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PROTECTION FROM COSMIC RADIATION IN LONG-TERM MANNED SPACEFLIGHTS

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ABSTRACT

Current space programs are shifting toward planetary exploration and in particular towards human missions to the moon and Mars. Space radiation, comprised of energetic protons and heavy nuclei, has been shown to produce distinct biological damage compared to radiation on Earth, leading to large uncertainties regarding the projection of health risks. Even if uncertainties in risk assessment are reduced in the next few years, there is little doubt that appropriate countermeasures will have to be taken to reduce the exposure or the biological damage produced by cosmic radiation. In addition, it is necessary to provide effective countermeasures against solar particle events which can have acute, even life threatening effects on inadequately protected crews. Unfortunately, passive (bulk) shielding is currently unable to provide adequate protection because cosmic rays have very high energy and nuclear fragmentation in the absorbers produce light fragments. Material science could provide new materials with better shielding properties for space radiation. Active (magnetic) shielding could be an interesting alternative pending technical improvements.

Keywords: *spaceflight, space radiation, protection*

ZAŠČITA PRED KOZMIČNIM SEVANJEM MED DOLGOTRAJNIMI ČLOVEŠKIMI POLETI V VESOLJE

IZVLEČEK

Aktualni vesoljski programi se dandanes osredotočajo predvsem na raziskovanje planetov in še posebej na človeške misije na Luno in Mars. Sevanje v vesolju, ki vključuje energijske protone in težka jedra, ustvarja izrazito biološko škodo v primerjavi s sevanjem na Zemlji, kar pomeni, da obstaja kar nekaj nejasnosti glede dokazov o tveganju za zdravje. Četudi se bodo te nejasnosti na področju ocene tveganj v naslednjih letih lahko zmanjšale, obstaja dvom, da bo potrebno izvajati ustrezne protiukrepe, ki bi pomagali zmanjšati izpostavljenost oziroma biološko škodo, ki jo povzroča kozmično sevanje. Poleg tega je prav tako potrebno omogočiti učinkovite protiukrepe na področju sončnih delcev, ki imajo lahko akutne oziroma celo smrtno nevarne učinke na nezadostno zaščitene ekipe astronavtov. Na žalost pasivna (obsežna) zaščita ne omogoča zadostnega varovanja, saj imajo kozmični žarki zelo visoko energijo, nuklearna fragmentacija v blažilnikih pa ustvarja svetlobne fragmente. Stvarna znanost bi lahko ponudila nove materiale z boljšimi zaščitnimi lastnostmi, ki so potrebne na področju sevanja v vesolju. Aktivna (magnetna) zaščita bi lahko predstavljala zanimivo alternativo, ki še čaka na tehnične izboljšave.

Ključne besede: *poleti v vesolje, sevanje v vesolju, zaščita*

INTRODUCTION

When human space exploration started over 40 years ago, it was soon recognized that space radiation represented a potential hazard for the crews (Maalouf, Durante & Foray, 2011). As a matter of fact, astronauts are exposed to galactic cosmic radiation (GCR) in space at a dose rate substantially higher than on Earth. Current plans for manned space exploration require longer and longer sojourns of astronauts in space (Figure 1). For long-term interplanetary missions such as a Mars mission, doses can exceed maximum recommended limits (Cucinotta & Durante, 2006).

In deep space human beings are exposed to protons and high energy and charge (HZE) ions in the GCR, along with secondary radiation including neutrons and recoil nuclei produced by nuclear reactions in spacecraft or tissue. Practically all nuclides are present in the GCR, although elements heavier than nickel (Z=28) are so rare that they do not provide a significant risk to crews. The energy spectrum of the GCR peaks near 1 GeV/nucleon, and consequently these particles are so penetrating that shielding can only partially reduce the doses absorbed by the crew.

Figure 1: Concept of a future Mars base. Current plans of space agencies (NASA, ESA, China, and Russia) put emphasis on planetary exploration. In a permanent Mars base, crews will have access to a greenhouse for growing their own fresh vegetables. Cosmic radiation is a major hindrance to this plan, both because of the exposure during the long interplanetary travel, and of the high background rate on the planet's surface (about 100-fold the Earth's background). Image credit: NASA Glenn Research Center ImageNet.

In traveling to Mars, every cell nucleus within an astronaut would be traversed by a proton or secondary electron every few days, and an HZE ion about once per month (Cucinotta & Durante, 2006). Whole body doses of 1–2 mSv/day accumulate in interplanetary space and approximately half this value on planetary surfaces. The large ionization power of HZE ions makes them the major contributor to the risk in spite of their lower cell nucleus hit frequency than protons (Figure 2). Iron alone (Z=26) provides approximately the same dose equivalent of the protons in deep space.

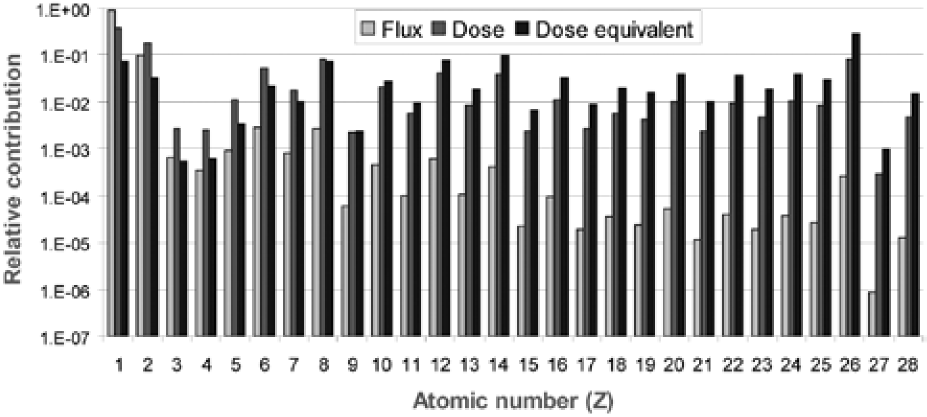

Figure 2: Relative contribution of different ions to flux, dose, and dose equivalent from galactic cosmic radiation. Nuclei heavier than nickel are very rare. Calculation by HZETRN kindly provided by Dr. Frank Cucinotta and Dr. Cay Zeitlin.

Major uncertainties on space radiation risk estimates (Durante & Cucinotta, 2008) are associated with the poor knowledge regarding the biological effects of HZE particles, with a smaller contribution coming from the characterization of space radiation field and its primary interactions (Figure 3). The goal of the NASA Space Radiation Health Program is to reduce these uncertainties to less than ±50% within the year 2023 (NASA, 1998). This ambitious goal can be fulfilled only by an international co-operative effort in the field of radiation physics, biology, and medicine.

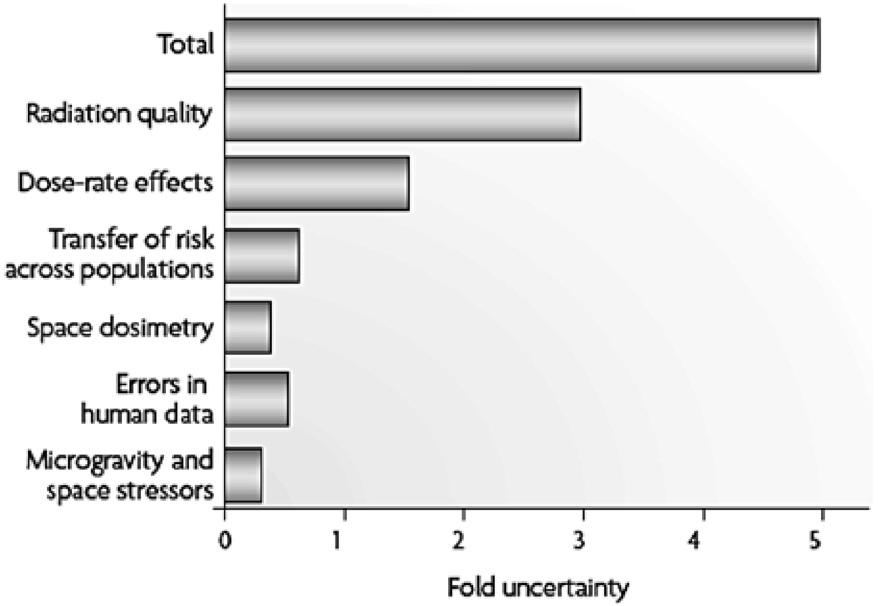

Figure 3: Estimates of uncertainties in projecting cancer risks for space and terrestrial exposures. Several factors such as radiation quality effects, space physics, and microgravity do not contribute on Earth and lead to large increases in risk projections. Predicting risks to individuals is difficult as there are very few quantitative measures of individual sensitivity. Only a select few individuals enjoy space travel and projecting risks for a few selected individuals rather than populations will be of utmost importance for space missions to Mars. The extrapolation from experimental models to humans is perhaps the greatest challenge to cancer risk assessments. Plot from Cucinotta et al. (2000).

Even if risk of uncertainties will be reduced in the next few years, there is little doubt that appropriate countermeasures have to be taken to reduce the exposure or the biological damage produced by radiation. In all basic radioprotection textbooks, it is clearly stated that there are three means to reduce exposure to ionizing radiation: increasing the distance from the radiation source, reducing the exposure time, and by shielding. Distance is not an issue in space, being space radiation isotropic. Time in space should be increased rather than decreased according to the plans of exploration and colonization. Shielding remains the only feasible countermeasure. Other strategies can be effective in reducing exposure or the effects of irradiation in space. These strategies include the choice of an appropriate flight time, i.e. mission planning and ability to predict solar particle events (SPE); the administration of drugs or dietary supplements to reduce the effects of radiation and a crew selection based on genetic screening (Durante & Cucinotta, 2008).

In this paper, we will concentrate on the impact of shielding on space radiation protection. Recent reviews on risk and countermeasures are found in ref. (Cucinotta & Durante, 2006) and (Durante & Cucinotta, 2008).

SHIELDING

For terrestrial radiation workers, additional protection against radiation exposure is usually provided through increased shielding. Unfortunately, shielding in space is problematic, especially when GCR is considered. High-energy radiation is very penetrating: a thin or moderate shielding is generally efficient in reducing the equivalent dose, but as the thickness increases, shield effectiveness drops. This is the result of the production of a large number of secondary particles including neutrons caused by nuclear interactions of the GCR with the shield. These particles have generally lower energy, but can have higher quality factors than incident cosmic primary particle.

NASA is using the analytical code HZETRN coupled with NUCFRG2 (Wilson et al., 1995), developed at the Langley Research Centre, to estimate GCR doses in different shielding configurations for the International Space Station (ISS) and Mars mission. The HZETRN code calculates the straight-ahead particle transport along 512 different rays converging on the point x, and provides as output the energy spectra of the charged particles in the point x within the ISS module or the astronaut's body.

The relative attenuation of the dose equivalent H(x) produced by GCR or trapped protons at solar minimum as a function of the thickness x (in g/cm^2) of different shield materials as calculated by HZETRN is given in Figure 4 (Cucinotta, Wilson, Williams & Dicello, 2000), assuming one year exposure. Low-Z shields, including water, provide satisfactory protection for trapped protons in low-Earth orbit (LEO). However, for GCR the shield effectiveness increases slowly for thickness exceeding 10 g/cm^2. Even very thick shields of polyethylene are unable to reduce the GCR dose below approximately 50% of the unshielded value.

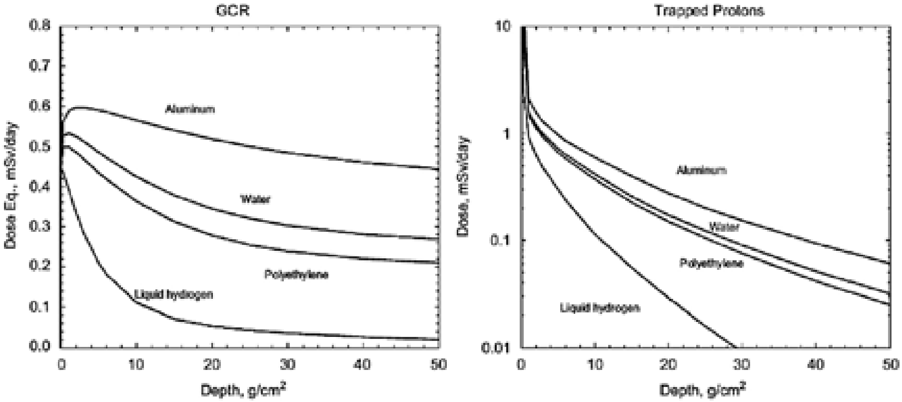

Figure 4: Dose calculations in dependence of shielding thickness for different shielding materials in the ISS orbit for solar minimum conditions. Left, galactic cosmic radiation; right, trapped protons in LEO. Shielding is effective for the low-energy trapped protons, while it is far less useful for GCR, especially when heavy materials are used. Calculations by NASA using HZETRN code, plots from reference Durante et al.(2010).

Liquid hydrogen appears to have the maximum performance as shield material. Unfortunately, hydrogen is not a practical shield material, being a low temperature liquid. Hydrogen storage in graphite nanofibers or lithium hydride (6LiH) may have a large impact in space shield design. So far, it appears that polyethylene could be a good compromise.

Simulation of space radiation at accelerators represents a useful tool for shielding material testing. Heavy ions at energies >1 GeV/n represent in fact a reasonable proxy of the heavy-ion component in the GCR (Guetersloh et al., 2006). The attenuation in doses achieved with thin shields is in fact qualitatively and quantitatively similar to what would be expected in space, and different materials can be easily compared for their effectiveness in shielding HZE particles. The large database collected by the Lawrence Berkeley Laboratory group is summarized in reference (Zeitlin, Guetersloh, Heilbronn & Miller, 2005). Figure 5 shows recent measurements of the Bragg curves of 1 GeV/n Fe-ions in different materials: polyethylene, aluminum, Kevlar and Nextel (Lobascio et al., 2008). These latter two materials are widely used to protect human space infrastructures from meteoroids and debris impacts in low-Earth orbit, both for rigid pressurized modules (such as Columbus on the ISS) and in inflatable space modules. The initial decrease in dose is caused by projectile fragmentation, of which the cross section per unit target mass AT is approximately proportional to AT-1/3. The percentage dose reduction dD per unit thickness (in g/cm^2) can be calculated from the initial slope of the Bragg curve by extrapolation at zero depth, and this value is close to that expected for galactic HZE nuclei in space (Guetersloh et al., 2006). The data show that: i) the initial decrease in dose is more pronounced for HDPE, followed by Kevlar, Nextel, and finally Al; ii) the minimum dose before the Bragg peak is the lowest for HDPE and the highest for Al; and iii) the Bragg peak is found first in HDPE, then in Kevlar, Nextel and finally in Al (Lobascio et al., 2008).

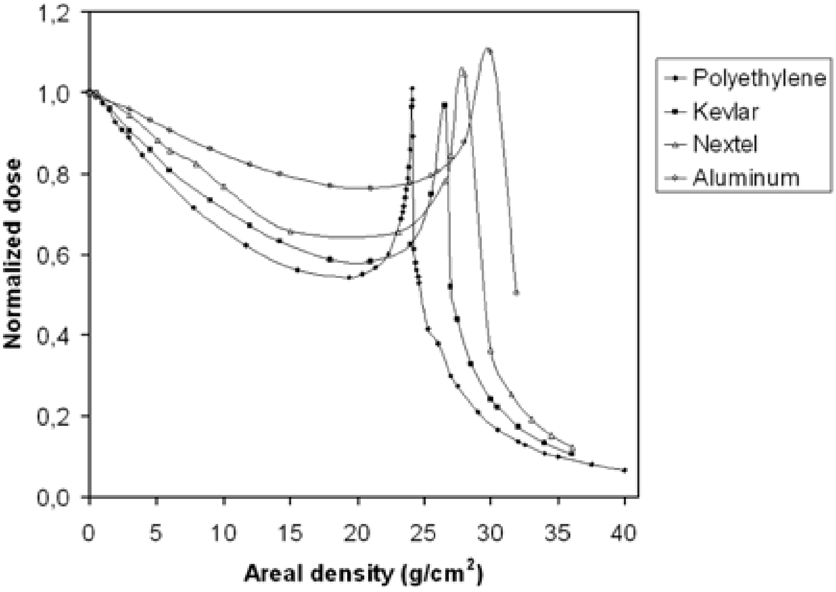

Figure 5: Bragg curves of 1 GeV/n ^{56}Fe-ions measured in polyethylene, Kevlar, Nextel, and aluminum. The beam was accelerated at the NASA Space Radiation Laboratory at the Brookhaven National Laboratory (Upton, NY, USA). Dose was measured by a egg chamber and is normalized to the value measured without shielding. Lines connect the data points. Data from Maalouf et al. (2011).

Accelerator-based tests are useful tools for comparing different shielding configurations to be used in space, and simulations suggest that using heavy ions at energies higher than 1 GeV/n will provide better quantitative simulations of the galactic heavy nuclei [7]. These very high energies will be available in the FAIR facility currently under construction at GSI in Germany (Durante, Reitz & Angerer, 2010).

Based on the results of tests and simulations, NASA has added polyethylene slabs in the crew sleeping quarters on ISS (Figure 6). Dose measurements were consistent with the expected dose reduction of around 20% in the shielded area (Shavers et al., 2004). In-flight tests are also under way on the ISS using the detector ALTEINO and shield blocks in polyethylene, Kevlar and Nextel (Figure 7) (Casolino et al., 2007). Research in the field of shielding is likely to have quick applications on ISS and for the mission to the moon.

Figure 6: Polyethylene panels installed in the crew sleeping quarters of ISS. Picture from NASA, Office of Biological and Physical Research.

Figure 7: The detector ALTEINO on the ISS during the ENEIDE mission in 2005. On top of the active detector it is visible a blue bag containing polyethylene, Kevlar, and Nextel shield blocks, and passive TLD detectors (ESCHILO tiles). Photo from Spillantini et al. (2007), courtesy of Dr. Marco Casolino (INFN, Rome, Italy).

ACTIVE SHIELDING

An attractive alternative to passive, bulk material shielding is the use of electromagnetic fields to deflect the charged particles from the spacecraft target (Figure 8). Several investigations started in the 60's using 4 different approaches (Townsend, 2001):

I. electrostatic fields; II. plasma shielding; III. confined magnetic fields;
IV. unconfined magnetic fields.

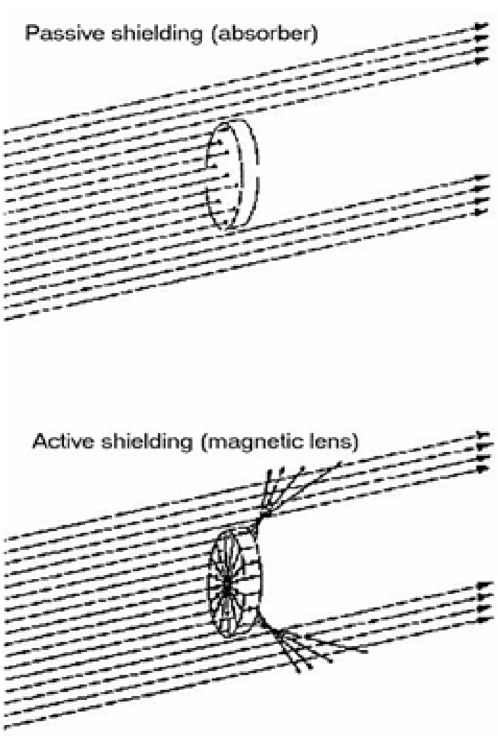

Figure 8: Protection from a directional solar particle event provided by passive shielding or defocussing magnetic lens [14]. For an equivalent Al absorber of 3,350 kg (upper part) the mass of the magnetic lens is below 1,100 kg (700 kg with 3 coils; 900 kg with 4 coils). Besides, in the passive shielding configuration, secondary fragments are unavoidably transmitted through the absorber. Image courtesy of Dr. P. Spillantini (Wilson et al. (1995)).

Most of the studies were dealing with active shielding on the shield against electrons and protons, especially in case of SPE. Active shielding against HZE particles from GCR is practically impossible by electrostatic fields. In fact, electrostatic potentials needed to deflect swift heavy ions from the GCR should be enormous, and this limitation also applies to plasma shielding that deflects positively charged particles by the electric field. Confined magnetic fields involve the use of concentric spheres and superconducting wires to obtain a strong magnetic field in a restricted volume surrounding the spacecraft. This configuration can be effective for protons up to 200 MeV, but is almost ineffective against GCR.

Unconfined magnetic field configurations typically involve a cylindrical or toroidal-shaped spacecraft having a dipole-like magnetic field, generated by an electric current through coils or the spacecraft skin. Since the Earth's magnetic field is clearly a very effective shield for solar and galactic radiation, some protection would be expected from an unconfined magnetic field against both SPE and GCR.

Protection by magnetic lenses from solar protons would be relatively easy in case of directional SPEs. However, detailed knowledge of the angular distribution of the SPE is very difficult to achieve. A non-directional active shield would be preferable, especially since it might protect against the isotropic GCR component. A solenoidal field of intensity around 2 T in a 1 m sheath around the module may provide good protection against most of the SPE, but poor protection against GCR (Spillantini et al., 2007). Perhaps the toroidal configuration has some advantages for GCR shielding, because the magnetic field reaches its maximum intensity in the internal volume, where magnetic forces can be better supported, and has smaller intensity in the outer part of the system where the large radius would require heavy structures to support the magnetic pressure of a very strong field.

As yet, magnetic shelters do not appear to be feasible for space radioprotection. However, technological progress in the field of high-temperature superconductors may provide a large impact in this field.

CONCLUSIONS

Passive or active shielding appear the best methods to protect crews of long-term space missions and humans living in the space (Durante & Cucinotta, 2011). Such countermeasures may not be necessary for a lunar base, but will likely be needed for the Mars mission, and most definitely for exploring Jupiter or Saturn's moon Titan or the nearby satellites (Durante & Cucinotta, 2008). Shielding with light, hydrogen-rich materials may substantially reduce the equivalent dose in space, but it is clear that more research in the radiobiology of heavy ions is needed to fully solve the problem. In fact, as shown in Figure 9, the shielding needed to reduce the risk to an acceptable level is controversial, because the uncertainty of the risk estimates is too high. Current radiobiology research programs sponsored by NASA at the Brookhaven National Laboratory

(USA) and by ESA at GSI (Germany) should provide the necessary knowledge for safe colonization of the Solar system.

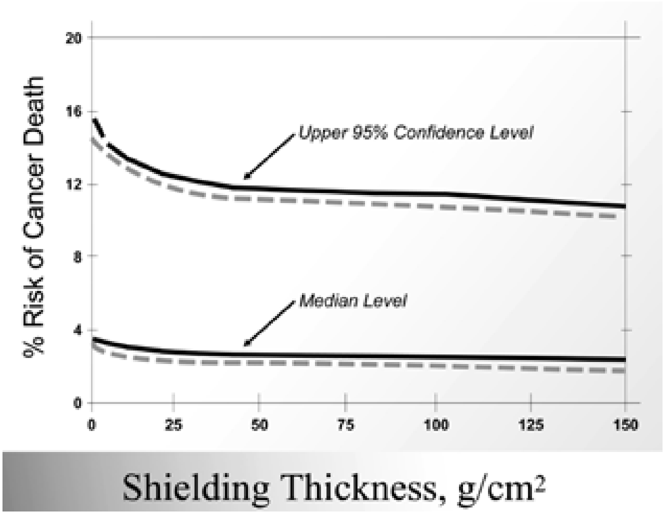

Figure 9: Cancer risk for a mission to Mars as a function of the mass thickness of shielding materials, after considering the tissue shielding of the human body. Black and red lines represent water and aluminium shield, respectively. Lower curves are median estimates, and upper curves provide the upper 95% confidence limits. This calculation shows that even very heavy shields will not be able to reduce the risk by a large factor, and the uncertainty on the risk makes it difficult to plan the shielding needed for the mission. Plot Cucinotta et al. (2000).

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