Quantities for Space Dosimetry
(ICRP Report 123)

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Task Group TG67

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The first step of ICRP towards radiation for astronauts

Reason: Mission doses to astronauts may far exceed 100 mSv

But the focus is not on radiation protection,

……….**but on assessment of exposure**

Approach:

Use of quality factors as function of LET (ICRP) or as function of particle charge and energy (NASA approach) instead of weighting factors

ICRP TG 67 “Radiation Protection in Space”

2007 Recommendation of ICRP

§ (190): *Exceptional cases of cosmic ray exposures, such as exposure in space travel, where doses may be significant and some type of control warranted, should be dealt with separately taking into account the special type of situation that can give rise to this type of exposure.*

- NCRP Report 132 (2000), 142 (2002) and 153 (2007) are dealing with these problems in detail and many other publications are available in this field,
- but international recommendations in this field do not exist !

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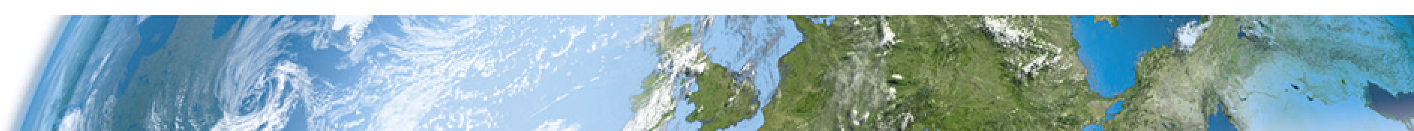
ICRP TG 67 “Radiation Protection in Space”

Goal: **Recommendation on Assessment of Radiation Exposure in Space**

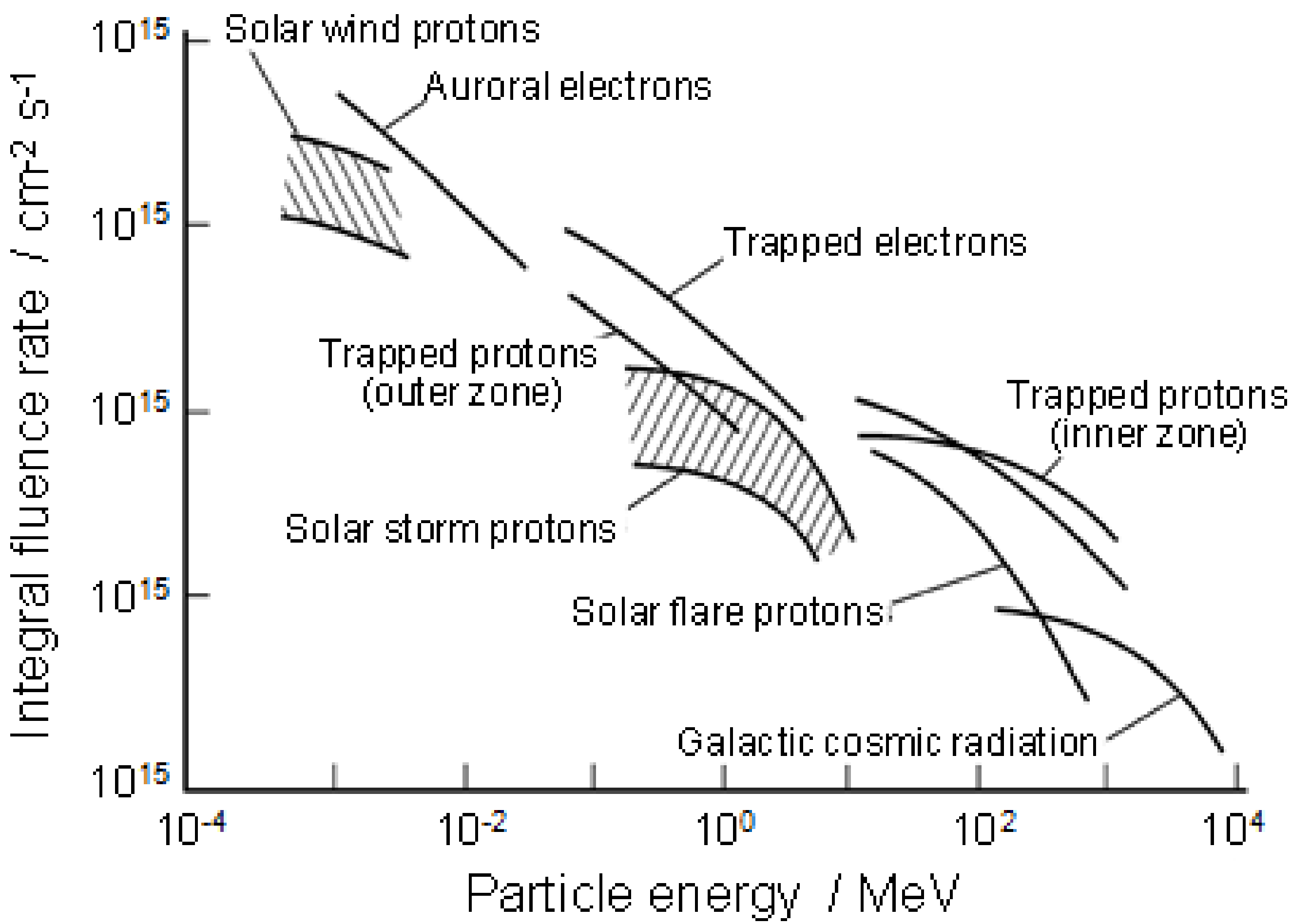
- Radiation fields in space
- Application of radiation protection quantities
- Dosimetry for astronauts in space
- Assessment of human exposure
- Conversion coefficients for particles of high energy



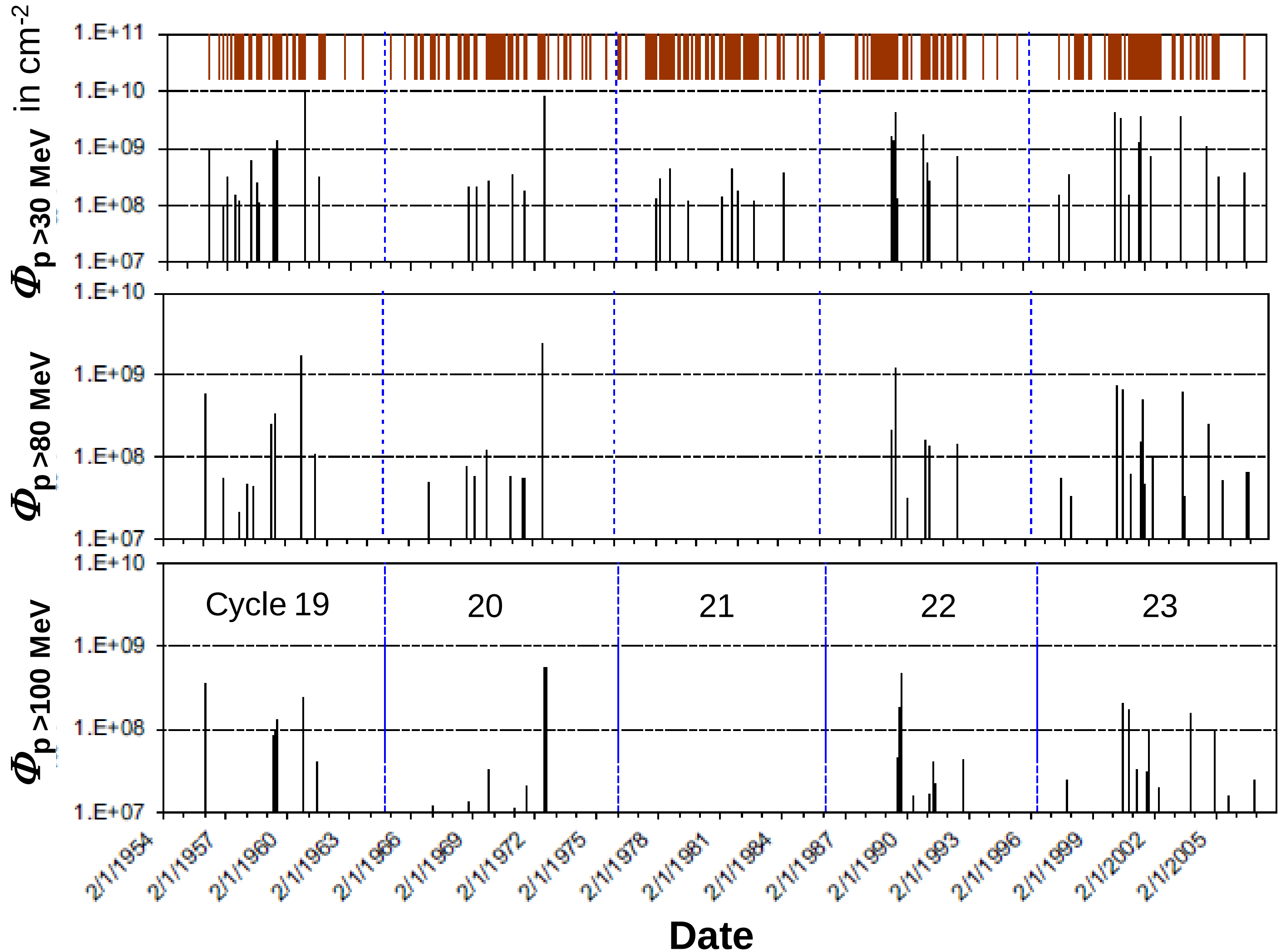
Radiation Environment

- Radiation Sources
  - Galactic Cosmic Radiation (protons and heavier ions)
  - Solar particle Events (protons, low contribution of heavier particles)
  - Radiation belts (protons and electrons)
- Magnetic Field Effects
  - Solar modulation
  - Geomagnetic shielding
- Altitude Effects
- Production of Secondaries in Interactions with Shielding Material
  - Projectile and target fragments
  - Neutrons
  - Secondary protons and electrons and bremsstrahlung

Synoptic view of integral particle fluence rate of space radiation versus upper boundary of particle energy



Occurrence of major solar particle events in solar cycles



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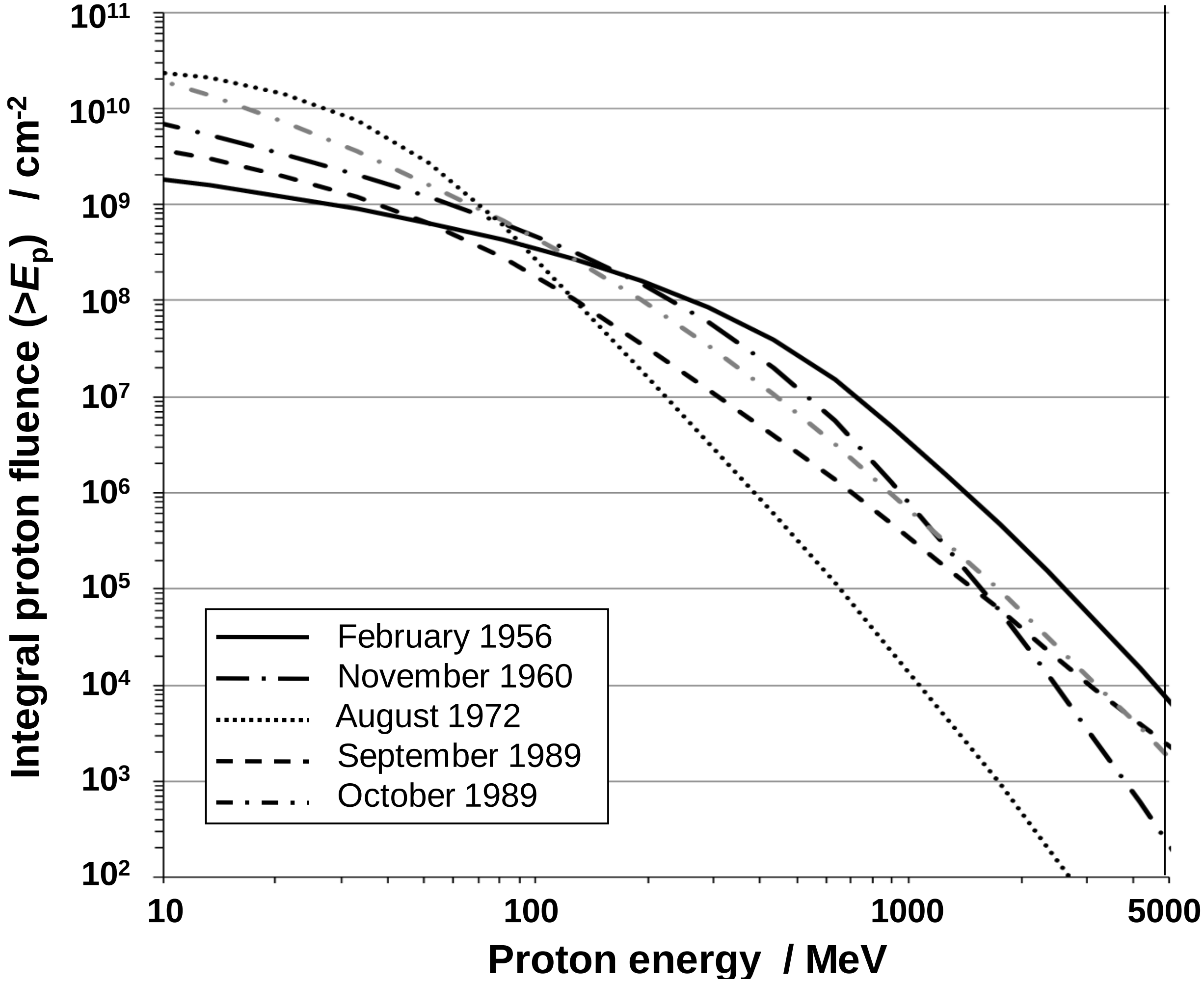
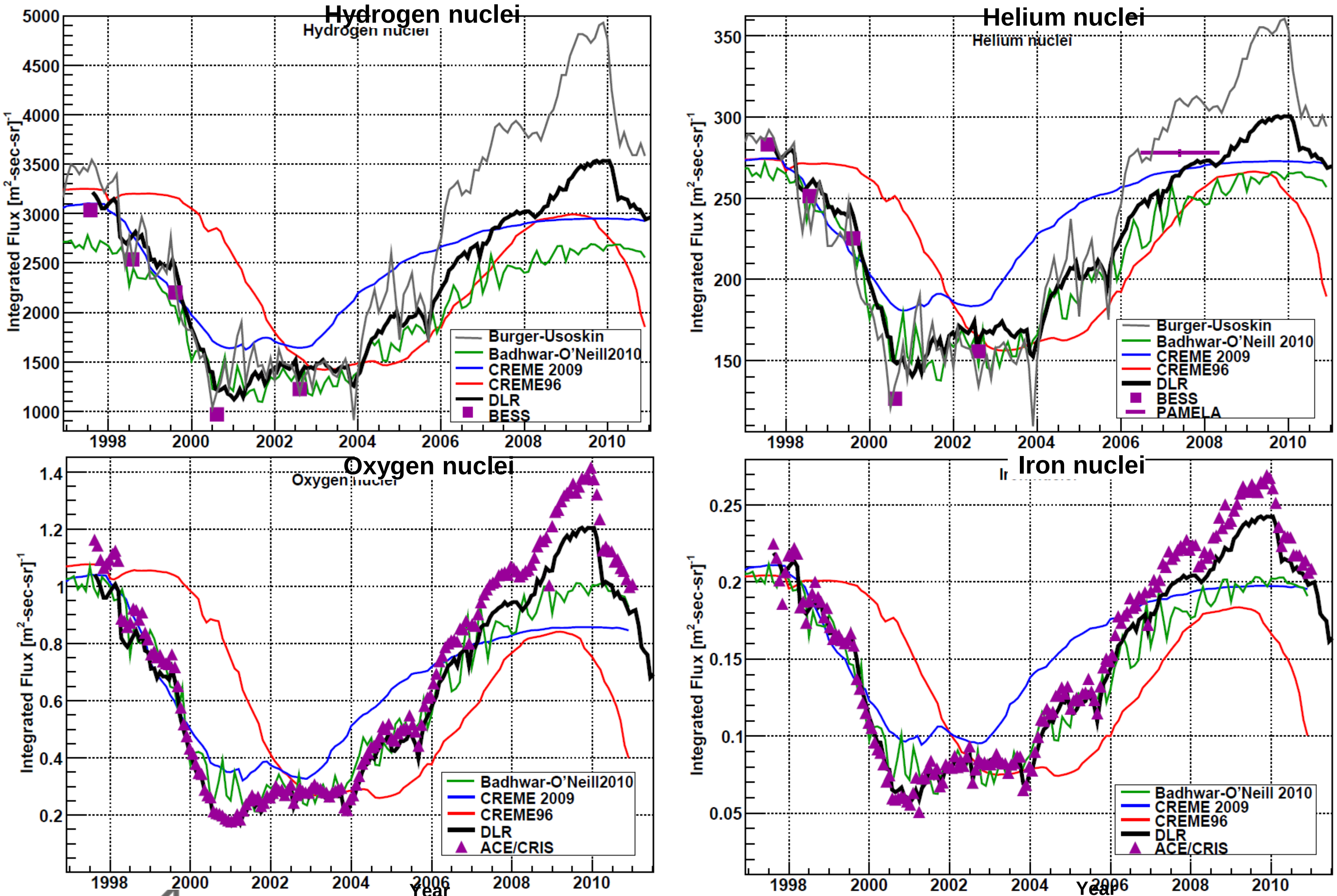
Integral particle fluence spectra from historical large events



Temporal variation in GCR flux



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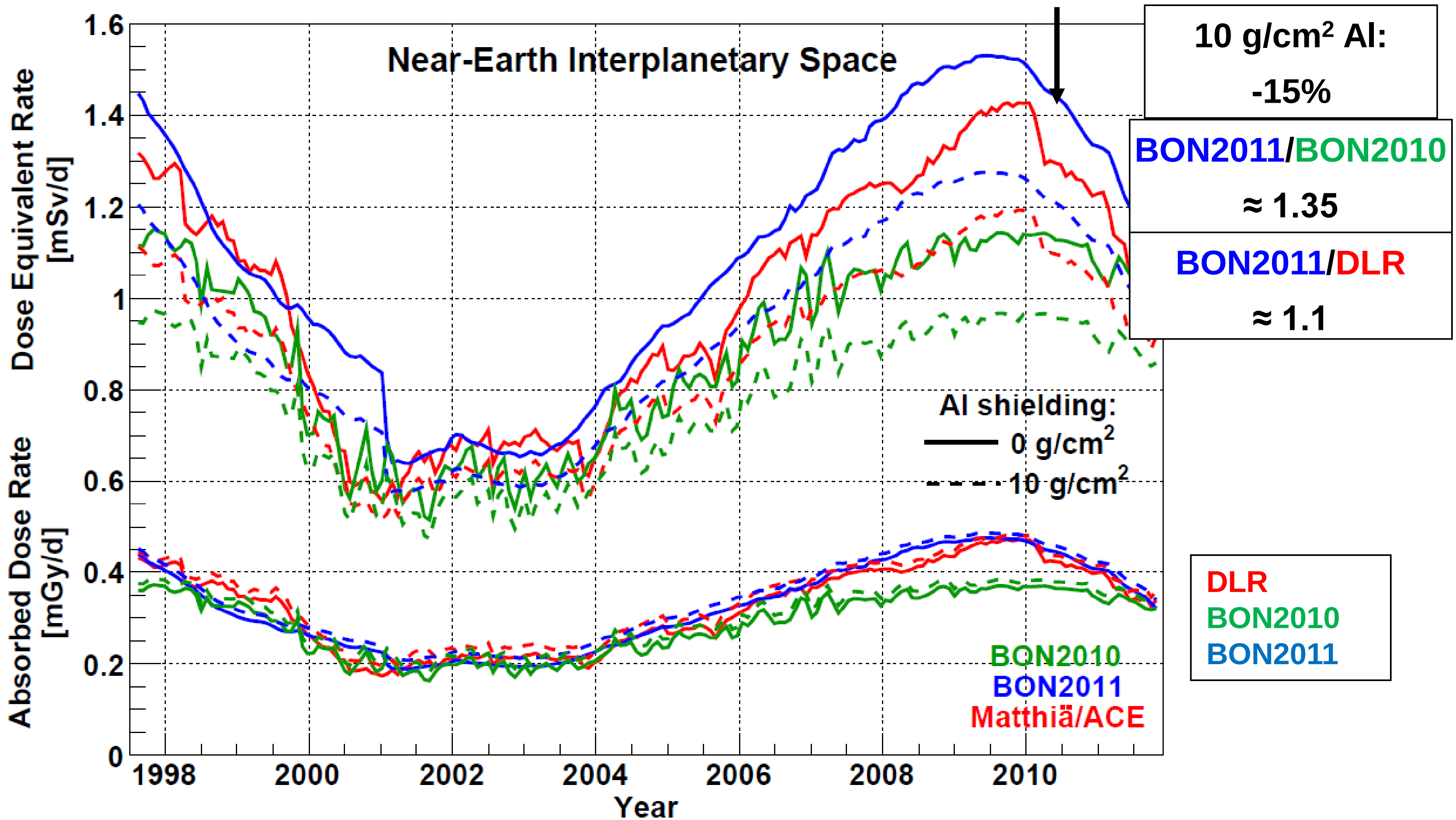
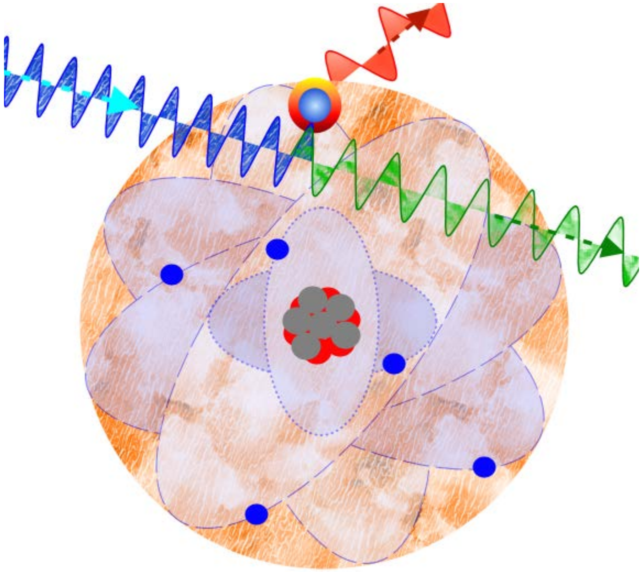
GCR exposure in interplanetary space



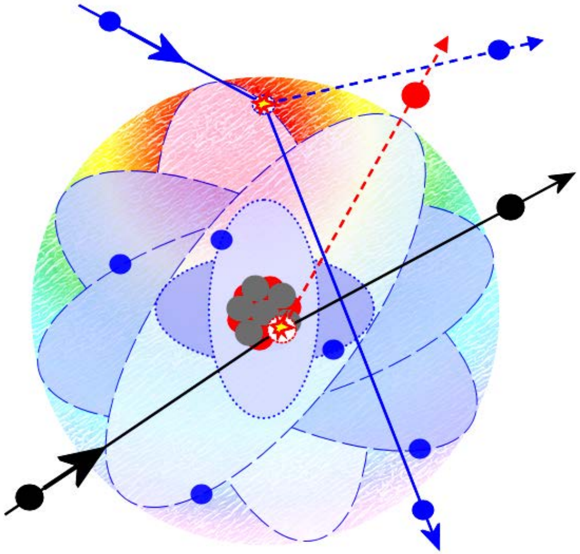
Energy Loss/Deposition Mechanisms

-**Photoeffect, Compton scattering, Bremsstrahlung, Collisions**,
-Pair production, Photonuclear effect, Cerenkov radiation, Strong interaction

-Excitation

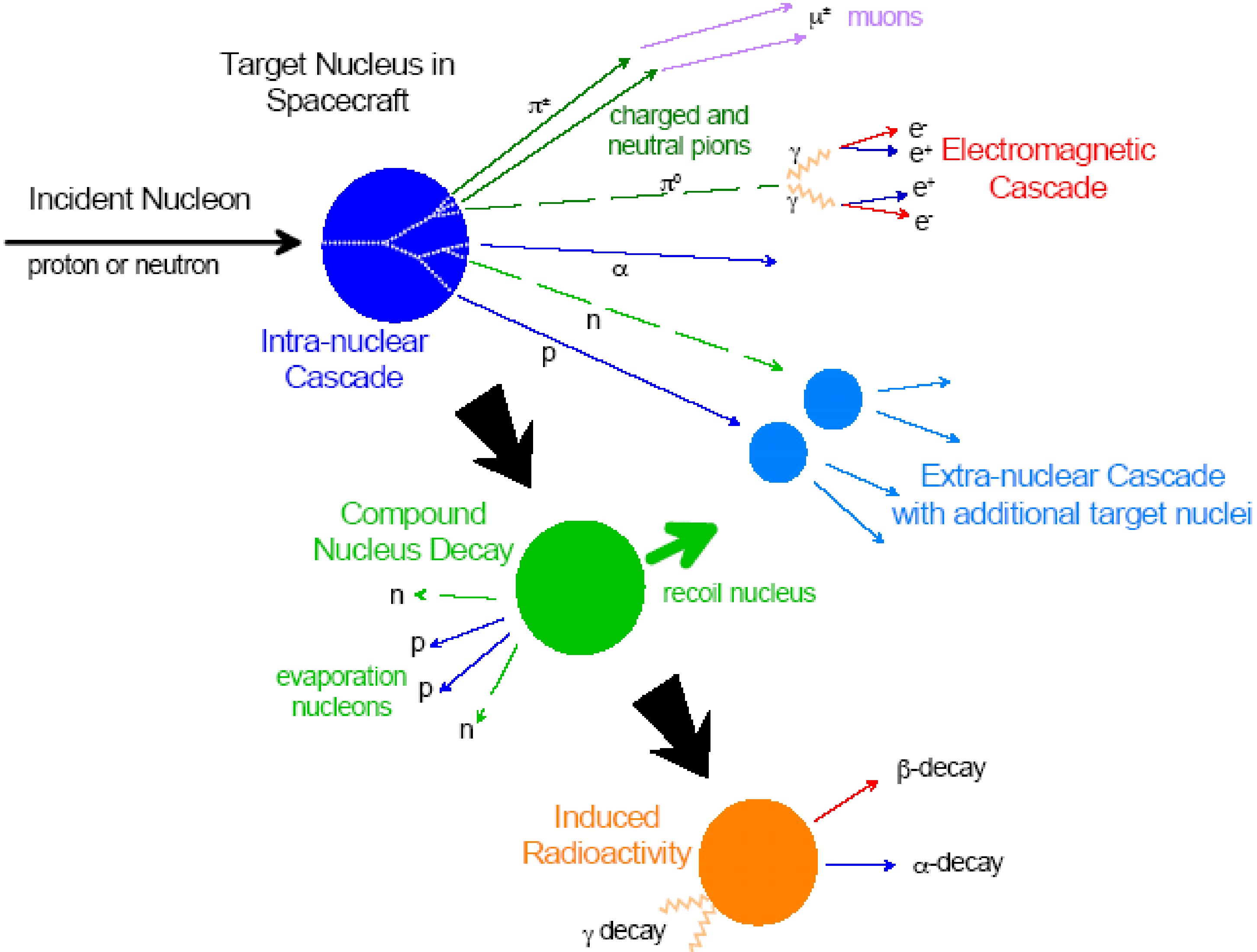


-Ionization



-**elastic/inelastic collisions**

Production of Secondary Particles



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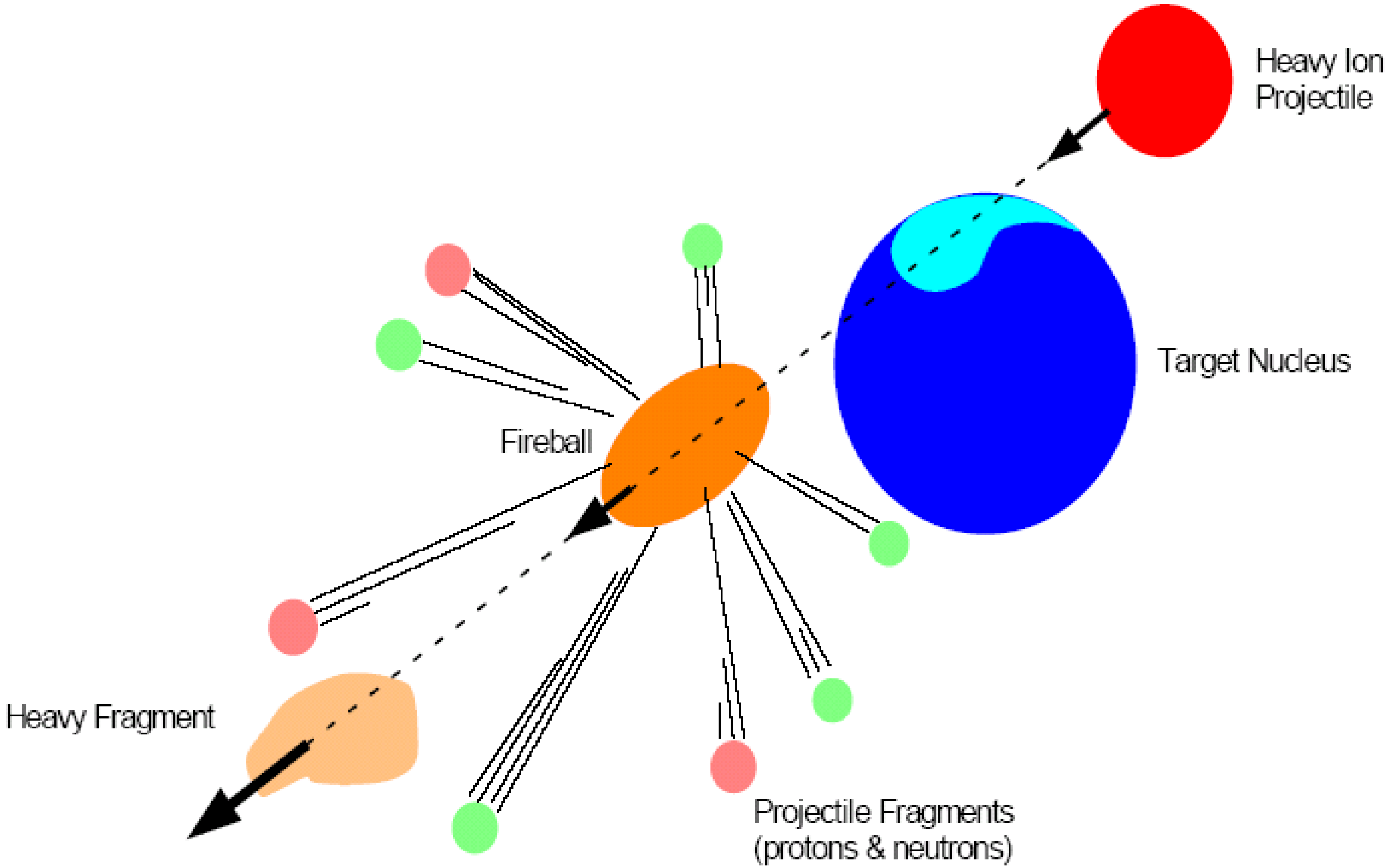
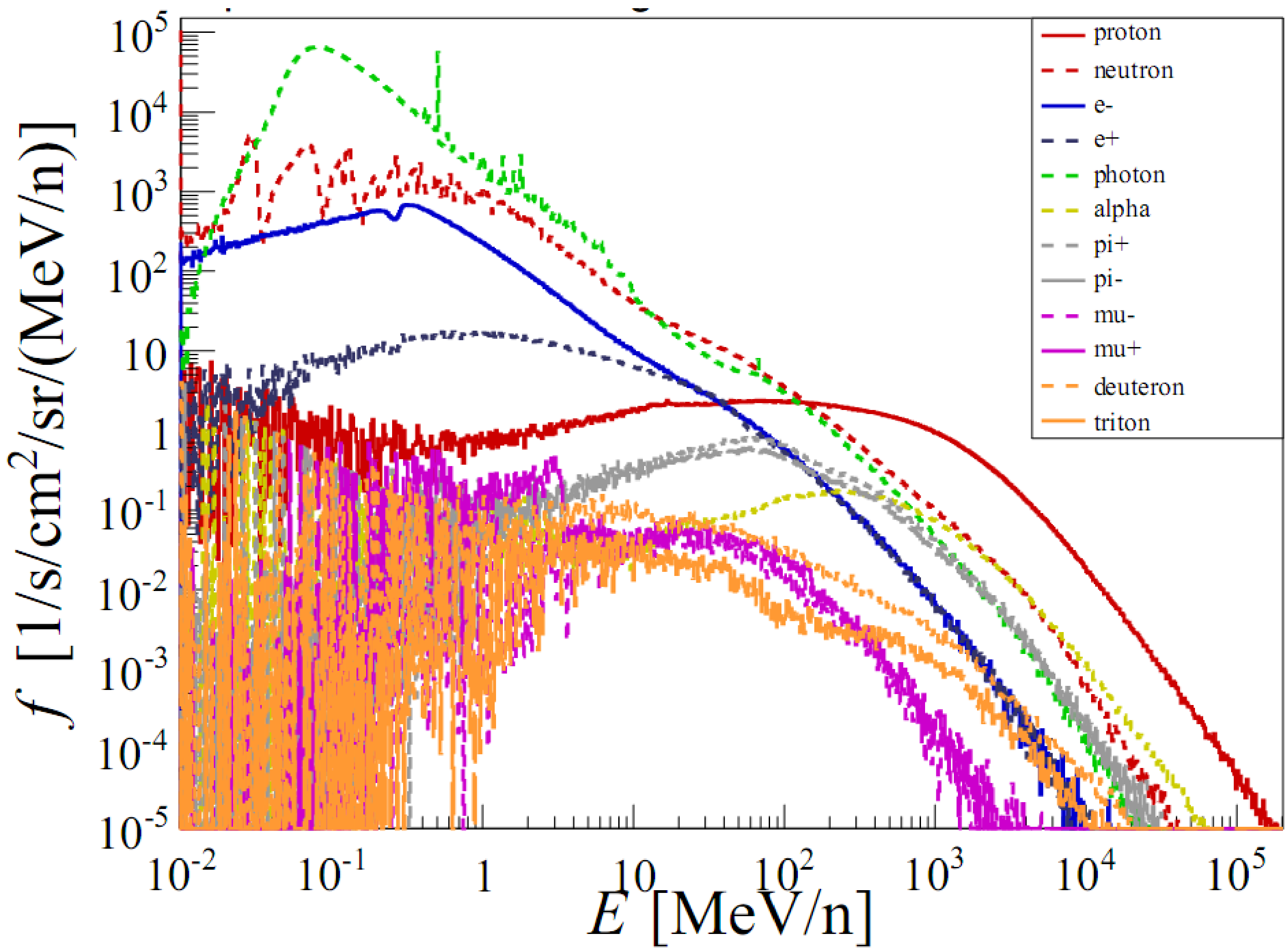
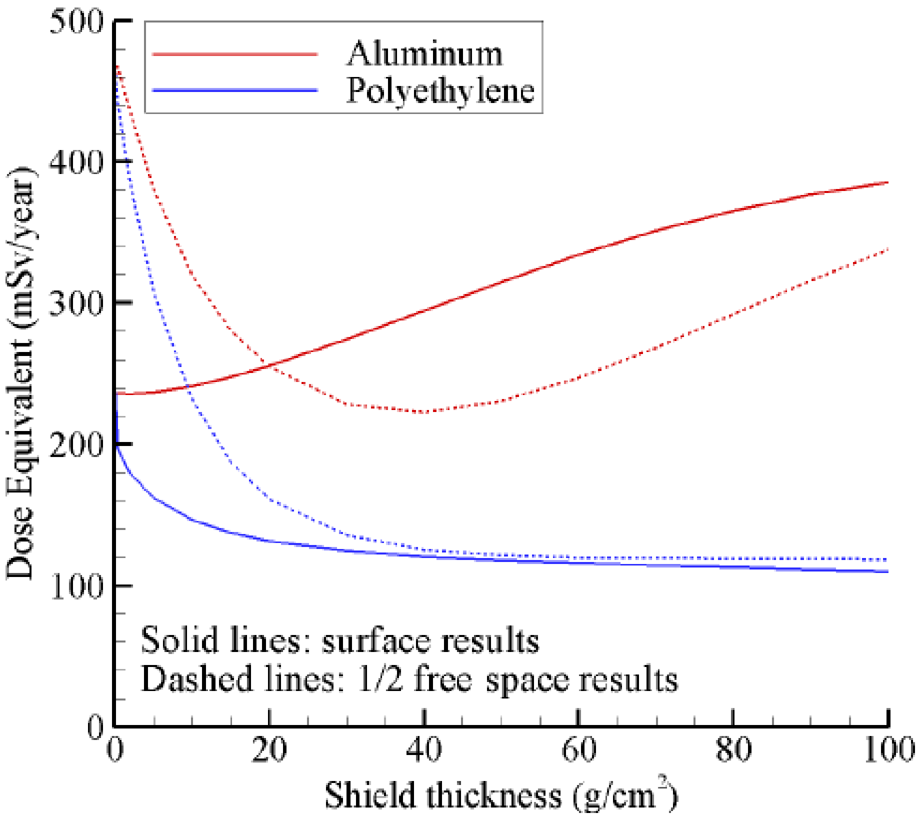
Heavy Ion Target Fragmentation

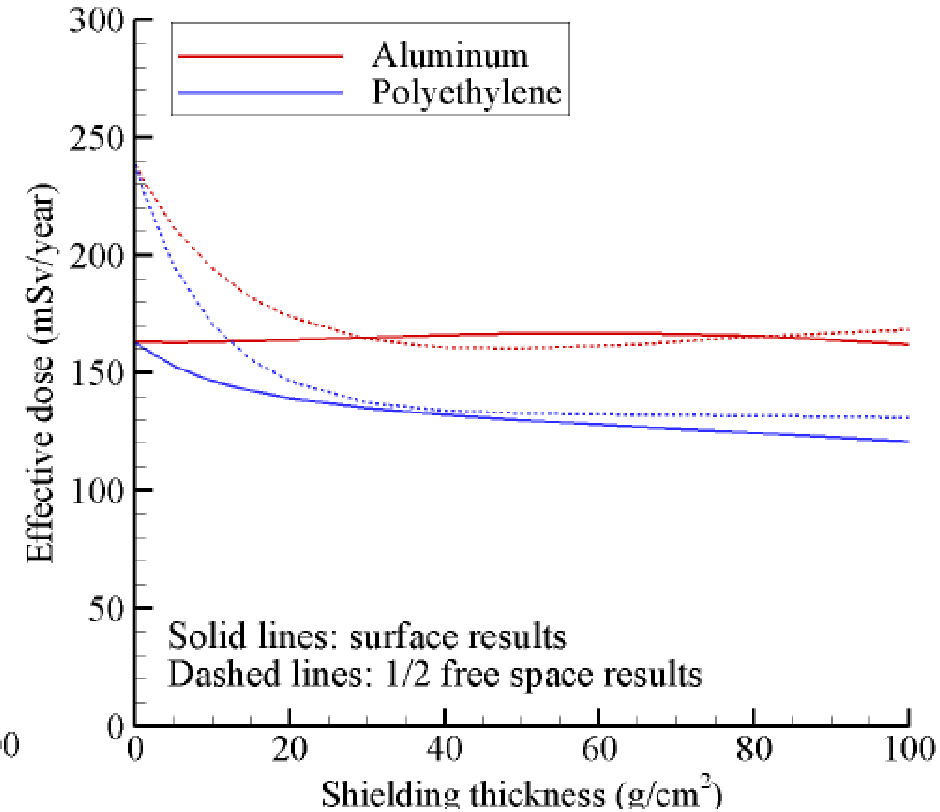


MSL Cruise energy-spectra



Comparison of Surface Exposure and half Space Exposure in dependence of Shielding Thickness





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Radiobiological Aspects of the Space Radiation Field

- Radiation exposures in space do not result in a uniform whole-body dose distribution
- Radiation exposures are non uniform both with respect to depth and with respect to area or region of the body involved
- The absorbed dose decreases rapidly with the depth in tissue due to the spectral characteristics of the primary sources, especially for solar energetic particle ejections
- The fluxes in space except for SEP events are lower by orders of magnitude which usually are applied to reference experiments on Earth.
- In interplanetary space the irradiation of the body by galactic cosmic radiation is chronically. The flux will vary on a long term scale within the solar cycle.

Radiobiological Aspects of the Space Radiation Field

- There are solar particle events, which are irregular and unpredictable with time scales in the order of hours to days.
- Radiation of a huge range of energies impinge on the body and becomes scattered, fragmented and degraded in energy as it penetrates to the deeper organs.
- The linear energy transfer (LET) as well as dose and dose rate change with depth. All three are factors that influence the biological effectiveness, but not necessarily in the same direction.
- Fragmentation leads to an enhancement (build up) of low LET components on the costs of high LET components.
- Low LET protons of high energy produce target fragments with higher LETs. Of particular importance for dose modifications towards higher quality factors is the increase of the number of nuclear disintegration stars with higher multiplicities near the bone marrow in osseous structures.

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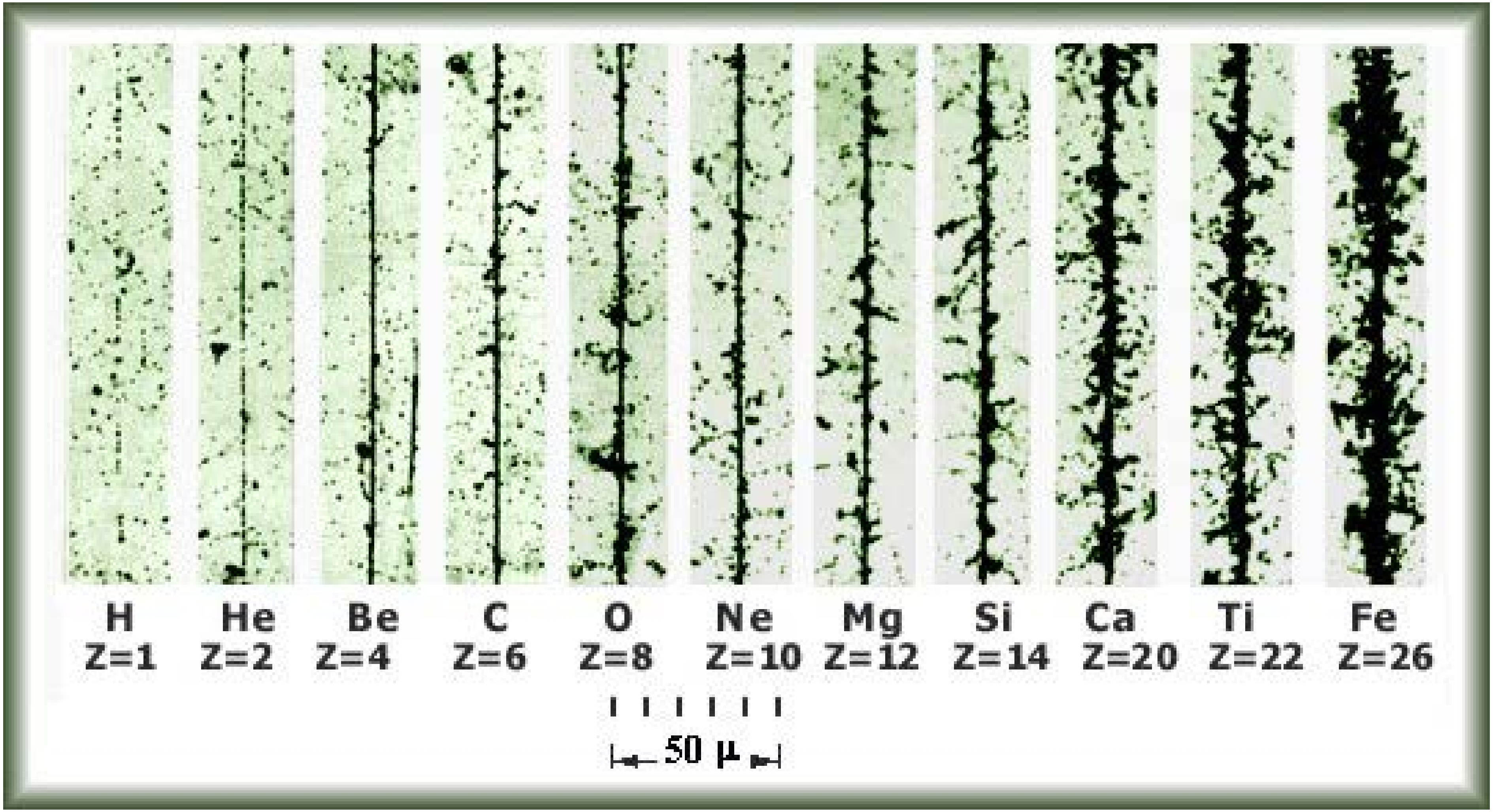
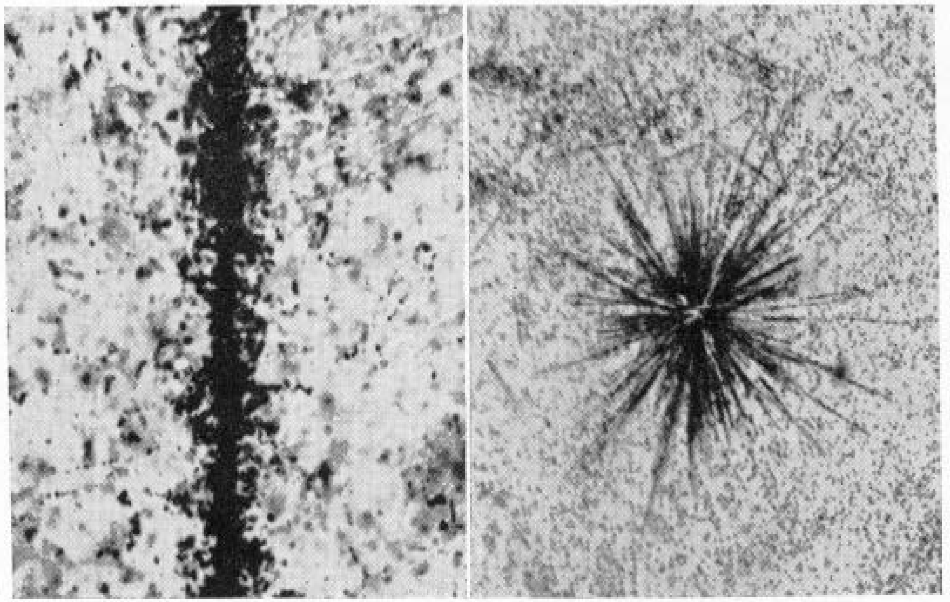
Tracks of Different Ions in Nuclear Emulsions

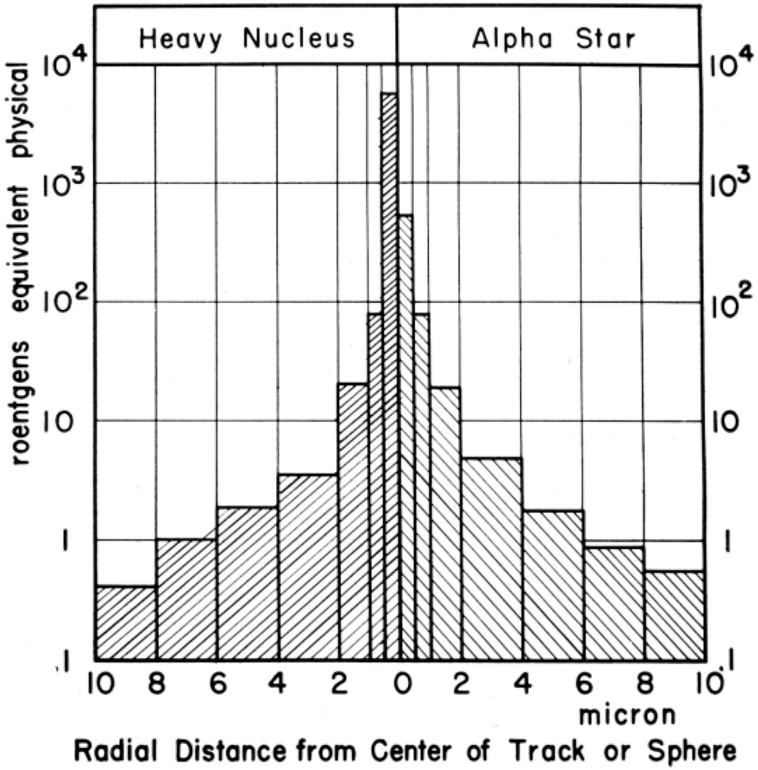


Energy distribution around particle tracks



Photomicrograph of a heavy nucleus track in nuclear emulsion (left),
Microradioautograph of an alpha-active star deposit in rabbit liver tissue (right)

Golden A, Schaefer H J, Microphocal alpha irradiation as a menas of simulating exposure to heavy nuclei of the primary cosmic radiation. Aviation Medicine 27#6(1956)322-327



Radial distribution of ionization dosage of a heavy nucleus track in nuclear emulsion (left), and of an alpha-active star deposit in rabbit liver tissue (right)

Golden A, Schaefer H J, Microphocal alpha irradiation as a menas of simulating exposure to heavy nuclei of the primary cosmic radiation. Aviation Medicine 27#6(1956)322-327

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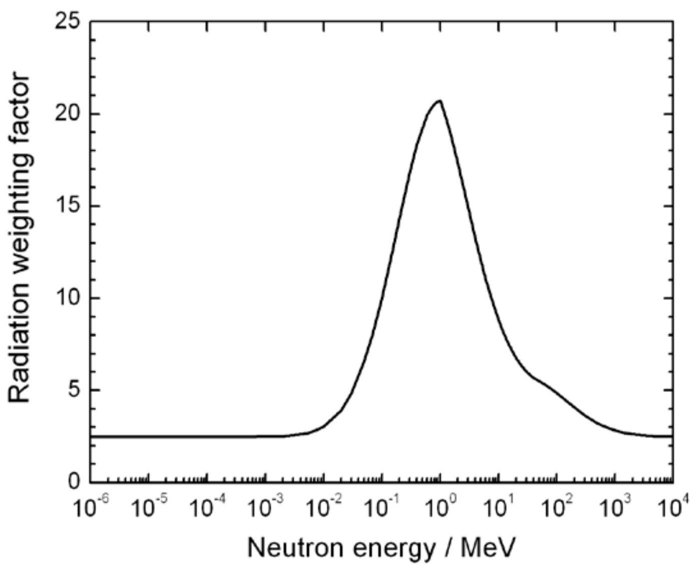
Radiation weighting factors[1], w_R (ICRP, 2007)

Radiation type	**Radiation weighting factor, w_R**
Photons	1
Electrons and muons	1
Protons and charged pions	2
Alpha particles, fission fragments, heavy ions	20
Neutrons	See Figure

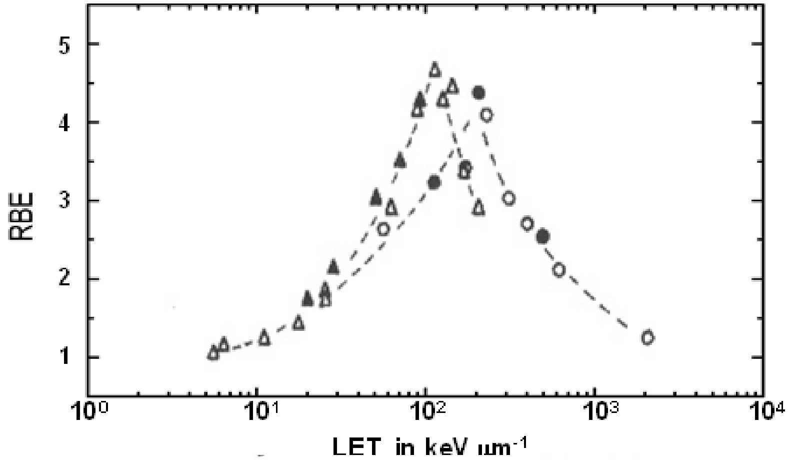


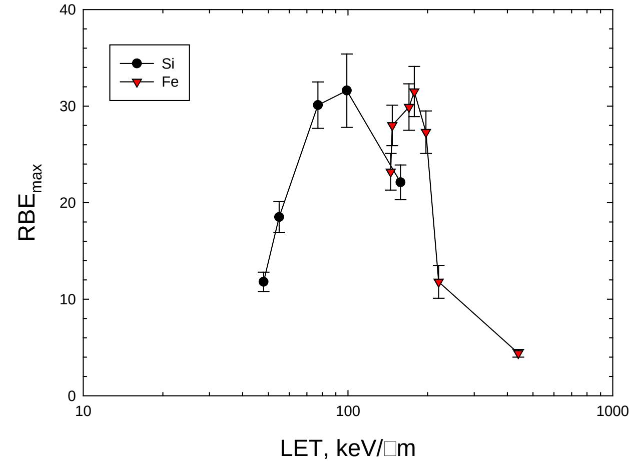
(1) All values relate to the radiation incident on the body or, for internal sources, emitted

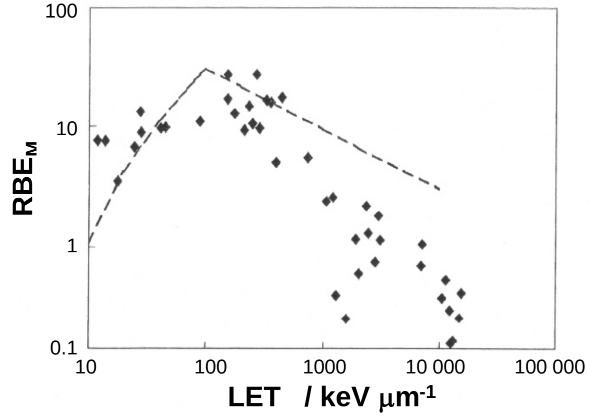
Quality Factor in dependence of LET (ICRP 60, 1991)

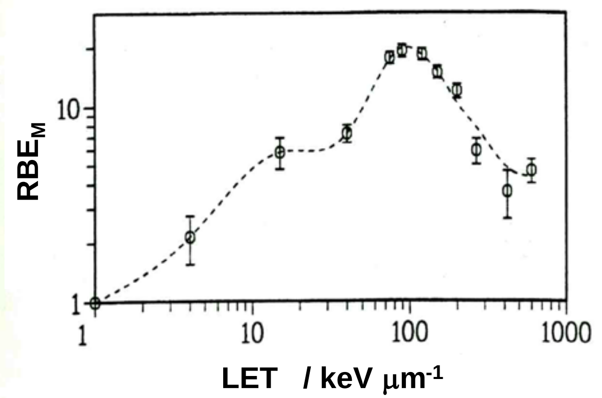
$$Q(L) = \begin{cases} 1 & L < 10\ \mathrm{keV\ \mu m^{-1}} \\ 0.32L - 2.2 & 10\ \mathrm{keV\ \mu m^{-1}} \leq L \leq 100\ \mathrm{keV\ \mu m^{-1}} \\ 300/\sqrt{L} & L > 100\ \mathrm{keV\ \mu m^{-1}} \end{cases}$$

RBE versus LET for deuterons, alpha particles and heavy ions



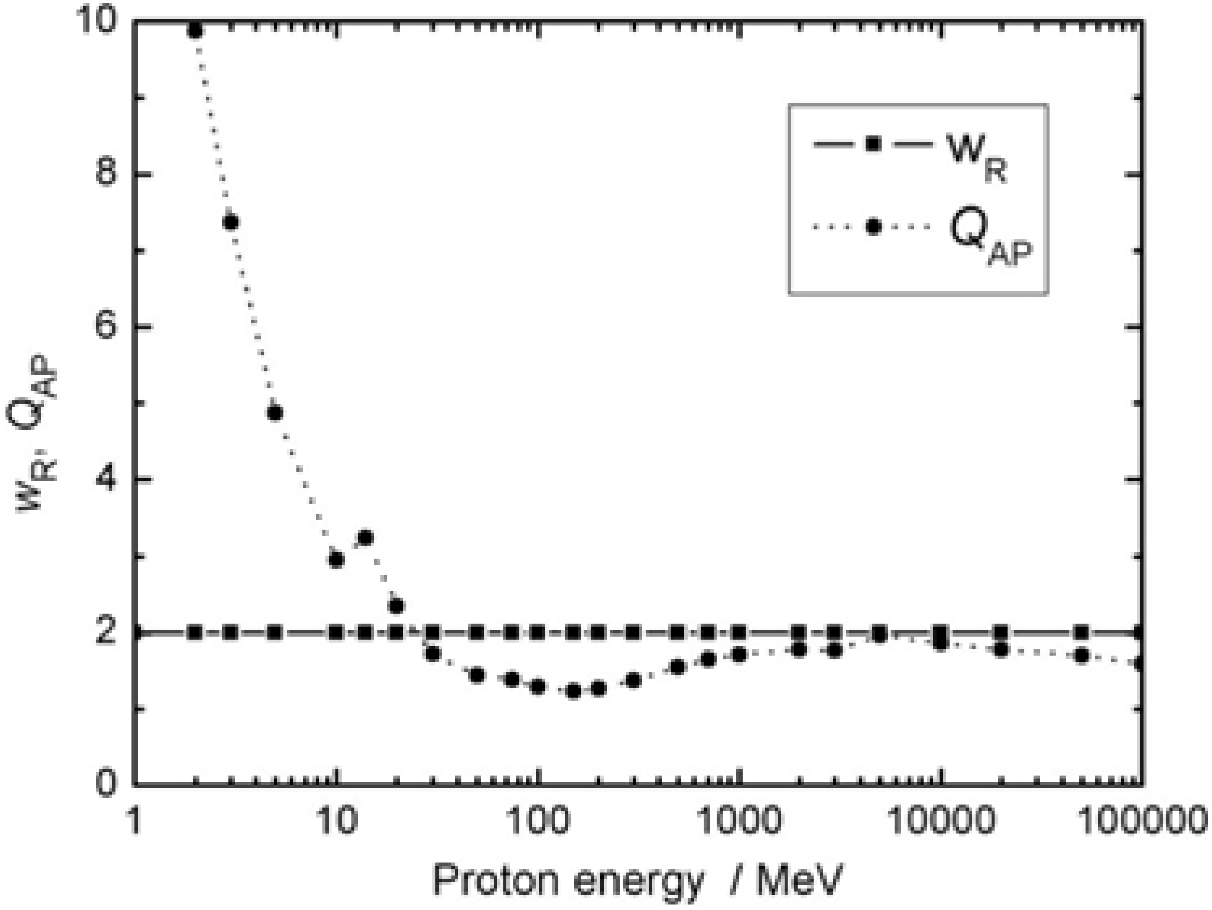




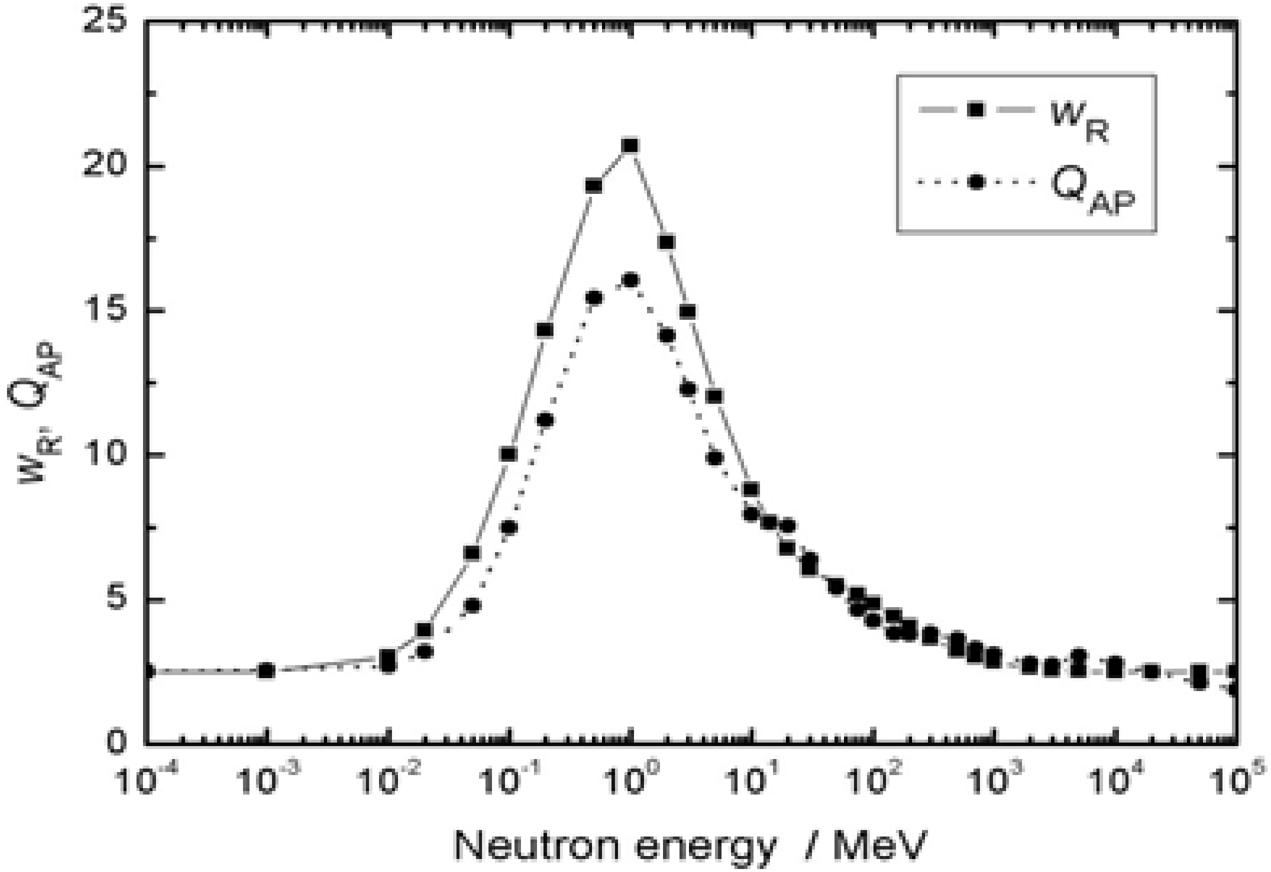


Inactivation V79 and T1 Mammalian cells (Thacker, 1979); chrom. abb. of human lymphocytes (George, 2007); Mutations in Chines Hamster V79 cells (Kiefer, 1999); Transformation in C3H10T1/2 cells (Brenner,1992)

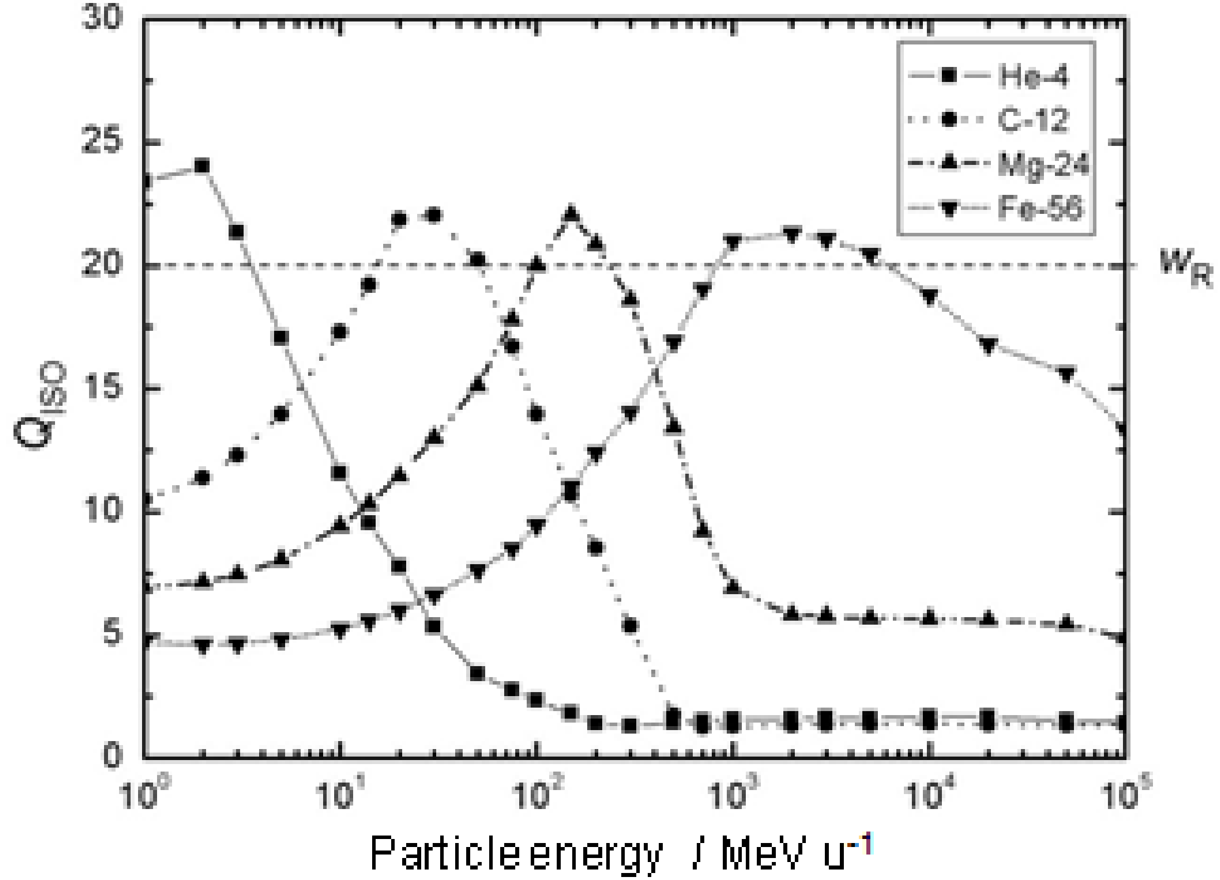
Radiation weighting factor, w_R, and body-averaged mean quality factor, Q_{AP}, calculated for protons (AP incidence) versus proton energy (Sato et al., 2009)



Weighting factor and body averaged quality factor versus neutron energy (Sato et. al 2009)



Radiation weighting factor and body averaged quality factor versus particle energy (Sato et al. 2010)



Approach for Space Application

Protection Quantities

(121) Obviously, $w_R = 20$ does not reflect the variation of RBE with type and energy of heavy ions and the Q-approach is better correlated with the assumption of a general dependence of RBE on LET and possibly on (Z^{*2}/β^2). It is, therefore, recommended to use the term **dose equivalent in an organ or tissue** T, $H_{T,Q}$, defined by

$$H_{T,Q} = Q_T\, D_T \qquad (3.16)$$

with the mean quality factor Q_T in an organ or tissue T for the given radiation field. When using the Q(L) function, Q_T is calculated by

$$Q_T = \frac{1}{m_T D_T} \int_{m_T} \int_{L=0}^{L=\infty} Q(L)\, D_L\, \mathrm{d}L\, \mathrm{d}m \qquad (3.17)$$

with the mass m_T of the organ or tissue considered.

Approach for Space Application

Protection Quantities

(122) If a quality factor is defined by a function Q(Z,E), a mean Q_T-value can be calculated by

$$Q_{\mathrm{T}} = \frac{1}{m_{\mathrm{T}} D_{\mathrm{T}}} \int_{m_{\mathrm{T}}} (\sum_{Z} \int_{E} Q(Z,E) D_{E}(Z,E) \mathrm{d}E \mathrm{d}m$$

or alternatively

$$Q_{\mathrm{T}} = \frac{1}{m_{\mathrm{T}} D_{\mathrm{T}}} \int_{m_{\mathrm{T}}} (\sum_{Z} \int_{L} Q(Z,L) D_{L}(Z,L) \mathrm{d}L \mathrm{d}m$$

(123) Similar to equivalent dose in an organ or tissue, H_T, the value of dose equivalent in an organ or tissue is defined for organs and tissues in males and females by:

$$H_{\mathrm{T,Q}}^{\mathrm{M}} = Q_{\mathrm{T}}^{\mathrm{M}} D_{\mathrm{T}}^{\mathrm{M}} \quad \text{and} \quad H_{\mathrm{T,Q}}^{\mathrm{F}} = Q_{\mathrm{T}}^{\mathrm{F}} D_{\mathrm{T}}^{\mathrm{F}} \qquad (3.19)$$

(124) In most cases the difference of Q_T for males and females is small and a tissue-mean quality factor, Q_T, may be used for both sexes.

Approach for Space Applications

Radiation Protection Quantities

(125) Based on the definition of effective dose, E, the **effective dose equivalent, H_E**, can then be calculated by applying the tissue weighting factors, w_T, as given in ICRP Publication 103 (ICRP, 2007)

$$H_E = \sum_T w_T H_{T,Q} \qquad (3.20)$$

where for $H_{T,Q}$ the mean value from doses for the male and female phantom is chosen.

(127) If a value of the effective dose equivalent is needed H_E should be calculated depending of the sex of the astronaut by:

$$H_E^M = \sum_T w_T H_{T,Q}^M \qquad H_E^F = \sum_T w_T H_{T,Q}^F$$

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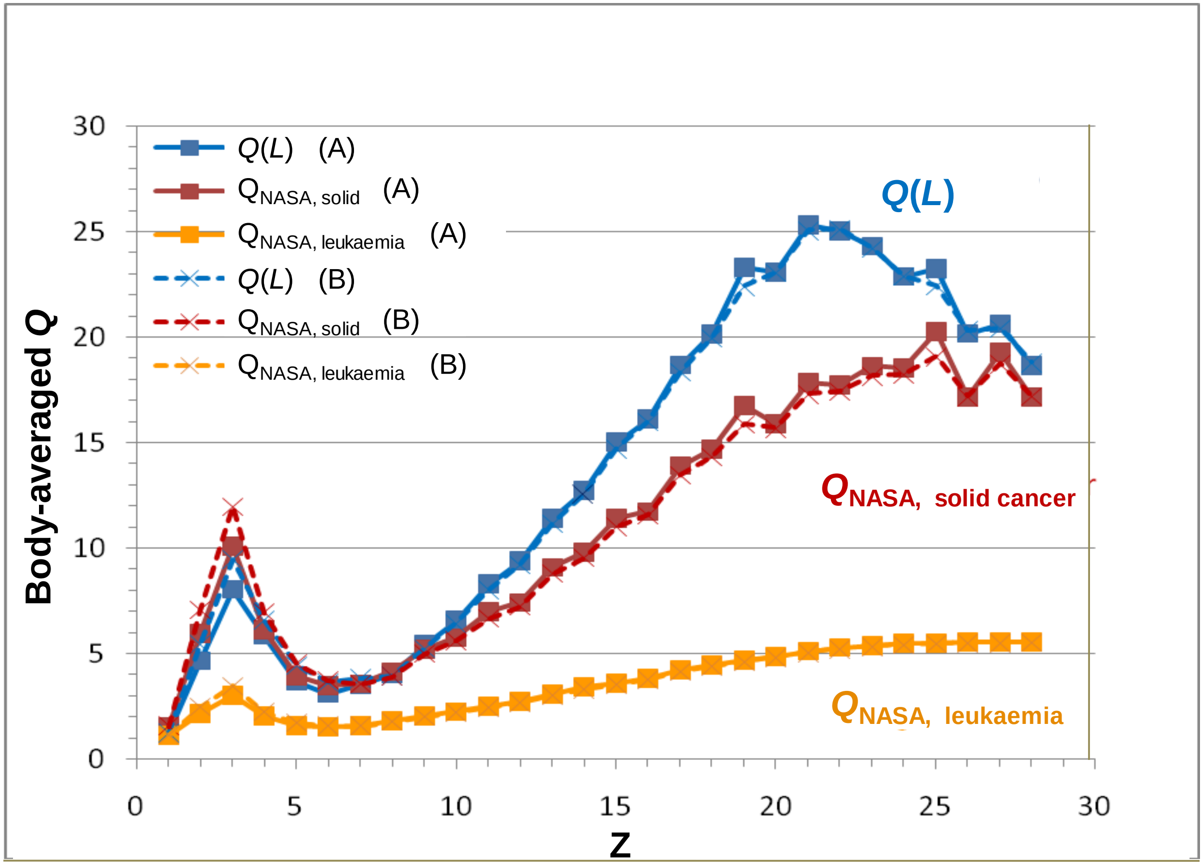
Body averaged Quality Factors



Comparison of body-averaged quality factor values as a function of primary incident particle of charge Z calculated by applying either the ICRP Q(L) function or the NASA quality factors for solid cancers or leukemia for thin or thick aluminum shielding conditions. (A) 5 g/cm2 Al shielding; (B) 20 g/cm2 Al shielding.

Operational Dose Quantities

Task	Operational dose quantities for	
	area monitoring	individual monitoring
Control of effective dose	ambient dose equivalent, $H^*(10)$	personal dose equivalent, $H_p(10)$
Control of doses to the skin, the hands and feet	directional dose equivalent, $H'(0.07, \Omega)$	personal dose equivalent, $H_p(0.07)$
Control of doses to the the lens of the eye	directional dose equivalent, $H'(3, \Omega)$	personal dose equivalent, $H_p(3)$

Approach for Space Applications

Operational Quantities

(131) In radiation fields in space with its large spectrum of different types of particles of very high energies the definition of H*(10) seems inappropriate (ICRP, 2012).

….. no specific dose quantity for area monitoring in space has been defined to date by ICRU or ICRP.

…The monitors used serve mainly as instruments for recording the environmental radiation outside or inside a spacecraft, and for warning in cases of very intensive SPEs. They measure particle fluence, LET distributions, or absorbed doses in detector materials. **These data are used as input or validation data for calculations of doses in the human body.**

Approach for Space Applications

Quantities for low doses

(133) Different quantities and procedures may be applied for an assessment of organ doses or effective dose equivalent. A combination of measurements of absorbed dose and LET-distributions at the surface of the body may become an appropriate way for individual dose assessment. Data from area monitoring within the spacecraft combined with calculated dose conversion coefficients can also be used to calculate organ dose equivalents or effective dose equivalents for persons present in that radiation field (requires fluence and energy distribution of all components).

Quantities for high doses

(136) The mean absorbed dose in an organ or tissue, DT, and the RBE weighted mean absorbed dose, RBE•D_T, when high-LET radiation is involved, is the appropriate quantity for assessing risks of deterministic effects at higher doses. The RBE-value to be chosen may depend on the organ or tissue considered and the specific dose and dose rate as well on the type and severity of the tissue reaction considered. In some cases of deterministic effects, however, not only the mean dose in an organ or tissue but also a local dose in that tissue may become important (e.g. local skin dose).

RBE values my be taken from ICRP Publication 58 (ICRP 1989)

Methods of Measurements of Radiations Fluences and Doses

(145) Mean absorbed doses and dose equivalent in organs and tissues of a human body are generally not directly measurable. An approach to the estimation of these quantities includes

- calculations of particle type and energy and direction distributions of fluence in radiation fields at the location of an astronaut plus the application of organ absorbed dose and dose equivalent conversion coefficients;
- direct assessment of organ absorbed doses and dose equivalents for an astronaut by radiation transport calculation using energy and direction distributions of fluence from outside of the spacecraft, or otherwise, at the astronaut's location; and
- measurement of absorbed dose or dose equivalent near or on the astronaut and the use of results from calculations applying anthropomorphic phantoms.

(146) The main objectives of environmental measurements are the provision of radiation field data of particle types, fluences and microdosimetric quantities, absorbed doses and dose equivalents, using detectors in assemblies of various sizes, both integral and differential (with respect to time, or LET, or energy, or direction, as appropriate) and, in some cases, normalized to calculations of the radiation field components. For personal monitoring, the same quantities might be determined, but more importantly data are required for the determination of absorbed dose and dose equivalent.

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Current Instrumentation on ISS

Active Detectors

- Tissue Equivalent Proportional Counter (JSC)
- IV/EV Charged Particle Directional Spectrometer (JSC)
- DB8 (Liulin Type) (IMBP/STILBAS)
- Altea/Alteino (IFN/Rome Univ.)
- Dosimetry Telescope (DLR/Univ. Kiel)
- TRITEL (KFKI)
- BNT-M (RAS/Energia)

Semi-Active

- Pille TLD System (KFKI)
- BNT Detectors (IBMP/CSA)

Passive detectors

- TLD/OSL (various Labs)
- CR-39 PNTD (various Labs)
- *Bubble Dosemeters (CSA)*

Radiation Field and Doses in the Human Body

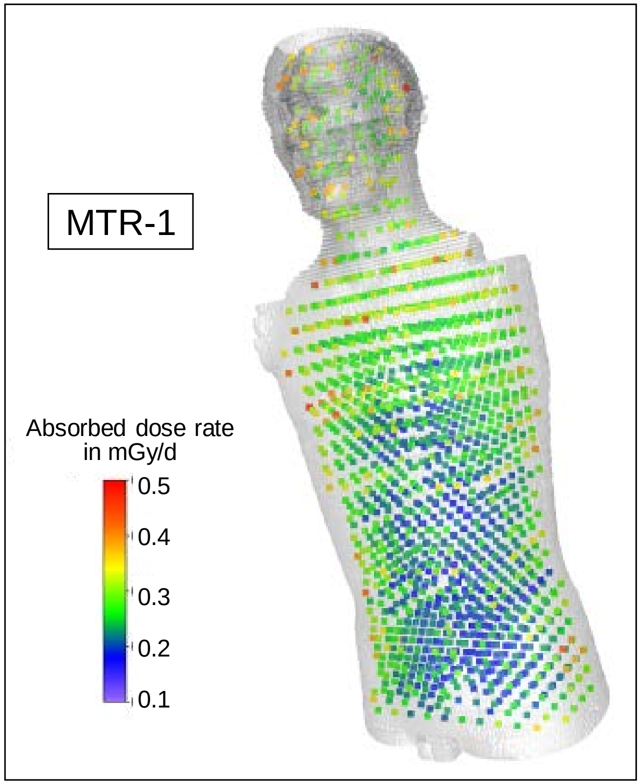
(263) Generally, two different procedures may be applied for the assessment of doses in the human body, either by calculations or by measurements combined with calculations. Radiation field parameters, e. g. particle fluence, particle spectra and LET-distributions, outside or within a spacecraft may be determined either by measurements or calculations and then doses in organs and tissues of the human body may be calculated using particle transport codes. There are two possibilities in performing this task.

- One may either assess the radiation field parameters (e.g. energy distribution of fluence, D(L)-distributions etc.) near to an astronaut and then apply fluence-to-dose conversion coefficients for all types of particles involved for the assessment of organ doses or

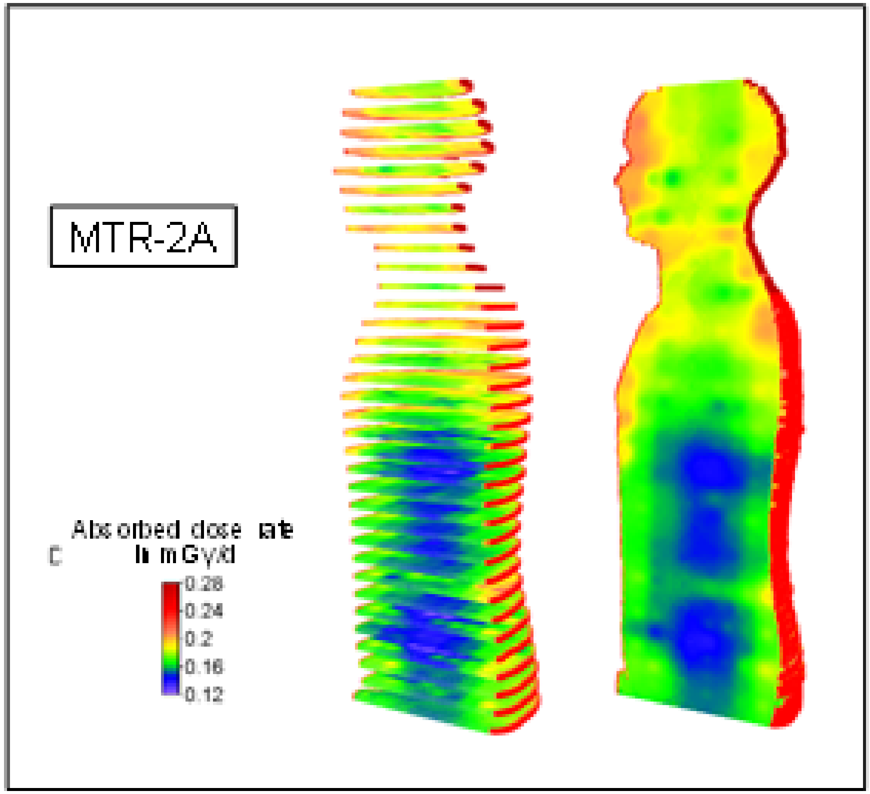
- one can generally calculate organ doses in a body using the radiation field data outside of the spacecraft and a code which combines radiation transport in the spacecraft and in the human body

(264) Alternatively , absorbed dose or dose equivalent may be measured near to to the body of the person, and these values may be directly correlated to doses in the human body.

Measured absorbed dose rate distribution in the MATROSHKA phantom

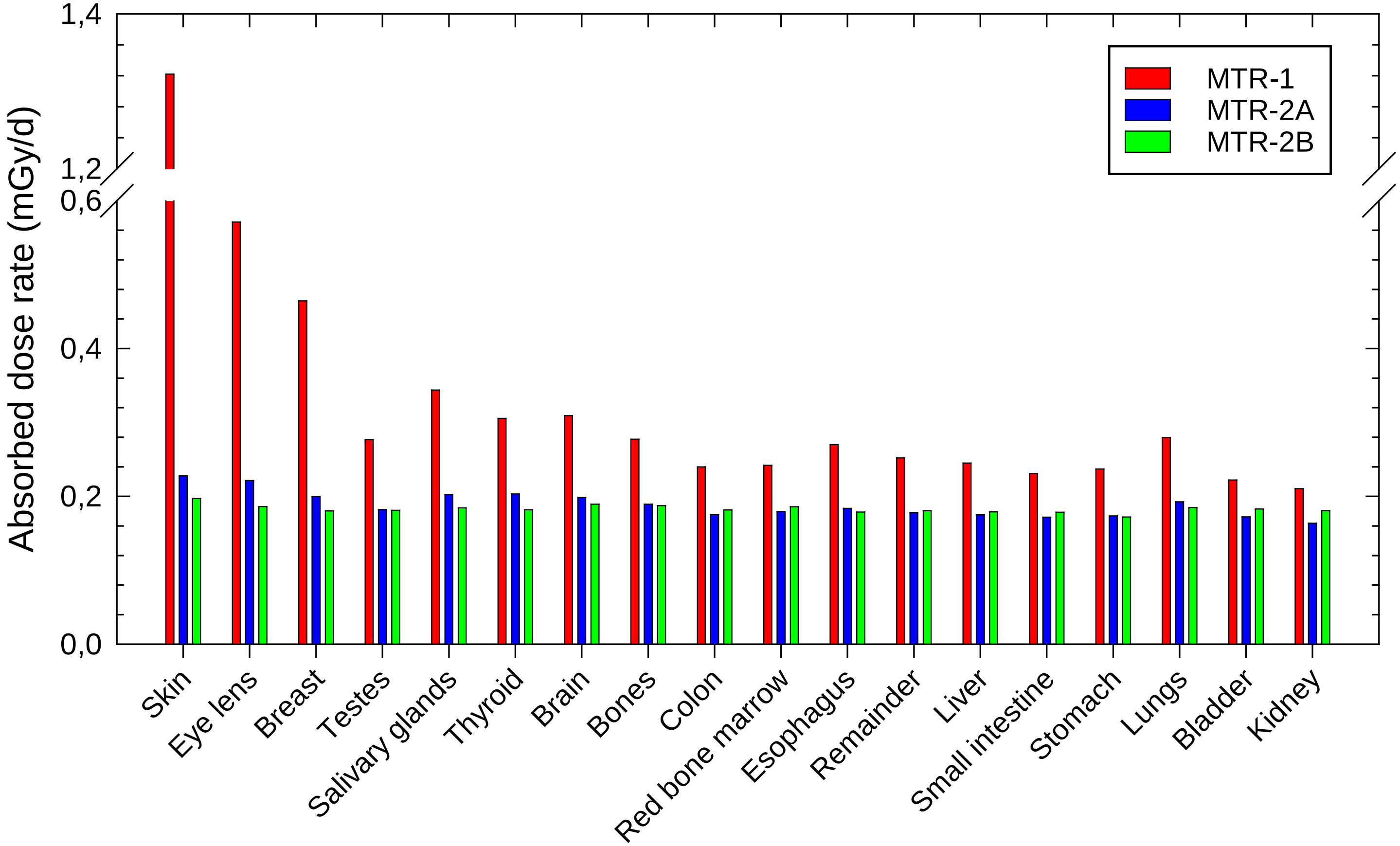


a)

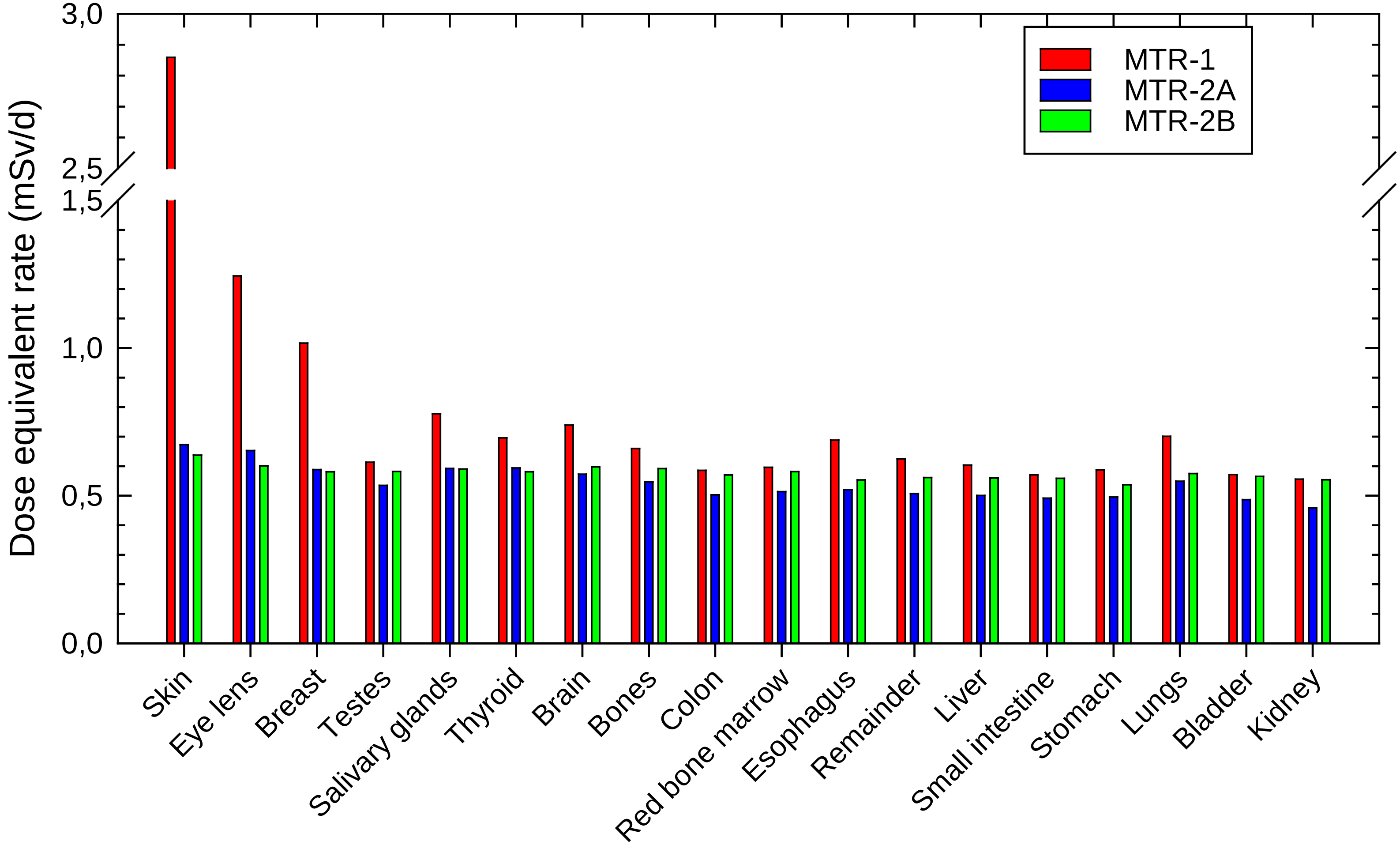


b)

Mean absorbed dose rates in organs and tissues of the MATROSHKA phantom

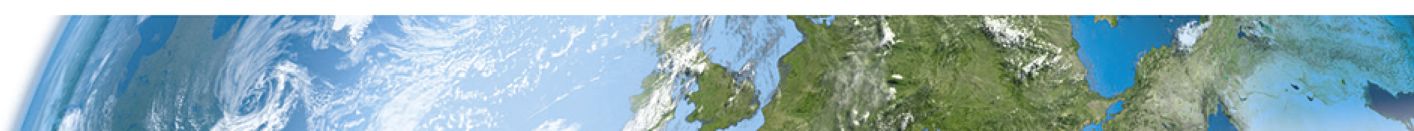


Mean dose equivalent rates in organs and tissues of the MATROSHKA phantom



Organ absorbed dose rates measured by the MATROSHKA experiment outside ISS (Reitz et al., 2009) in comparison with corresponding calculated dose rates obtained from PHITS simulations (Sato et al., 2011).

Organ/Tissue	Measured absorbed dose rate mGy/d	Calculated absorbed dose rate mGy/d
Skin	0.944	1.814
Salivary glands	0.33	0.435
Breast	0.39	0.690
Lung	0.26	0.279
Oesophagus	0.24	0.250
Stomach	0.242	0.245



Operational Radiation Protection in Space

- Preflight Mission design

The design of the flight mission needs to have the aim of reducing radiation exposures in line with optimisation concepts.

- Area Monitoring

Area monitors at well-selected locations in the spacecraft can determine the environmental conditions, and are appropriate for an immediate warning about changing exposure conditions

- Individual Monitoring

The assessment of organ and tissue absorbed doses, together with radiation quality factors, of individual astronauts can be accomplished by calculations using anthropomorphic phantoms or by measurements using personal dosimeters.

- Dose Recording

Astronauts in space are exceptionally exposed and the assessment of their individual exposures should be part of the radiation protection program for space flight.

- Consideration of Uncertainties

There are large uncertainties in projecting cancer risks and the risks of other late effects from ionising radiation on Earth.

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Conclusions I

- The simple concept of considering the differences in radiobiological effectiveness by radiation weighting factors, w_R , e.g. a constant radiation weighting factor of 20 for all heavy ions of all energies, is not appropriate for dosimetry in space and the quality factor (Q) is applied for the definition of the quantity dose equivalent in an organ or tissue of the human body.

- The basis for risk assessments for the astronauts is the dose equivalent in organs and tissues of adult males and females, $H_{T,Q}^{M}$ and $H_{T,Q}^{F}$, which are based on mean absorbed doses, D_T , and mean quality factors in the corresponding organs or tissues, Q_T.

- Conversion coefficients which relate particle fluence to mean absorbed doses in organs and tissues of the human body and corresponding mean quality factors for all types of radiation present in space, are an important data base for the assessment of the exposure of astronauts. For the estimation of radiation risks of astronauts based on mean absorbed doses in the body, an assessment of the uncertainty of D_T and Q_T would be very useful.

- The concept of operational dose quantities for area monitoring of external exposure and an assessment of effective dose is not applicable because many different types of particles are involved with very high energies. Instead the measurement and determination of particle fluence and its distribution in energy and direction is more important and provides a basis for an assessment of doses.

Conclusion II

- Although astronauts are exposed to ionising radiation during their occupational activities, they not usually classified as being occupationally exposed in the sense of the ICRP system for radiation protection of workers on Earth and aircraft crews.
- Thus, for a specific mission reference levels for risks or doses may be selected at appropriate levels, and no dose limits may be applied for a given mission.