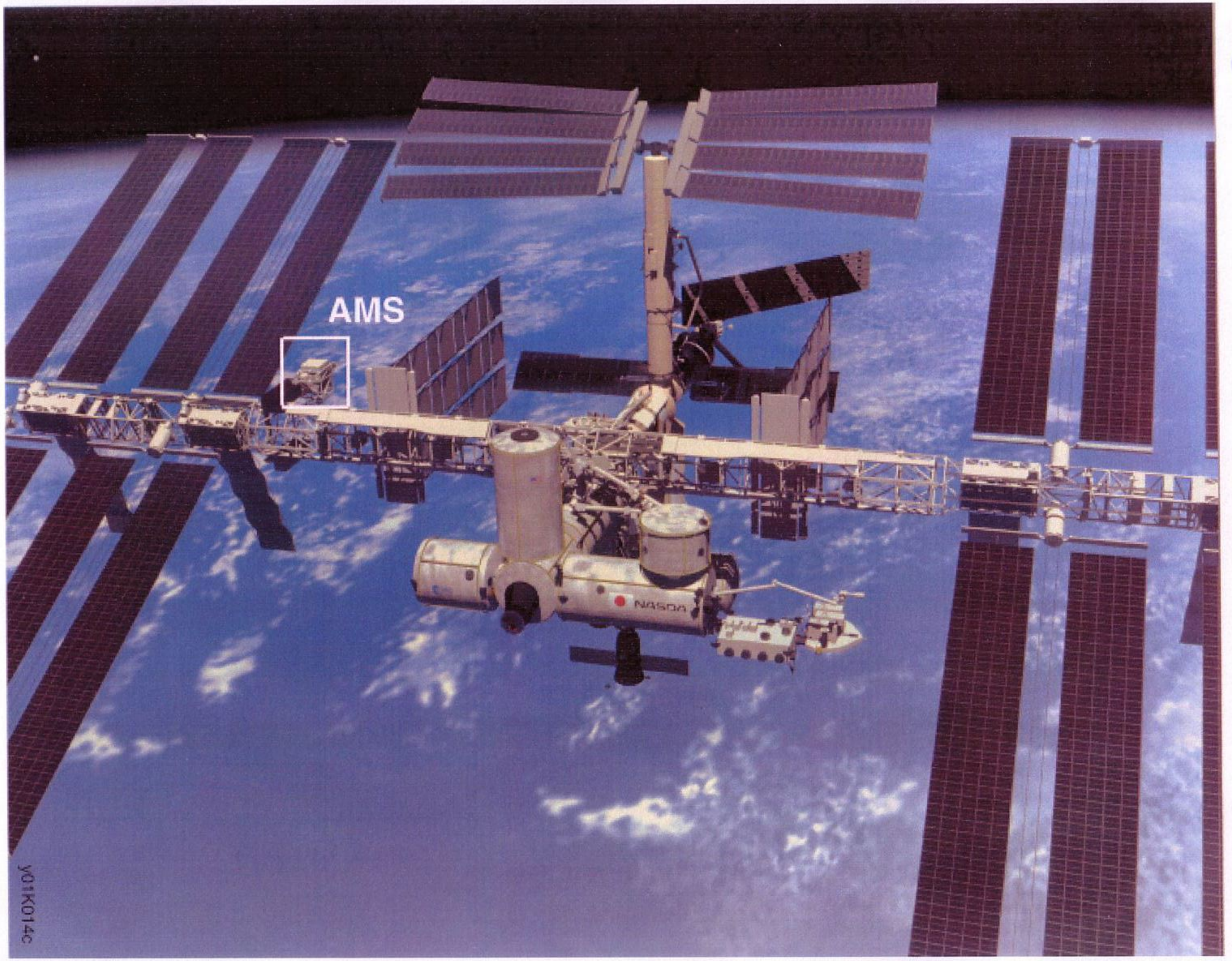
A practical magnetic shield needs a coil system with mechanical support as well as control and cooling systems. We need to assess:

- Weight
- Power Consumption
- Helium Coolant Amount
- Stored Energy
- Internal Mechanical Forces

Scaling from AMS

- Original inspiration for study came from Alpha Magnetic Spectrometer (AMS) experiment, to be flown on ISS.




AMS
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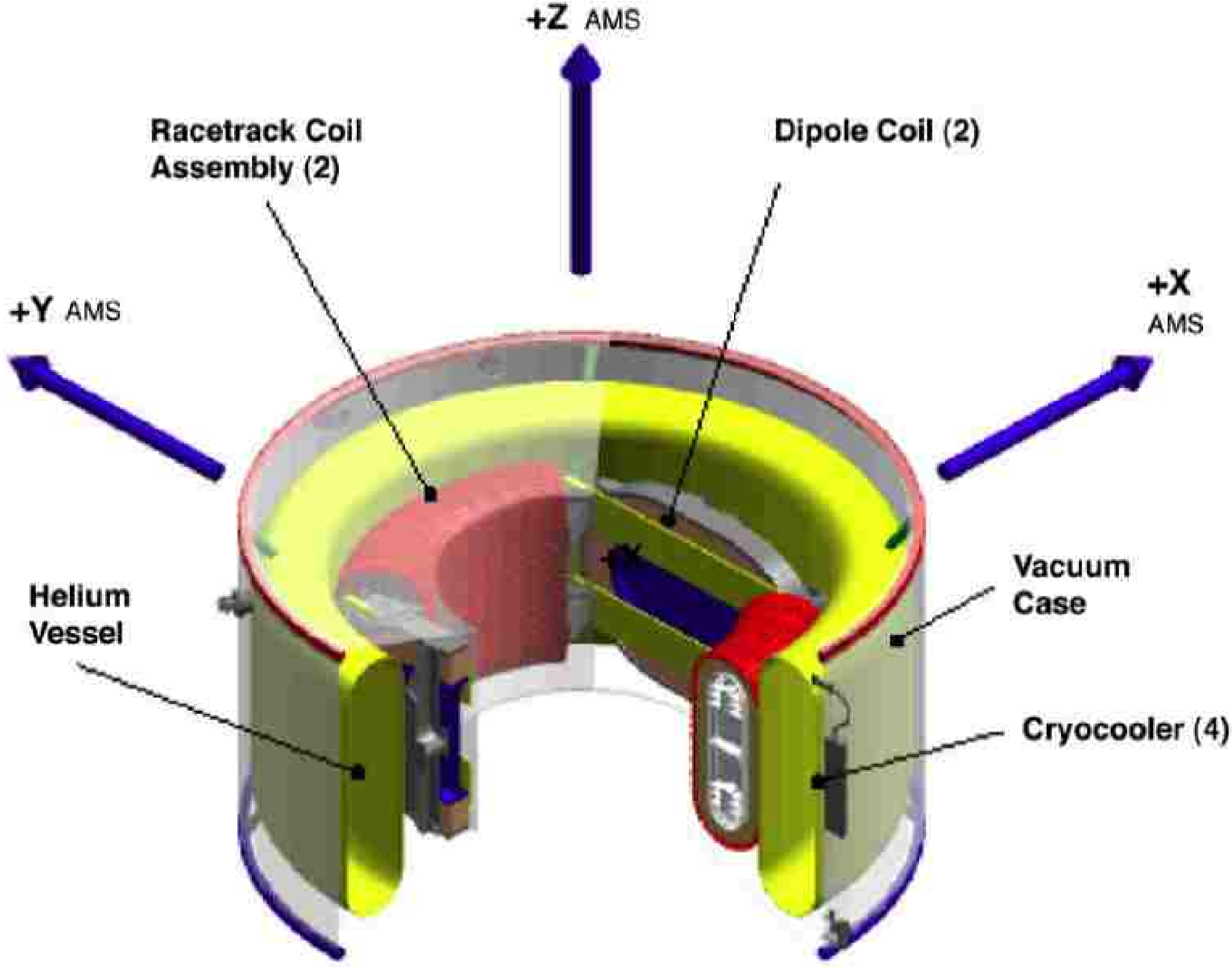
AMS Cryomagnet



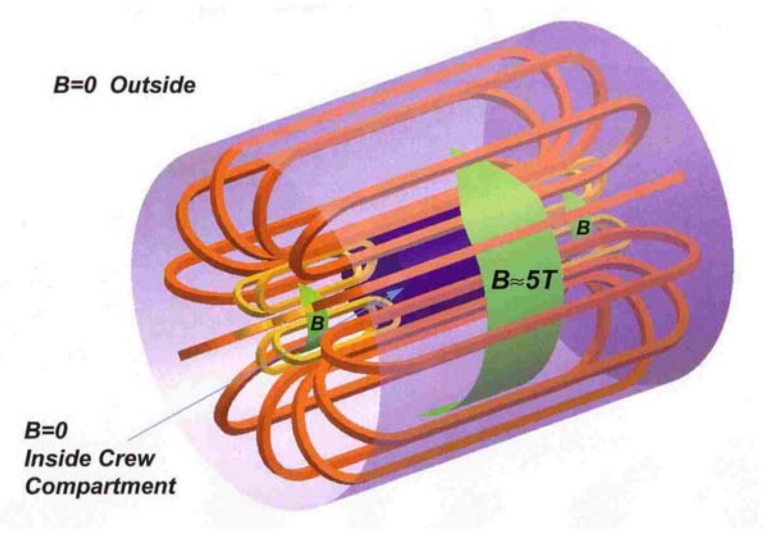
Cryomagnet Scaling

The AMS cryomagnet has the following characteristics:

- A central field of 0.9 T.
- A bending power 0.8 Tm^2 is over a volume of 0.7m^3.
- The heat load is about 10 W.
- 2500 l (312 kg) of liquid helium will be carried.
- 5.5 MJ is stored in the magnetic field.
- A coil mass of roughly 1000 kg and a total mass of roughly 2357 kg.
- A power consumption of 700 W to power four cryocoolers.

Mass Scaling

- Assuming ρ=5 gm/cm^3 for coil conductor gives coil mass ~244 T.
- AMS coils are 61% of total mass of 2357 kg, giving ~395 T for the magnetic shield.
- Need to revise scaling to handle magnetic field stress, which wants to push magnets apart.



Magnetic Field Stress

- Stress forces α B^2
- Strength of support structure α cross-sectional area
- Support size α $[M_{shield}/M_{AMS}]^{1/3}$ ~ 5, so area ~ 25.
- B_{shield}/B_{AMS} ~ 10, so need 100X strength vs. 25, so need an extra factor of 4 $\Rightarrow$ M_{shield} ~ 1600 T.

Helium Requirements

- Two ways to estimate Helium requirements:
  - Radiative transfer heat load α surface area of coils

    ⇨ 2.4 kW for magnetic shield

    75 T LHe (for 3 year mission)

    169 kW to run cryocooler system
  - Conductive transfer through cryomagnet supports

    α cross-sectional area (like strength), which scales with M_{coil}

    ⇨ 1.7 kW for magnetic shield

    52 T LHe (for 3 year mission)

    117 kW to run cryocooler system

Handling Quenches

- AMS magnets store 5.5 MJ
- Sudden loss of superconductivity dumps energy into 1500 kg of structure ⇨ $\Delta T \sim 30\ C^o$
- Magnetic Shield stores 16 GJ, requiring ~ 5000 kg for same temperature rise.

Summary of Simulation Results

- Overall radiation flux (dose) reduced by 3-10 X in a ~ 200 m^3 habitable volume
- Mass between 400-1600 T
- 52-75 T liquid Helium for a 3 year mission
- 117-169 kW to run cryocoolers
- Needs “dump mass” of 5000 kg to limit temperature rise following quench (16 GJ) to
  $< 30\ C^o$

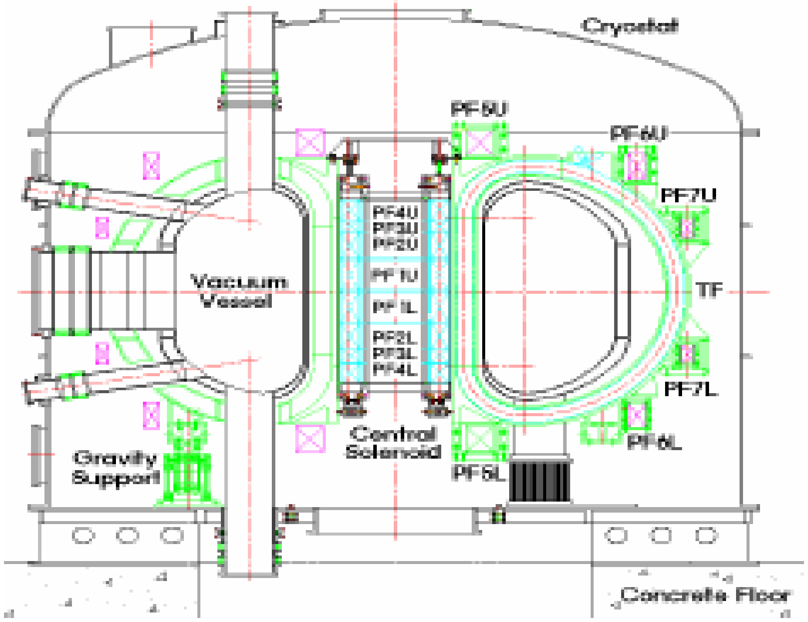
Design Optimization - (conceptual)

- Mass of support structure α B^2L
- Bending α BL^2
- Reducing field by 10% and increasing L by 7% keeps same bending but reduces mass by 13%.
- In a real spacecraft design, one end of habitable volume will be connected to spacecraft services, so no coil is required, reducing mass ~ 20%.

Need for detailed analysis

- All scaling arguments are based on reasonable physics, but must be considered naïve and limited in accuracy (first-order).
- Need detailed study of various AMS systems to allow extrapolation over the range we are proposing.
- e.g. Cooling loop expansion from 10 W to 2 kW, but liquid He heat transfer ultimately limited by Gorter-Mellink effect, which needs more study.

MIT-designed magnets for KSTAR



ATLAS Barrel Toroid Integration

y04K167Atlas.ppt

Note: Superconducting magnets of the size and strength needed for magnetic shielding are being built!

Contacts with NASA

- Frank Cucinotta - JSC radiation protection group
  - Can take our flux numbers and translate more accurately into doses.
  - Sees 2 GeV as "critical threshold" for efficacy of alternative shielding systems.
- Franklin Chang-Diaz - JSC Plasma Propulsion Lab
  - Interested in superconducting magnets in space for use with propulsion systems
  - Concentrating on high-temperature superconductors rather than low-temperature helium-cooled superconductors
  - Planning an Integrated Concurrent Engineering (ICE) exercise to look at integrating magnetic shielding into a human space flight vehicle.

    (Good opportunity to compare high- and low-temperature magnetic shielding systems.)

Contacts with NASA (cont.)

- Trent Martin - JSC AMS Deputy Project Manager
  - Wants to work with us on scaling AMS systems to size usable for human exploration.
- Bill Polowski - JSC artificial gravity study
  - Could use magnetic shielding coils as a stator to suspend and rotate interior crew cabin to make a short-radius centrifuge
- Kirk Sorensen - MSFC In-Space Propulsion Technology Projects Office (Tethers)
  - Electrodynamic tethers can provide propulsion near Jupiter
  - Need to protect electronics and scientific instrumentation against radiation for extended missions

Exploring the Jovian Magnetosphere

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Future Work

Objectives of Study	Phase I	Phase II
• Detailed study of the trajectories of a realistic spectrum of cosmic rays through the proposed magnetic shield to determine actual shielding efficacy	X	X
• Examine the feasibility of enlarging the AMS superconducting magnets		X
• Reduce the mass of the magnet system	X	
• Integrate superconducting magnetic shield into a human space vehicle	X (conceptual)	X (systems design)
• Detailed comparison of magnetic radiation shielding with traditional shielding technologies (Al, H_2O, LH_2, Pb)		X
• Additional applications of superconducting magnetic technology for long-duration human space flight		X
• Other exploration applications of this technology		X

HIGHEST-PRIORITY RESEARCH QUESTIONS (1)

1. What are the carcinogenic risks following irradiation by protons and HZE particles?
2. How do cell killing and induction of chromosomal aberrations vary as a function of the thickness and composition of shielding?
3. Are there studies that can be conducted to increase the confidence of extrapolation from rodents to humans of radiation-induced genetic alterations that in turn could enhance similar extrapolations for cancer?
4. Does exposure to heavy ions at the level that would occur during deep-space missions of long duration pose a risk to the integrity and function of the central nervous system?

HIGHEST-PRIORITY RESEARCH QUESTIONS (2)

5. How can better error analyses be performed of all factors contributing to estimation of risk by a particular method, and what are the types and magnitude of uncertainty associated with each method? What alternate methods for calculation of risk can be used to compare with conventional predictions in order to assess absolute uncertainties? How can these analyses and calculations be used to better determine how the uncertainties in the methods affect estimates of human risks and mission costs?
6. How do the selection and design of the space vehicle affect the radiation environment in which the crew has to exist?
7. Can solar particle events be predicted with sufficient advance warning to allow crewmembers to return to the safety of a shielded storm shelter?

LOWER-PRIORITY RESEARCH QUESTIONS

1. What are the risks of reduced fertility and sterility as a result of exposure to radiation on missions of long duration in deep space?
2. What are the risks of clinically significant cataracts being induced by exposure to radiation at the levels that will occur on extended space flights?
3. Can drugs be used to protect against the acute or carcinogenic effects of exposure to radiation in space?
4. Is there an assay that can provide information on an individual's sensitivity to radiation-induced mutagenicity and that can be predictive of a predisposition for susceptibility to cancer?
5. Are there differences in biological response arising from exposure to particles with similar LET, but with different atomic numbers and energies?

Radiation Exposure Limits (radiation workers and astronauts):

Constraints in REM	Bone 5 cm	Skin 0.1 mm	Eye 3 mm	Testes 3 cm
1 yr average daily rate	0.2	0.5	0.3	0.1
30 day max	25	75	37	13
Quarterly max	35	105	52	18
Yearly max	75	225	112	38
Career Limit	400	1200	600	200

(Double the statistical chance of leukemia in 20 years from 1 in 50,000 to 2 in 50,000)

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