1-1-2005

Radiation exposure and mission strategies for interplanetary manned missions

C Cougnet
Eads Astrium Sas, Av. Des Cosmonautes

N Crosby
Belgian Institute for Space Aeronomy

C Foullon
Belgian Institute for Space Aeronomy

D Heynderickx
Belgian Institute for Space Aeronomy

S Eckersley
Eads Astrium Ltd

See next page for additional authors

Recommended Citation

Cougnet, C; Crosby, N; Foullon, C; Heynderickx, D; Eckersley, S; Guarnieri, V; Lobascio, C; Masiello, S; Parodi, P; Perino, M A.; Rampini, R; Guatelli, Susanna; Pia, Maria G.; Holmes-Siedle, A; Nieminen, P; Parisi, G; Tamburini, V; Spillantini, P; and Tracino, E: Radiation exposure and mission strategies for interplanetary manned missions 2005, 279-285.
https://ro.uow.edu.au/engpapers/4976

Authors

C Cougnet, N Crosby, C Foullon, D Heynderickx, S Eckersley, V Guarnieri, C Lobascio, S Masiello, P Parodi, M A. Perino, R Rampini, Susanna Guatelli, Maria G. Pia, A Holmes-Siedle, P Nieminen, G Parisi, V Tamburini, P Spillantini, and E Tracino

Earth, Moon, and Planets (2005) 94: 279–285
DOI 10.1007/s11038-005-9014-1

RADIATION EXPOSURE AND MISSION STRATEGIES FOR INTERPLANETARY MANNED MISSIONS (REMSIM)

C. COUGNET
EADS Astrium SAS, Av. des Cosmonautes, 31-31402, Toulouse Cedex 4, France

N. B. CROSBY, C. FOULLON[†] and D. HEYNDERICKX
Belgian Institute for Space Aeronomy, Ringlaan Av. Circulaire 3 1180, Brussels, Belgium

S. ECKERSLEY
EADS Astrium Ltd, Gunnels Wood Rd., Stevenage, SG1 2AS Hertfordshire, England

V. GUARNIERI, C. LOBASCIO*, S. MASIELLO, P. PARODI, M. A. PERINO and R. RAMPINI
Alenia Spazio S.p.A., Strada Antica di Collegno, 253 10146, Torino, Italy

S. GUATELLI and M. G. PIA
INFN, Sezione di Genova, Via Dodecaneso 33 16146, Genova, Italy

A. HOLMES-SIEDLE
REM Oxford Ltd., 64A Acre End St., Eynsham, OX29 4PD Oxford, England

P. NIEMINEN
ESA, ESTEC Keplerlaan 1, 2200, AG Noordwijk ZH, The Netherlands

G. PARISI and V. TAMBURINI
RxTec S. a. S., Piazza G. Alessi 2/2 A 16128, Genova, Italy

P. SPILLANTINI
INFN, Sezione di Firenze, Largo E. Fermi 2 50125, Firenze, Italy

E. TRACINO
Università del Piemonte Orientale, Via Bellini 25/G 15100, Alessandria, Italy

(Accepted 26 May 2005)

Abstract. Cosmic radiation is an important problem for human interplanetary missions. The ‘‘Radiation Exposure and Mission Strategies for Interplanetary Manned Missions–REMSIM’’ study is summarised here. They are related to current strategies and countermeasures to ensure the protection of astronauts

---

* Corresponding author: E-mail: cesare.lobascio@aleniaspazio.it
[†] Present address: University of Warwick, Coventry, U.K

from radiation during interplanetary missions, with specific reference to: radiation environment and its variability; radiation effects on the crew; transfer trajectories and associated fluences; vehicle and surface habitat concepts; passive and active shielding concepts; space weather monitoring and warning systems.

Keywords: Active shield, astronaut, dose, GCR, Geant4, inflatable, radiation protection, shielding, SPE

1. Introduction

Human interplanetary missions are widely considered the next logical step in the worldwide cooperation for space exploration, after the Low Earth Orbit (LEO) based International Space Station. Scientific motivations include the search for extraterrestrial life, in particular on Mars, given the recent indication of the presence of water. Inspirational, technological, cultural and economic considerations are key factors for this extremely challenging endeavour. The European Space Agency (ESA) is planning robotic and human exploration of the Solar System as part of the Aurora Programme (Aurora). The protection of astronauts from cosmic radiation is recognised as an enabling aspect for Aurora missions: without the protection of Earth's magnetic field, inhabited spacecraft are exposed to much more severe levels of radiation than in LEO (Benton and Benton, 2001; Holmes-Siedle and Adams, 2002) and require more extreme radiation protection countermeasures. Following the recommendations of the ESA study HUMEX (Harris, 2003), strategies for radioprotection in Aurora human missions were elaborated in the REMSIM project, providing greater insight into this important and complex domain.

2. The Space Environment in Interplanetary Missions

The space radiation environment is the result of components of different origin: solar X-rays, particles from solar events, Jovian electrons and X-rays, cosmic ray protons, α particles and heavier ions, galactic X-rays, γ-rays and electrons.

Among the radiation environment components, it is widely recognized that Galactic Cosmic Rays (GCRs) and Solar Particle/Proton Events (SPEs) can produce harmful effects on astronauts (Nieminen, 1999). The effect of these components was evaluated in the REMSIM study in various mission scenarios; in a conservative approach, the worst cases of GCRs and SPEs were considered as input to the simulations for radioprotection studies in human missions to the Moon and Mars. Since the solar magnetic field significantly influences the GCR background, the solar modulation of the GCR background (also called the Forbush effect) is lowest in solar minimum, hence the higher penetration.

Under such conservative assumptions, the worst cases were identified as the condition of solar minimum activity using 1977 GCR fluxes, and the envelope of the events registered in October 1989 and August 1972 for SPEs.

3. Evaluation of Radiation Damage to Humans

The exposure to the space radiation environment can produce harmful stochastic and deterministic effects in humans, like cancer (Cucinotta et al., 2001). Recommendations from reviews of existing literature and from the legislation of various countries were studied to define dose equivalent limits for a mission to Mars (Lobascio et al., 2004b); they are summarised in Table I. Considering the availability of a radiation warning system described in Section 5, we introduced the warning thresholds to allow countermeasure application before reaching the dose limits.

Mission limits, valid for elder crew (male above 35 and female above 45-year-old), are based on a 3% stochastic increase of cancer risk (NCRP, 2000). The risk can be accepted for human deep space operations given the other mission risks. The 1 year and 1 month limits are based on deterministic effect considerations, and are referred to blood forming organs (BFO) tissues. The 1 hour and 1 minute limits are intended as a tool for the early detection of SPEs (Wilson et al., 1997). In particular, to avoid false alarms, the 1 minute alarm is activated only after three consecutive triggers of the warning condition.

4. Materials and Magnetic Fields for Shielding

Various mission scenarios for the transport of crew to Mars and back, have been under study (Lobascio et al., 2004a). The REMSIM project focused on evaluating the shielding properties of an innovative concept, consisting of an inflatable habitat, currently investigated by Alenia Spazio for ESA and ASI (Agenzia Spaziale Italiana), as an alternative to conventional rigid structures. Inflatable habitats (Kennedy, 2002) consist of an external thermal

TABLE I

Proposed dose equivalent limits in Sievert (Sv) for a mission to Mars

	1 minute	1 hour	1 day	1 month	1 year	Mission
Warning	3 μSv	0.8 mSv	10 mSv	0.20 Sv	0.40 Sv	0.80 Sv
Alarm	3 warnings	1.0 mSv	12 mSv	0.25 Sv	0.50 Sv	1.00 Sv

protection blanket, a meteoroid and debris protection, a structural restraint layer and an internal pressure bladder. The structure is complemented by a shielding layer to protect the crew from GCRs. Inside the inflatable habitat, an additional shelter protects the crew from SPEs.

Various scenarios are also envisaged for planetary surface habitats; the option of using local material is considered.

A simulation based on Geant4 (Agostinelli et al., 2003) was developed for the REMSIM study. It evaluated the effects of GCRs and SPEs in vehicle concepts and moon surface habitats protected with regolith; various shielding options were compared. The simulation showed that inflatable spacecraft structures offer protection against GCRs at least as good as that of traditional aluminium structures. Further details about the results of the simulation study can be found in Guatelli et al. (to be submitted).

The feasibility of active shields based on strong magnetic fields produced by superconducting coils was considered (Lobascio et al., 2004a). The preliminary evaluation of the mass of a toroidal magnetic system composed of 3 to 5 superconducting lenses of 4 m in diameter was compared with an equivalently effective passive absorber, as a function of the energy of the arriving protons (Papini, 2002; Spillantini, 2002). The widely used and established technology based on classical NbTi and NbSn superconductors was considered. The value of 500 A/mm^2 for the overall current density in the coils was assumed. The lens dimensions were chosen to fully protect a cylindrical shelter volume, 2 m in diameter and 3 m long, from 200 MeV protons with a 20° total divergence. For protons of much higher energy the protection would not be complete, but still highly efficient up to 500 MeV. The magnet should be powered only in case of "radiation alarm" (e.g., SPE). The time needed to energize the toroid can be less than 1 hour, compatible with the delayed arrival of the protons and ions. The option of an active shielding system was considered not only for the SPE shelter, but also for the complete habitat, where astronauts spend most of their time Figure 1.

5. Monitoring and Warning Systems

Human Lunar and Mars missions will require space weather as well as crew habitat monitoring to mitigate the continuous background flux of GCRs and the unpredictable SPEs. The steady cosmic ray dose rate, being a "chronic condition", is one of the serious hazards of a Mars mission. Comparing to terrestrial conditions and using the well-know "clicks" of a Geiger counter it can be said: *"one click per second on Earth, a hundred clicks per second in deep space, except in a large flare, when the click rate would be off-scale"* (Foullon et al., 2004). Proposals for ergonomic cosmic ray mitigation methods to deal with the steady GCR background are an original contribution of this study.

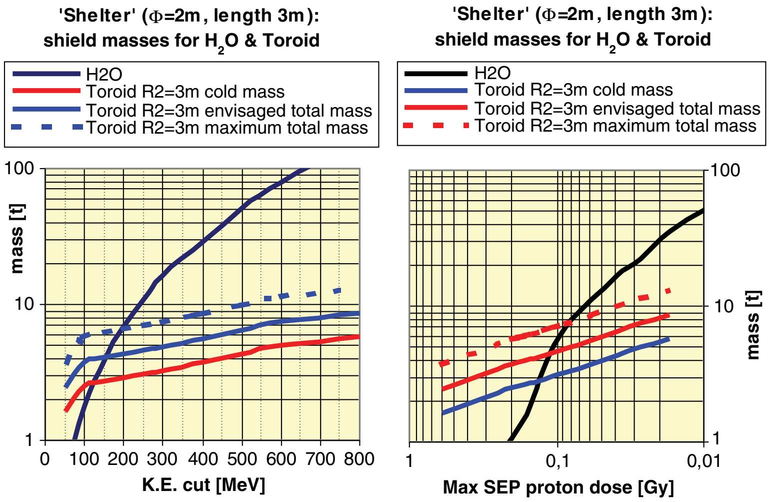
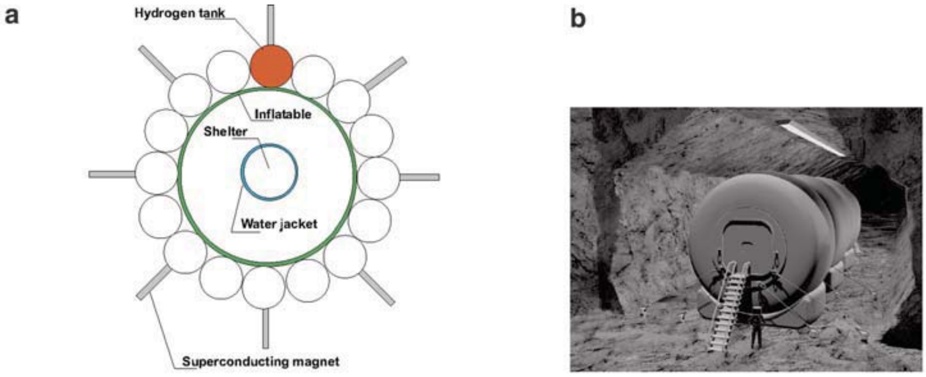


Figure 1. Mass of the water absorber and of the toroid system shielding a shelter volume. The considered toroid is 10m long, its inner radius is R1 = 1 m and the outer radius R2 = 3 m, and it covers the end caps of the shelter down to R = 0.5 m. The left graph shows the cold mass, the envisaged total mass and the maximum total mass of the toroidal system, reported at the same Kinetic Energy (K.E.) cut that gives for the protons of the SPE worst case the same dose in Gray (Gy) of the absorber, The right graph shows the same masses, reported as a function of the proton SPE worst case dose.

Furthermore, in the case that a flare event occurs, emergency condition recommendations for generating instructions to shelter were made and also embodied in a demonstration programme, linking the various hour, day and month dose limits with the time profile of the solar event. Space weather forecasting strategies were summarized into three main requirements: on-board warning and forecasting systems, a multi-viewpoint detection system and the development of interplanetary models to be tested against data. The development of "Sentinel" spacecraft, e.g., SOHO follow-on, Near-Side and Far-Side Sentinels, and Mars Orbiters is essential. Updated and new SPE and GCR engineering models will rely on future observations and geophysical research as well as existing data. It was emphasized that the development of on-board warning instruments and forecasting systems for SPE precursors has a high priority. The systematic assessment of state-of-the-art radiation protection equipment (dosimeters) and space science instrumentation produced useful pointers to possible future space weather monitoring and warning systems. A comprehensive plan for the development of dosimeters for deep-space missions, especially solid-state detectors, was developed. Size can be reduced and functionality increased by such development, possibly with the support of the Aurora programme.



Example of integrated solution with active and passive shields (spacecraft cross section)

Inflatables habitat inside a lavatube

Figure 2. (a) Cross section of transfer vehicle, where the resources present on board are exploited for passive shielding. Liquid hydrogen tank and superconducting magnets provide a general protection against GCRs and SPEs. Drinking water stored around the crew quarters provides additional protection and shelter against strong SPEs. (b) Artistic view of an Inflatable habitat inside a lavatube on the moon (Courtesy of M. Villanti).

6. Conclusions

ESA's study "Radiation Exposure and Mission Strategies for Interplanetary Manned Missions (REMSIM)", in the frame of the Aurora programme (Aurora) has greatly advanced the investigations of ESA's 2001 study, HUMEX, in several important and complex technical areas. REMSIM has contributed to the reduction of the huge uncertainties related to the assessment of spaceflight radiation effects.

The REMSIM project has proposed innovative vehicle and habitat solutions (Figure 2) as candidate for further studies. In addition, recommendations for short and long-term activities in the Aurora programme were provided.

Potential benefit to medical applications on ground, such as the improvement of particle transport codes for radiotherapy and brachytherapy, are envisaged as spin-off's from this study.

Acknowledgements

This work was funded by the European Space Agency under the ESA ESTEC Contract No.17696/03/NL/AG – Radiation Exposure and Mission Strategies for Interplanetary Manned Mission.

References

Agostinelli, S. et al.: 2003, *NIM A* **506**, 250–303.

Aurora, http://www.esa.int/SPECIALS/Aurora/, ESA publication SP-1264.

Benton, E. R. and Benton, E. V.: 2001, *NIM B* **184**, 255–294.

Cucinotta F. A., Schimmerling W., Wilson J. W., Peterson L. E., Badhwar G. D., Saganti P. B., and Dicello J. F.: 2001, *Radiat. Res.* **156**(5).

Foullon C., Holmes-Siedle A., Crosby N. B., and Heynderickx D.: 2004, *Radiation Hazard and Space Weather Warning System (REMSIM technical Note 5)* Alenia Spazio Technical Note.

Guatelli S. et al., *IEEE Trans. Nucl. Sci.*, to be submitted.

Harris R. A.: 2003, *Humex: A Study on the Survivability and Adaptation of Humans to Long-Duration Exploratory Missions*, European Space Agency, Noordwijk, The Netherlands.

Holmes-Siedle A. G. and Adams L.: 2002, *Handbook of Radiation Effects* Oxford University Press, England, ISBN 0-19-850733-X.

Lobascio C., Cougnet C., Guarnieri V., Guatelli S., Pia M. G., Rampini R., and Tracino E.: 2004a, *Review and Analysis of Existing Vehicle Concepts (REMSIM Technical Note 2)* Alenia Spazio Technical Note.

Lobascio C., Guarnieri V., Parisi G., Parodi P., and Tamburini V.: 2004b, *Review of Space Radiation Hazards (REMSIM Technical Note 1)* Alenia Spazio Technical Note.

Kennedy K. J.: *Lesson from TransHab: an architet's experience* NASA JSC, AIAA 2002–6105.

Nieminen P.: 1999, *Spectral Input Code for Induced X-ray Emission Calculations from Solar System Bodies* ESA/ESTEC Working Paper, E.W.P. 2009.

NCRP: 2000, *Radiation Protection Guidance for Activities in Low-Earth Orbit* NCRP report No. 132.

Papini P., Spillantini P., Taccetti F., Casolino M., Furano G., Imbasciati L., and Rossi L.: 2002, *Protection of the astronauts from the solar and galactic components of the ionizing cosmic radiation in the interplanetary space*, Nara, August 2002.

Spillantini P.: 2002, *Protection of the astronauts from the solar and galactic components of the ionizing cosmic radiation in the interplanetary space: toward a Shielding Strategy in the Human Space Exploration* XII Conference on Space Biology and Aerospace Medicine, Moscow, June 10–14, 2002.

Wilson J. W., Cucinotta F. A., Tai H., Simonsen L. C., Shinn J. L., Thibeault S. A., and Kim M. Y.: 1997 *Galactic and Solar Cosmic Ray Shielding in Deep Space NASA* Technical Paper 3682, December 1997.