THESEUS

Cluster 3: Space Radiation - Report

CLUSTER 3

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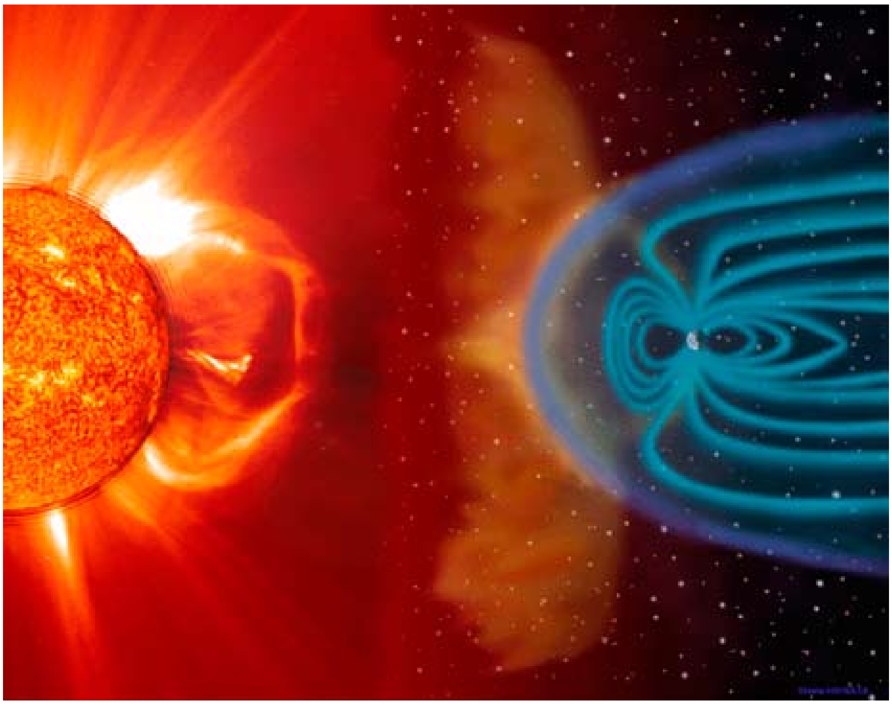
Towards Human Exploration of Space: a EUropean Strategy



Cluster 3: Space Radiation - Report

Radiation Effects on Humans
Radiation Dosimetry

THESEUS: Towards Human Exploration of Space – a European Strategy

Past space missions in low Earth orbit have demonstrated that human beings can survive and work in space for long durations. However, there are pending technological, medical and psychological issues that must be solved before adventuring into longer-duration space missions (e.g. protection against ionizing radiation, psychological issues, behaviour and performance, prevention of bone loss, etc.). Furthermore, technological breakthroughs, e.g. in life support systems and recycling technologies, are required to reduce the cost of future expeditions to acceptable levels. Solving these issues will require scientific and technological breakthroughs in clinical and industrial applications, many of which will have relevance to health issues on Earth as well.

Despite existing ESA and NASA studies or roadmaps, Europe still lacks a roadmap for human exploration of space approved by the European scientific and industrial communities. The objective of THESEUS is to develop an integrated life sciences research roadmap enabling European human space exploration in synergy with the ESA strategy, taking advantage of the expertise available in Europe and identifying the potential of non-space applications and dual research and development.

THESEUS Expert Groups

The basis of this activity is the coordination of 14 disciplinary Expert Groups (EGs) composed of key European and international experts in their field. Particular attention has been given to ensure that complementary expertise is gathered in the EGs.

EGs are clustered according to their focus:

Cluster 1: Integrated Systems Physiology
Bone and muscle
Heart, lungs and kidneys
Immunology
Neurophysiology
Nutrition and metabolism

Cluster 2: Psychology and Human-machine Systems
Group/team processes
Human/machine interface
Skill maintenance

Cluster 3: Space Radiation
Radiation effects on humans
Radiation dosimetry

Cluster 4: Habitat Management
Microbiological quality control of the indoor environment in space
Life support: management and regeneration of air, water and food

Cluster 5: Health Care
Space medicine
Medication in space

Identification of Research Priorities and Development of the THESEUS Roadmap

Each Expert Group based their work on brainstorming sessions dedicated to identifying key issues in their specific field of knowledge. Key issues can be defined as disciplinary topics representing challenges for human space exploration, requiring further attention in the future. These key issues were addressed to the scientific community through an online consultation; comments and inputs received were used to refine them, to consider knowledge gaps and research needs associated to them, as well as to suggest potential investigations.

The outcomes and main findings of the 'Integrated Systems Physiology' EGs have been synthesised into this report and further integrated to create the THESEUS roadmap.

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1 Radiation Effects on Humans

1.1 Introduction

Cosmic radiation is considered the main health hazard for human exploration and colonisation of the solar system. Radiation risk is characterised by a high uncertainty and lack of simple countermeasures. Most of the uncertainty on space radiation risk is associated with the poor knowledge of biological effects of cosmic rays. In particular, gaps in knowledge are mostly related to:

- Relative Biological Effectiveness (RBE) factors of energetic heavy ions for late effects, both cancer and non-cancer;
- Dose and dose-rate reduction effectiveness factors (DDREFs);
- Errors in human data including statistics, dosimetry and transfer between populations in application to space radiation risks;
- Effects of exposure to the mixed high- and low-LET space radiation field;
- Shape of the dose-response curve at low doses for charged particles;

Interaction of radiation damage with other space environment stressors, particularly microgravity.
The main biological effects associated with exposure to cosmic radiation are:

- Carcinogenesis;
- Late degenerative tissue effects;
- Acute effects;
- Hereditary effects.

Currently, cancer dominates risk estimates and dose limits are primarily constrained by cancer mortality risk. However, non-cancer effects are becoming an increasing source of concern. They can be again divided into:

- Acute and late damage to the central nervous system (CNS);
- Cataract formation;
- Cardiovascular diseases including coronary heart disease and stroke;
- Digestive and respiratory diseases;
- Accelerated senescence leading to endocrine and immune system dysfunction.

Reducing the uncertainty of the risk estimates is clearly the main research priority. Effective countermeasure design can only become possible once the uncertainty of risk estimates is reduced.

The priorities of research that are necessary to support foreseen space travel and planetary exploration represent a unique set of problems whose solution demands an in-depth understanding of the whole human body and cross-disciplinary work between life scientists, engineers and technologists. All the necessary expertise has been acquired by European scientists during the past decades. In the context of the THESEUS project, the objective of this Expert Group was to gather this European expertise to create synergies, facilitating an integrated approach on emerged research priorities. Because of the necessary holistic approach, those research programmes obviously required the involvement of scientists whose expertise is disseminated across Europe.

The following section reports the conclusions of the 'Radiation Effects on Humans' Expert Group. This group met during two Expert Workshops in 2010. The workshops were organised sessions aimed at considering the key questions to address, the latest developments, the gaps to fill and the Earth-based applications.

1.2 Group/Team Processes– Key Issues

1.2.1. Key Issue 1: What is the particle and dose rate dependency for acute effects?

Relevance for space exploration missions

One of the unknown aspects of long-duration space missions is the influence of different spaceflight parameters on the occurrence of acute radiation effects. Crewmembers may be exposed to different doses and qualities of radiation, threatening life quality and individual survivability, thereby disrupting mission success.

Earth benefits and applications

The main applications are in the fields of medical treatments in terms of normal tissue damage in particle therapy and protection from high-dose exposures in nuclear accidents or radiological terrorism.

Brief review of latest developments

Recent experiments at the NASA Space Radiation Laboratory (Brookhaven National Laboratory, NY, USA) show that protons at low dose rate (around 10 mGy/min) are less effective than at high dose rate. This sparing effect, similar to what would be expected for X-rays, should be considered in assessing the acute risk, as many solar particle events (SPEs) deliver doses at dose rates below 10 mGy/min.

Knowledge gaps and research needs

The different phases of acute radiation syndrome have been studied in humans in radiation-accident related cases, therapy-related cases and animal experiments under normal terrestrial conditions. Little is known on the occurrence of the prodomal syndrome (which can be relevant especially for long-term missions outside the magnetic shield of Earth) dependent on the special conditions of the space environment. More needs to be known on the dose (fluence) and dose rate dependency for the prodomal syndromes and other acute tissue effects for protons and helium ions at different energies. Furthermore, the inter-individual variability for acute effects should be studied in mechanistic detail.

Proposed investigations and recommendations

- Reviewing data from proton and heavy ion therapy;
- Performing mechanistic in-vitro and 3D human tissue models as well as animal experiments in accelerators;
- Performing energy and dose rate dependent studies in accelerators;
- Providing an adequate infrastructure such as access to accelerator facilities, low dose rate radiation sources, mixed radiation fields, and animal facilities.

Trans-disciplinary aspects

This issue is linked to radiation dosimetry and immunology aspects for the impact of acute exposure on immune system and health care for radio-protective drugs.

1.2.2. Key Issue 2: How is the sensitivity to acute effects modified by the space environment?

Relevance for space exploration missions

For cancer treatments with high and moderate doses from X-rays, protons and heavy ions (carbon) under terrestrial conditions, the occurrence of acute radiation effects has been seen. However, only little or nothing is known on the possible contribution of spaceflight factors other than radiation. Interaction of space environment (e.g. microgravity) and radiation is a possible risk for long-term human space missions.

Earth benefits and applications

General applications to ground-based radiation research concern the interaction of radiation with various stressors.

Brief review of latest developments

There is increasing evidence that acute effects from protons are modulated by the immune system and this can affect the colonisation of the gastrointestinal tract by bacteria. This stresses the importance of measuring of acute radiation effects in realistic space environment conditions where the immune system is impaired.

Knowledge gaps and research needs

The interaction of radiation with other spaceflight factors is currently under study for systemic biological responses related to the prodomal syndrome. However, little is known on the impact on acute radiosensitivity of the following factors: immune status, influence of multiple stressors in the space environment, nutrition, physical exercise protocols, pre-existing motion sickness, sleep deprivation and biorhythm disturbances, high oxygen concentrations and altered body fluid distribution. Age and gender influence should also be considered.

Proposed investigations and recommendations

- Spaceflight experiments with animals exposed to high doses from an on-board radiation source;
- Animal experiments at accelerators using simulated microgravity and/or other space factors;
- Structuring investigations in a hypothesis-driven manner and appropriate design to generate statistically significant results;
- Providing adequate infrastructure such as access to spaceflight animal cabinets, access to artificial on-board radiation sources and access to ground-based accelerator facilities equipped with microgravity simulation devices.

Trans-disciplinary aspects

Similar to Key Issue 1, this issue is mostly related to radiation dosimetry, immunology and medication in space, but habitat management is also of interest as the exposure conditions depend on the life support system.

1.2.3. Key Issue 3: What is the effectiveness of GCR at low doses for carcinogenesis?

Relevance for space exploration missions

Exposure of astronauts to galactic cosmic radiation (GCR) is a continuous threat for spaceflight missions. During long-term missions, doses can be reached that have been reported to be relevant for carcinogenesis and other stochastic radiation effects. Accordingly, the contribution from galactic cosmic-ray exposure to late effects, such as carcinogenesis, has to be known to assess the risk for astronauts and other space travellers.

Earth benefits and applications

General applications for Earth primarily include ground-based radiation protection, and research for medical applications of radiation in the fields of radiation-induced secondary tumours after particle therapy.

Brief review of latest developments

Recent results in animal models have demonstrated that the RBE for hematopoietic cancers is lower than for solid tumours. NASA is now recommending two different RBE values for leukaemia and solid cancers.

Knowledge gaps and research needs

Data on radiation carcinogenesis have been obtained from animal experiments and from survivors of the atomic bomb explosions in Hiroshima and Nagasaki. These data are mostly obtained for sparsely ionising radiation and only limited data exists for densely ionising radiation qualities. The main general question is the shape of the dose-response relationship for different radiation qualities and different dose rates. Among others, the following questions have to be answered for understanding stochastic radiation effects: what is the dependency on space radiation quality; do differences in mechanisms (e.g., latency) from high- versus low-LET exist; can biomarkers of cancer risk be validated for astronauts; what is the contribution of individual sensitivity and (epi-)genetic predisposition to cancer induction and progression; what is the contribution of spaceflight environment parameters; do single particle traversals in cells affect cellular late effects; what are the track structure characteristics for determining effectiveness, and what is the role of non-targeted effects in carcinogenesis?

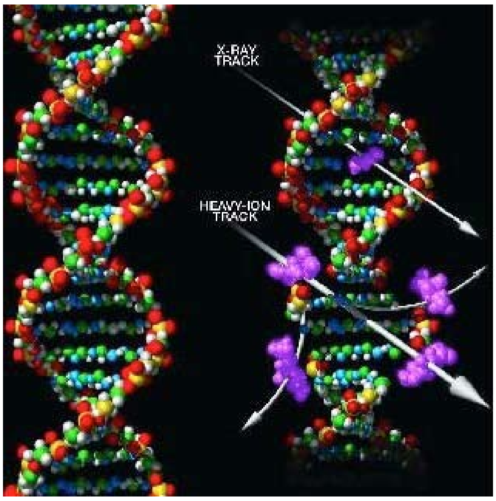

Figure 1: An artist's concept of DNA battered by galactic cosmic rays (Credit: OBPR).

Proposed investigations and recommendations

- Accelerator experiments using innovative biological systems to model radiation-related endpoints relevant for carcinogenesis;
- Investigations of biomarkers in astronauts;
- Mechanistic experiments with genetically modified cell or animal models;
- Particle microbeam facilities and access to ground-based accelerator facilities are needed for the suggested experiments. For verification of data obtained under terrestrial conditions, access to spaceflight platforms will be necessary.

Trans-disciplinary aspects

The link to radiation dosimetry is obviously very important, but a strong interaction with integrated physiology aspects is also necessary, considering that the dose-response curves for carcinogenesis are organ-specific.

1.2.4. Key Issue 4: Is there a risk of CNS damage from low doses of GCR?

Relevance for space exploration missions

Central nervous system (CNS) damage in astronauts from radiation may be a critical point for mission success, as changes in behaviour and/or individual stress response may result in critical situations. Results from animal experiments demonstrate the impact of even low doses from high-LET radiation on performance and premature ageing. Accordingly, the contribution from galactic cosmic-ray exposure to CNS damage has to be known for risk assessment in astronauts and other space travellers.

Earth benefits and applications

Late effects in patients treated for brain diseases with particles. Reactive radical species are linked to radiation-induced CNS damage. Since the same mechanism has been postulated to modulate Alzheimer and Parkinson's disease, this provides a mechanistic linkage to these common neurological disorders.

Brief review of latest developments

Although behavioural experiments are still unclear, much progress has been made in the mechanisms, particularly in measuring the effects of radiation on brain stem cells. Tissue models are particularly useful to this goal. Most of the data point to a strong effect of reactive oxygen species (ROS) and inflammation in the hippocampus.

Knowledge gaps and research needs

The following questions have to be answered to understand space radiation-induced CNS damage: can behavioural changes occur as consequence of single heavy ion traversals; what is the molecular basis of radiation induced neurological damage; is there a role of ROS in CNS damage; do long-term effects exist for CNS; what are the sensitive structures and/or cell types in the brain; is there a contribution of multiple stressors during spaceflight with regard to radiation-induced CNS damage?

Proposed investigations and recommendations

- A thorough review of normal tissue complications in patients with brain tumours and/or other diseases treated with X-rays, protons or heavy ions would be the first approach for performing meta-analysis of the corresponding human data;
- Meta-analysis data should be verified with accelerator experiments using animals and innovative biological model systems;
- For these studies, particle microbeam facilities and access to ground-based accelerator facilities are needed. For verification of data obtained under terrestrial conditions access to spaceflight platforms will be necessary.

Trans-disciplinary aspects

This issue has strong relations with neurophysiology.

1.2.5. Key issue 5: Is there a risk of non-cancer late effects from low doses of GCR?

Relevance for space exploration missions

Currently, little is known on non-cancer late effects in astronauts after radiation exposure. So far, radiation-induced cataracts are best understood, where most data are derived for terrestrial radiation and some data are obtained with astronauts. Less is known on non-cancer effects in other organs or tissues.

Earth benefits and applications

More research in this area could produce better knowledge of non-cancer effects and their relevance for radiation protection and particle therapy on Earth.

Brief review of latest developments

The epidemiological studies are still unable to provide information at doses below 0.5 Gy for cardiovascular disease. It has been suggested that one possible biological mechanism is damage to endothelial cells and subsequent induction of an inflammatory response.

Knowledge gaps and research needs

The main general question is the shape of the dose-response relationship for different radiation qualities and different dose rates. Burning questions in this field are: why are heavy ions highly efficient in cataract induction; is there a threshold for different non-cancer late effects; are there radiation-induced effects on immune and cardiovascular systems, muscle and bone; what are the molecular bases for these effects; and what is the contribution of spaceflight environment?

Proposed investigations and recommendations

- A thorough review of heart complications in patients treated with X-rays or heavy ions would be the first approach for performing meta-analysis of the corresponding human data;

- Innovative biological models for cardiovascular diseases in radiation experiments have to be tested first with X-rays and thereafter with high-LET radiation;
- For these investigations, access to ground-based accelerator facilities and to spaceflight platforms are needed.

Trans-disciplinary aspects

This issue is linked to cardiovascular system alterations in space.

1.2.6. Key Issue 6: Is there a risk of hereditary effects from low doses of GCR?

Relevance for space exploration missions

It is generally accepted that there is a genetic component in many diseases. Radiation-induced hereditary effects not only concern the space travellers themselves, but also their offspring. Accordingly, the appearance and transmittance of hereditary effects to future generations is a health risk for space travel.

Earth benefits and applications

Understanding the mechanisms of hereditary effects and its dependence of radiation quality would be of help for the definition of radiation protection criteria.

Brief review of latest developments

The results on germ-line mutations and trans-generational instability in mice challenge the recommendations of the International Commission on Radiological Protection (ICRP) on hereditary effects, but are not confirmed by epidemiology. Animal experiments show increased cancer risk in the offspring of male mice irradiated with neutrons, but no heavy ion data are available.

Knowledge gaps and research needs

Very little is known on the hereditary effects induced by heavy ions. Critical questions include: are there biomarkers suitable for determination of radiation induced teratogenic and trans-generational effects; what is the effectiveness of heavy ions in inducing hereditary effects; are there interactions of radiation and multiple stressors in spaceflight environment on fertility and hereditary effects?

Figure 2: Astronaut David Wolf performing an extravehicular activity (EVA) outside the ISS (Credit: NASA).

Proposed investigations and recommendations

- Hereditary effects have to be investigated in accelerator-based experiments followed by space based experiments using animal models;
- Germline mutation rate and trans-generational instability following exposure to heavy ions and X-rays should be compared;
- Effects on spermatogenesis and oogenesis should also be determined;
- For that, access to ground-based accelerator facilities and, in the future, to spaceflight platforms including on-board radiation facilities is needed.

Trans-disciplinary aspects

This issue is relevant to the design and management of the life support system.

1.2.7. Key Issue 7: How will multi-scale mechanistic-based modelling of space radiation improve risk estimates?

Relevance for space exploration missions

Radiation protection is essential for humans to live and work safely in space. Modelling approaches for simulating the radiation field in space, for dose approximation and for determination of depth dose distributions are currently being used to determine the space radiation risk. Biology-based modelling will also add knowledge to mechanistic understanding of space radiation risk and should be integrated in the design of experiments.

Earth benefits and applications

Significant modelling will contribute to the development of evidence-based radiation protection, important for ion therapy, and comparison to normal tissue response. Mechanism-based models will also lead to better regulation of low dose effects of ionising radiation.

Brief review of latest developments

NASA is now proposing a different model for radiation risk estimates based on risk of radiation-induced death (REID) probability distributions and revised quality factors depending on particle charge and energy.

Knowledge gaps and research needs

Mathematical modelling approaches are currently being used for determination of space radiation risk in the field of physics. Biological modelling is needed to solve urgent questions such as: how can systems radiation biology approaches unravel the risk of late effects; is it possible to model signalling pathways following radiation exposure; how can the quality factor approach be replaced to model radiation quality dependent risk; how can the effects of mixed radiation fields be modelled?

Proposed investigations and recommendations

- Modelling approaches which are based on microdosimetry and/or particle track structures have to be developed and investigated for space radiation risk assessment;
- Studies are needed to transfer small scale molecular and cellular models into larger multi-scale models representing the overall response of a tissue;
- Modelling should include immune response and inflammation;
- Such large macroscopic models will most likely require rule-based modelling such as agent-based models.

Trans-disciplinary aspects

Radiation dosimetry aspects are heavily involved in this modelling effort.

1.2.8. Key Issue 8: How can radiation effects be effectively mitigated?

Relevance for space exploration missions

Mitigation of radiation effects by shielding or other countermeasure strategies have to be improved to protect astronauts from space radiation. Although it is known that radiation can be shielded using different absorbers, optimal shielding conditions for space radiation have not been defined. As physical shielding is not always effective, biological countermeasures may be necessary to protect against the harmful effects of space radiation.

Earth benefits and applications

Findings and developed countermeasures could potentially have a high impact on mitigating the side effects from particle therapies, radiological accidents, and terrorism.

Brief review of latest developments

Improvements in the Monte Carlo transport codes are useful in shielding design. The failure of the Alpha Magnetic Spectrometer (AMS) superconducting magnet, which was dismissed because of an anomalous heating and replaced with a conventional permanent magnet, shows that the technology of cryogenic magnets is still not mature enough for spaceflight and active shielding. Using non-cryogenic superconducting magnets remains only a possible future perspective.

Knowledge gaps and research needs

The following information is needed: how is the radiation field and biological response modified by shielding; do influences on biorhythms and physical activity modify radiation response, which dietary or pharmacological supplements are effective countermeasures for radiation protection; which radioprotectors are effective against solar particle events; and how can biological pathways relevant for radiation protection be targeted by molecular medicine approaches?

Proposed investigations and recommendations

- Accelerator-based experiments on biological systems exposed behind different shielding materials;
- Biologically motivated optimisation of the shielding;
- Development of low-toxicity radioprotectors;
- Development of specific biomedical countermeasures for cancer and non-cancer effects;
- Development of innovative biomolecular approaches;
- For these investigations, access to ground-based accelerator facilities and to spaceflight platforms including on-board radiation facilities are needed, as well as access to clinical cohort databases.

Trans-disciplinary aspects

Shielding and physical countermeasure development obviously requires interactions with radiation dosimetry experts. Also, developments of radioprotective drugs and dietary supplements are of interest for this issue.

1.3. Conclusion

A thorough risk assessment of space radiation requires a large research effort in multiple fields. To study the biological effects, ground-based experimentation is crucial to understand the risks associated with space radiation exposure, since the dose rate of space radiation is too low to get sufficient data in reasonable time. Although space experiments are difficult and expensive, further experiments with selected endpoints are necessary to investigate the effects of microgravity on radiation damage expression. Investigating the interplay between microgravity and radiation is only possible through space studies, using an artificial on-board radiation source.

The NASA-funded Space Radiation Health Programme is built upon the capabilities of the NASA Space Radiation Laboratory (NSRL) at Brookhaven National Laboratory (Upton, NY, USA), and has produced experimental data in the past few years of great relevance for reducing uncertainty of the risk. However, the complexity of the issues at hand require large, international efforts. To foster European research in the field, the European Space Agency (ESA) has recently initiated a ground-based radiobiology programme, which will be located at the high-energy synchrotron of the Gesellschaft für Schwerionenforschung (GSI) in Darmstadt (Germany).

A clear terrestrial application of this research is in heavy-ion cancer therapy (hadron therapy), where beams of high-energy carbon ions are used to sterilise solid cancers. One major consequence of this treatment is the risk of secondary cancer, especially for pediatric patients. Information on heavy-ion cancer risk, sought by researchers in space radiation, is also essential for estimating the incidence of secondary malignancies in these patients. Therefore the two research fields share many common issues and concerns.

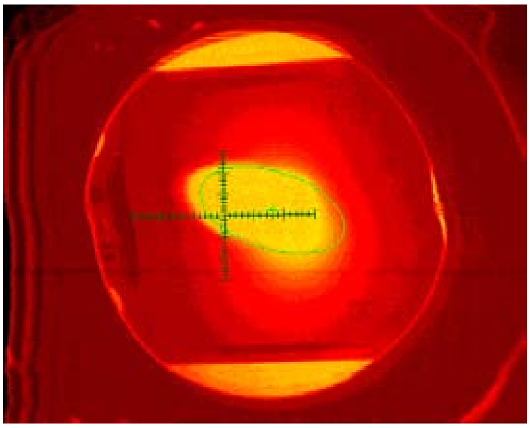

Figure 3: Profile of a heavy-ion beam (yellow spot) shown on one of four fluorescent 'flags' (Credit: BNL).

While translation from basic research to cancer risk assessment is far from straightforward, for moon-based activities, cancer risk does not appear to be a showstopper, while the uncertainty is still too high for a go/no-go decision on a mission to Mars. Cosmic radiation exposure certainly presents a major hurdle for extended space exploration, but much can still be done to better understand and mitigate it. A fruitful NASA-ESA collaboration in accelerator-based research should be fostered in the future years in order to reach a consensus on radiation cancer risk for a Mars mission within the next ten years. Intensified research on countermeasures is also urgently needed in order for such a mission to become reality.

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2 Radiation Dosimetry

2.1 Introduction

The major objective of space radiation research is to assure that during any mission the crew will be subject to as low of a radiation exposure as reasonably achievable (ALARA), enabling human exploration of the solar system within an acceptable radiation risk. This requires quantification and reduction of space radiation health hazards, with the goal of maximising the number of days that may be spent in space. The research to be carried out will support all phases of human exploration including mission planning, component design, operation and post-flight studies. In mission planning, over-estimating the risk of radiation would result in a reduction of mission duration, while on the other hand under-estimating might cause mission aborts. Accurate assessment of radiation exposure is therefore needed to avoid curtailment of mission objectives and minimising danger to the crew.

Radiation constitutes one of the most significant hazards for crew members participating in long-duration space missions, especially outside of the geomagnetic field. Astronauts face exposures to radiation levels that exceed those routinely received by terrestrial radiation workers. Radiation fields encountered in space include GCR, solar energetic particles (SEPs), mostly protons from sporadic solar particle events, protons and electrons during traversals of the radiation belts, as well as exposure to possible radioactive sources used on board for power generation or medical testing. In low-Earth orbit (LEO) the exposure to GCR and SEPs is reduced thanks to protection by the Earth's magnetic field, which deflects galactic and solar ions with low rigidities, preventing them from reaching the spacecraft orbit. The degree of protection is therefore a function of spacecraft orbital inclination. In addition, significant shielding is provided by the Earth itself. Hence, particle fluence rates from GCR and SEP sources are much lower in LEO compared to what will be encountered in future lunar and interplanetary missions.

Currently, radiation exposure inside a spacecraft can only be reduced through shielding provided by the spacecraft structure and its interior. Radiation transport codes, which model the atomic and nuclear interactions of the incident particles, are usually applied to describe how the external radiation field is altered on its passage through the spacecraft structure. However, the high degree of complexity of both the shielding distribution and the generation of secondary charged and uncharged radiations make it virtually impossible to simulate in detail the change of the resulting particle fluence and energy distributions of the radiation field constituents within a spacecraft. Unlike terrestrial exposures, the high cost of launching mass into space puts limitations on spacecraft size and shielding thicknesses, precluding the purely engineering solution of providing as much additional shielding material as needed to reduce radiation exposure to a desired level. Also, shielding materials need to be properly selected to limit the production of secondary particles, like target and projectile fragments, which can cause secondary radiation fields with even higher biological consequences than the incident field.

In order to effectively minimise radiation exposure and assess space radiation risk, the radiation protection programme must also include the development of radiation detectors and data processing tools to evaluate changes in the exposure characteristics, ideally in real time. This evaluation must include sufficient physical characterisation and mapping of the radiation fields to determine the radiation doses received by astronauts and to estimate the reduction in these doses that could be achieved by moving to areas of the spacecraft that provide better shielding.

Therefore, an essential first step in radiation research is to produce a detailed understanding of the radiation environment the astronauts will live in: in LEO, during interplanetary cruise phases, on the Moon and the Mars, in space habitats (temporary and permanent planetary bases) and during extravehicular activities.

Radiation biology findings strongly suggest that one of the main issues to address is the role and effects of different kinds of radiation. Recent results lead us to assume that the risk from irradiation with low versus high linear energy transfer (LET) can be very different. Therefore, the results obtained for the former should not be extrapolated to the latter just on the basis of rescaling factors, but rather are specific strategies needed for high-LET radiation. To understand specific features of high-LET radiation damage and its mechanisms, the starting point must be based on track structure studies. Moreover, the quantity 'dose' (absorbed dose) for low-dose, high-LET exposures is of limited meaning. Very low doses of high-LET radiation must be considered (and studied), with small numbers of cells irradiated with significant doses. The particular spatial distribution of excitation and ionisation and their clustering properties may cause phenomena that are peculiar to high-LET radiation. Moreover, the very short timescale (of the order of picoseconds) relative to energy deposition of a high-LET particle traversal can have a crucial effect in modifying the radiobiological effectiveness. It is probable that the concept of dose itself (and dose rate) is in need of new specific approaches.

The described evidence requires increasingly detailed knowledge of the radiation field characteristics in terms of elemental abundance (input energy, nuclei, fluence rate and angular distribution). To this end, more detailed measurements and advanced radiation detectors are needed. Currently, Europe is a leader in this field and should maintain its position as the state-of-the-art.

The following sections present the conclusions of the 'Radiation Dosimetry' Expert Group. This group met during two expert workshops in 2010. The workshops were organised sessions focused on considering the key questions to address, the latest developments, the gaps to fill and the Earth-based applications.

2.2. Key Issues

2.2.1. Key Issue 1: Experimental determination of radiation field parameters

Relevance for space exploration missions

Currently, there is a substantial lack of radiation instruments and measurements that sufficiently characterise the radiation field in free space, as well as inside and outside a spacecraft. This calls for novel and improved radiation detector assemblies as well as extended calibrations, detector inter-comparisons and analysis algorithms. New measurements are a prerequisite for reliable risk assessment, a crucial input for radiation source modelling, and are also needed for real-time calibration of the detectors. This would allow for detailed understanding of the radiation environment the astronauts are going to live in: in LEO, during interplanetary cruise phases, on the Moon and the Mars, in space habitats (temporary or permanent planetary bases) and during extravehicular activities.

Furthermore, determination of radiation field parameters on the ISS is a mandatory issue from the standpoint of medical operations. Eventually, this information can be provided directly to the crew, allowing decision autonomy of the crew with regard to radiation risks, which will be necessary for deep space exploration (see Key Issue 7). For exploration missions, radiation risk assessment will predominately rely on models. The reliability of these models needs to be optimised through a series of tests against a wide set of measurements at sites/conditions where instruments are available or can be made available. More and more radiation details are needed to correctly assess radiation risks, and this requires detailed model outputs to be tested against proper measurements.

Earth benefits and applications

The development of new and higher performing space radiation detectors will require pushing forward the limits of the knowledge about radiation detection, thus providing benefits to the production of tools (hardware, software) needed for monitoring and controlling instances where ionising radiation is an issue on Earth as well as in space (particle accelerator facilities, nuclear plants). Improved description of the radiation environment in free space, as well as the larger degree of confidence obtained by models and simulations through optimised testing against measurements will have significant value also on several terrestrial activities such as: (i) monitoring and improving the reliability of spacecraft electronics, for example terrestrial and satellite telecommunication and navigation systems (GPS, mobile communication, Galileo etc.); (ii) monitoring aircrew exposure; (iii) understanding failure rates in aircraft electronics; (iv) improving ion therapy and nuclear medicine; (v) developing climate models.

Brief review of latest developments

Figure 4: Figure 4: ESA astronaut Paolo Nespoli installing ALTEA hardware for the ALTEAshield-survey experiment, aimed at performing a 3D survey of the radiation environment in the US Laboratory of the ISS. (Credit: NASA).

On the ISS, several radiation measurements have been/are performed, either under the frame of science experiments or as operational monitoring for crew safety. The Dosimetric Mapping (DOSMAP) experiment was the first effort to map dose and dose equivalent as a function of location in the US Laboratory and in Node 1 of the ISS. The experiment was flown as part of NASA's Human Research Facility (HRF) between March and August 2001, together with the Japanese Bonner Ball experiment, a US tissue-equivalent proportional counter (TEPC), and a human phantom torso. Italian scientists have used various silicon strip detectors over the last years, as part of the Alteino/ALTCRISS and the ALTEA experiments, which aim for a precise determination of the abundance of heavy ions in the space radiation environment. ALTEA is also designed to study the 'light flash phenomena' mostly caused by space radiation in the eyes of astronauts. In two different experiments, ALTEA is currently surveying the 3D heavy-ion radiation flux in the US Laboratory, able to measure the trajectory of each particle, determine the nuclear species of the radiation and calculate the input energy.

The operational systems are based on the concepts of microdosimetry (TEPC), silicon detector technology (CPDS and DB-8) or on ionisation-chamber principles (R-16). A semi-active device is the Hungarian Pille system, which is an automatic on-board reader for passive thermoluminescence detectors (TLDs), also used for dose determination during an astronaut's EVA. The main advantage of the active system lays in the constant monitoring capabilities as well as in the built in 'Radiation Alert Functions', as in the NASA TEPC, providing 'real-time' information about the radiation load and the possible fast change of it due, for example, a solar particle event. In free space, well-established contributions have come from GOES (measuring X-ray, electron and proton fluxes at geostationary orbit) and of ACE (measuring solar wind, interplanetary magnetic field and higher energy particles accelerated by the Sun, as well as particles accelerated in the heliosphere and the galactic regions beyond). More recently, Pamela has provided free space radiation monitoring at variable altitude (350 to 610 km) of electrons, positrons and ions up to oxygen.

Knowledge gaps and research needs

Determination of radiation field parameters such as elemental abundance, energy and fluence rate is still incomplete: thorough spatial and temporal mapping inside and outside a space vessel is still lacking. There is also a strong demand for further development of improved radiation detectors. Measured values for the radiation fluence rate, energy and charge distributions as well as ion composition and direction inside and outside LEO are missing. The neutron role in the total radiation environment has also yet to be fully quantified. Obviously, a large amount of available radiation data has not been fully exploited.

Proposed investigations and recommendations

- Available experimental data should be reviewed, and fully evaluated.
- Detailed characterisation of the radiation environment (input energy, charge, fluence rate, direction) needs to be carried out through continuous measurements over successive solar cycles in preparation for long-duration exploration missions.
- New radiation detector assemblies should be calibrated (and inter-compared) to a well-defined subset of the space radiation environment using ground-based accelerator facilities. These facilities, when possible, should implement mixed radiation fields to mimic the space radiation field as close as possible.
- Space-borne inter-comparison of detector responses is also seen as an important prerequisite for operational implementation.
- Development should address area detectors providing real-time information about the radiation field parameters and having alert capabilities.
- Real-time calibrations while the instruments are in operation should be explored.

Trans-disciplinary aspects

The Expert Group identified clear links between this issue and radiation effects on humans, habitat management and medication in space.

2.2.2. Key Issue 2: Modelling of radiation environments

Relevance for space exploration missions

An accurate modelling of the radiation environment is a mandatory step in the radiation risk assessment process. This task features a high integration with several other tasks: the understanding of the sources of space radiation and of the processes behind the radiation flux transformation during transport in materials (Key Issues 4, 5 and, with respect to the body, 6). The goal is to allow construction of valuable simulations/models describing the dynamics of the whole radiation spectra, from the sources to almost anywhere in space and time. These models, once benchmarked and validated against proper measurements, will permit, as an example, the prediction of the radiation field inside a spacecraft during a Mars voyage or determination of the radiation impinging on human inner organs.

This Key Issue addresses the required improvement of simulations/models of GCR, SEPs and the trapped radiation in the quest for an efficient and possibly fully integrated model of the radiation environment impinging on space habitats. It addresses model improvements, advances in the understanding of fundamental physics and processes involved in radiation generation including new benchmarking.

Earth benefits and applications

The development of detailed and fully tested radiation environment models to support space exploration will also provide significant value for several terrestrial activities. The design of spacecraft electronics, including terrestrial and satellite telecommunication and navigation systems (GPS, mobile communication, Galileo etc.), as well as aircraft electronics, will benefit from a more accurately determined radiation environment. This will allow proper countermeasures to be taken to minimise radiation-driven electronic failure rates. Deeper insights into aircrew exposure, which can be provided based on these advances, will permit further optimisation of the crew utilisation. Also, accuracy of climate modelling may benefit from the outcome of these studies.

Brief review of latest developments

Various models have been developed for each of the radiation components, many of which are available online through SPENVIS (http://www.spenvis.oma.be/) and CREME96 (https://creme96.nrl.navy.mil/ or, recently, https://creme.isde.vanderbilt.edu/). NASA uses the Badhwar-O'Neil model for galactic cosmic rays. Improved AE-9/AP-9 models are under development as part of the Proton Spectrometer Belt Research (PSBR) Programme by a consortium of institutions, such as the National Reconnaissance Office, Aerospace Cooperation, the Air Force Research Laboratory (AFRL), the Los Alamos National Laboratory and the Naval Research Laboratory.

Knowledge gaps and research needs

While the mentioned models are easily available, they still suffer several shortcomings.

GCR models
There is an inadequate characterisation of solar-cycle dependency and of the scaling with heliocentric distance.

SEP models
The understanding of the acceleration mechanism of the transport through the heliosphere is still inadequate, and the prediction capability is mostly missing (this aspect is also addressed in the next Key Issue).

Radiation belt models
The current state of the Earth's magnetosphere is no longer reflected in the radiation belt models, and there is still a substantial lack in ability to properly describe the dynamic behaviour of the trapped particles.

Proposed investigations and recommendations

- Improve the understanding of the fundamental physics processes on the Sun and of transport and acceleration of the solar wind through the heliosphere.•Develop a strong research effort towards a deeper knowledge of the fundamental processes in the magnetosphere (wave-particle interactions, source and loss processes and acceleration mechanisms).
- Perform reliable benchmarking and validation against experimental data.
- Process and calibrate existing data, make them available to the scientific community and feed them into improved source models.
- Data availability must be improved. For the future, investigations should always include resources to properly process and make available data products to the scientific community.

Trans-disciplinary aspects

The Expert Group identified clear links between this issue and radiation effects on humans, habitat management and medication in space.

2.2.3. Key Issue 3: Space weather forecast

Relevance for space exploration missions

The space environment is highly variable on different time scales as a result of the variability of the Sun, which in general affects all aspects of the space environment. SPEs are an obvious manifestation of explosive processes on the Sun, are the most dramatic radiation events and may constitute in several mission scenarios a potentially serious hazard. All the radiation components (including GCR and trapped particles) are also modulated by SEPs. A clear example is the rapid decrease in the observed GCR following a SPE due to the magnetic field of the plasma solar wind, known as Forbush decrease. While SPEs are probably the most dramatic radiation events, they are mostly composed of low-energy protons, for which a successful shielding strategy can be set up. This, however, requires an accurate prediction of the SPEs. A usable solar system forecast for the SPEs is therefore a mandatory element for an efficient shielding approach during an exploration mission.

Earth benefits and applications

The understanding and proper forecasting of solar events is an important part of the more general issue of radiation source modelling. Possible spill-over effects on Earth applications are therefore very similar to those mentioned for the previous Key Issue. As stated, these will focus on minimising radiation driven electronic failures (for example, for terrestrial and satellite telecommunication and navigation systems as well as for aircraft electronics, or to avoid potential damage to power grids, pipelines, aircraft electronics and navigation), but also on radiation protection for occupational exposure (commercial and military flights, first responders). Additionally, it will help optimising the utilisation of aircrew personnel and preparing, for example, best-choice 'escape flight routes' during SPEs. Climate modelling may also benefit from the outcome of these studies.

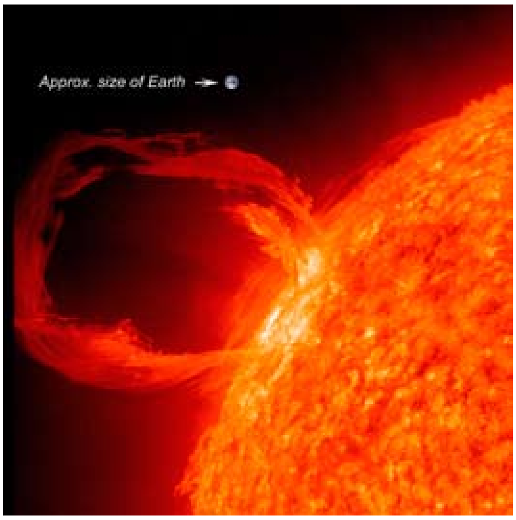

Figure 5: The Earth is superimposed on this image of a solar eruptive prominence as seen in extreme UV light (Credit: NASA).

Brief review of latest developments

There are some observation platforms available, such as GOES, SOHO, ACE and STEREO, on which – together with neutron monitor information – space weather will be described and forecasted. Through observation of several hundreds of coronal mass ejections (CMEs) by the STEREO mission, it has been found that the general structure of a CME is consistent with large-scale magnetic flux ropes. This was the first time that direct, continuous tracking of CMEs over the entire distance from Sun to Earth became possible. At higher solar activity, several bipolar magnetic regions on the Sun can be destabilised in turn, leading to the release of multiple CMEs in a few hours. These CMEs can merge in interplanetary space. A fast CME is a necessary ingredient for a strong SPE. For the forecast of particle fluxes and energy spectra of SPEs, magnetic coupling to the source regions of solar eruptions, especially to CME onset regions, plays a fundamental role. This will be investigated in detail in the newly selected EU project eHEROES (Environment for Human Exploration and Robotic Experimentation in Space).

A more reliable space weather forecasting system is only possible with the provision of additional instrumentation in the different fields of space weather. There is an on-going ESA design study, in which based on customer requirements a list of needed instruments are defined together with their location in space, their characteristics, and the degree, to which user requirements can be fulfilled. The selected instruments will proceed to Phase 2 of the project for concrete mission/platform definition/specification/implementation.

The ESA Space Weather Working Team (SWWT), a forum of experts in scientific and application oriented fields relating to space weather, seeks to identify and discuss potential collaborations and/or synergies with other structures or organisations such as EC Framework & COST programmes, INTAS and SpaceGRID. The SWWT advises ESA about the response to the pilot project activities observed within the scientific and user communities. It also assists ESA in evaluating the lessons learned from the operation of pilot projects and how these changes can be implemented within a strategy for any future space weather programme.

Knowledge gaps and research needs

Knowledge and understanding of the processes occurring on the solar surface and in the photosphere, including sunspot formation, coronal mass ejections, flares and transmission through space, is still inadequate and should be improved. Propagation modelling must be improved as well. This will provide information to improve forecasting through real time observation, which is needed to set up the proper countermeasure strategies.

Proposed investigations and recommendations

- Develop SPE forecasting and prediction capabilities able to describe interplanetary shocks and coronal mass ejections.
- Develop and/or improve predictions for fluence distribution and time evolution at different positions in space and on different planets. This would allow identifying precursors and signatures, which would improve the detection of fast CMEs.
- Forecast and identify quiet periods of solar activity to support mission planning.
- Intense observations using present and new spacecraft are necessary to improve our understanding of basic space plasma physics phenomena in the solar-terrestrial environment and to improve our understanding of short-term and long-term solar variability.

Trans-disciplinary aspects

The Expert Group identified clear links between this issue, radiation effects on humans and medication in space.

2.2.4. Key Issue 4: Transport codes

Relevance for space exploration missions

Passing through a space suit during an EVA or through the spacecraft/base walls, the radiation field is transformed by fragmentation, scattering, Coulomb interaction, neutron production etc. before entering the body of an astronaut. Once inside the body, the radiation field undergoes further transformation. Transport codes are needed to describe the interactions during the traversal of radiation through matter, both shielding matter (such as the spacecraft hull, but also the material, such as racks and experiments, inside the spacecraft) and living matter (skin, tissue etc.). The development of reliable transport codes is therefore mandatory to produce accurate risk assessments for personnel and equipment on long-term space missions.

Earth benefits and applications

Optimised transport codes would be of significant value in the improvement of ion therapy strategies as well as in the optimisation of radiation protection for occupational exposure (in hospitals, accelerators, nuclear plants, commercial and military flights and first responders), and for aircrew exposure. Protection of electronics in environments where radiation is an issue would also provide benefits to other applications, including terrestrial and satellite telecommunication and navigation systems (GPS, mobile communication, Galileo etc.), aircraft electronics as well as electronic circuit and accelerator design and nuclear plant design.

Brief review of latest developments

Codes may be one- or three-dimensional, deterministic or based on Monte Carlo (MC) methods. Deterministic computer codes are based on approximations of the Boltzmann transport equation and rely on models for the relevant quantities in the transport calculation. Many existing codes are tailored to a specific application, often leading to significant simplifications. Some well-known deterministic computer codes include the High-Charge-and-Energy Transport (HZETRN) code and the Heavy-Ion Bragg Curve Calculator (HIBRAC). HZETRN and HIBRAC are based on the one-dimensional formulation of the Boltzmann transport equation with a straight-ahead approximation. Deterministic codes do not take into account all action products and their correlations, but rather focus on only one reaction product at a time. All information about correlations on event-by-event basis is therefore lost. The main advantage of deterministic codes, however, is seen in the low demand for computational resources and the comparatively small calculation times. The interaction of a heavy ion with a material is a complex process that includes a variety of diverse activities including ionisation, excitation, nuclear fragmentation, production of positron-emitting nuclei and de-excitation through gamma rays. These processes are not fully accommodated with deterministic models, and their complexity requires the use of a numerical method for solving the probabilities of different events, e.g., a MC method. Several MC codes are used nowadays throughout the world (MCNP, FLUKA, GEANT4, SHIELD-HIT, HETC-HEDS, MARS, PHITS). However, in several instances deterministic codes give results that agree with those from the more complex MC codes.

Knowledge gaps and research needs

A detailed understanding of the physics governing the traversal of an ion, electron or neutron through matter is a key point in defining transport codes. Understanding the hadronic physics at the basis of the particle transport and cross sectional data tables must therefore be improved to further develop the codes. There is especially a lack of experimental cross-section data for light fragments and neutrons. In this panorama, it is also of paramount importance to define in detail the strengths and weaknesses of the codes via properly designed validation and benchmarking procedures against experimental data, including data obtained with advanced anthropomorphic phantoms exposed at accelerators.

Proposed investigations and recommendations

- Codes need to be improved to treat all primary and secondary cascades including photons, protons, light ions, heavy ions, mesons and electromagnetic cascades.
- The nuclear interaction database needs to be updated, especially for neutrons and light ions.
- The codes should be carefully benchmarked against ground-based experiments, using both thin and thick targets as well as anthropomorphic phantoms. The projectiles should range from protons up to iron, with suitable targets, e.g., polyethylene, Kevlar®, Nextel® and other different polymers, aluminium, iron, copper etc. The energies should range from below 100 MeV/u to at least 10 GeV/u. It is important to measure differential (angular distributions) and double differential (energy and angular distributions) cross-sections as well as multiplicities for the light fragments. Measurements are needed for both projectile and especially target fragmentation.

Trans-disciplinary aspects

This issue is mostly related to the study of radiation effects on humans.

2.2.5. Key issue 5: Shielding

Relevance for space exploration missions

This issue includes the work needed to characterise and develop shielding materials, as well as the studies and developments needed to make active shielding a feasible alternative. Continuous optimisation of shielding measures and strategies is of primary importance in order to keep the radiation exposure of space travellers as low as reasonably achievable (ALARA). Exposure to ionising radiation can be reduced by (i) increasing the distance from the source, (ii) reducing the exposure time (for example, exploiting nuclear-based propulsion for exploration missions), and (iii) using active or passive shielding. Currently, the only proven and practical physical countermeasure to reduce the exposure to cosmic radiation during space travel is passive shielding and reducing exposure time. Passive shielding, however, does not always reduce the radiation risks. Unlike for low-LET gamma or X rays, the shielding of energetic charged particles may even cause an increased risk. Secondary radiation, composed of projectile and target fragments (including neutrons) from the interaction with the shields, may deliver a higher dose than what would have been absorbed from the primary radiation. For physical reasons, a shielding material with a low mean atomic mass is needed to provide an efficient reduction of the radiation risk. Understanding the effects of shielding materials and the optimisation of the shielding strategy is therefore a mandatory issue for deep space exploration.

Earth benefits and applications

The knowledge of cosmic ray shielding will have significant value for terrestrial activities wherever exposure to a significant amount of ionising radiation is an issue. This includes, but is not limited to, ion therapy centres, radiation protection for occupational exposure (hospitals, accelerators, nuclear plants, commercial and military flights), and aircrew exposures. Significant contribution could also be given to nuclear plant design and operational support. Finally, protection of electronics from radiation-driven failures would benefit from these studies. This includes the failure induction/propagation in electronic circuits and accelerators.

Brief review of latest developments

It has been shown that in order to provide an efficient reduction of the radiation risk, a shielding material with a low mean atomic mass (high content of hydrogen) is needed. This would minimise fragmentation and the consequent production of secondaries. A large number of materials (several with low content of hydrogen) have been properly tested on ground and some of them in space. Passive shielding produces limited risk reduction, in the order of a few tens of per cent.

Active shielding has been studied in Europe during 2002 to 2004 by two research programmes supported by the European Space Agency: one through a dedicated Topical Team group (on the thematic 'Shielding from cosmic radiation for interplanetary missions: active and passive methods') in the framework of life and physical sciences, and the other an industrial study (through an Invitation To Tender) concerning the 'radiation exposure and mission strategies for interplanetary manned missions to Moon and Mars'. Both programmes were primarily aimed at finding a solution for the shielding against energetic solar events and concluded that, outside the protection of the magnetosphere and in the presence of the most intense and energetic solar events, mission protection from radiation cannot rely solely on the mechanical structures of the spacecraft, but rather a temporary shelter must be provided. Because of the limited mass budget, the studies suggested the use of superconducting magnetic systems. For protection against galactic cosmic rays during long-duration missions, it was concluded that the use of active shielding is mandatory. However, the mass and power budget required by the available technology on superconducting systems at the time of the studies is prohibitive.

Knowledge gaps and research needs

Shielding optimisation is required. This relies on the maximum permissible radiation doses for exploration missions beyond LEO (considering also the risk of early deterministic and late stochastic effects) and must take into account all new knowledge about simple and multilayer materials. An important point will be to determine the shielding distribution function of the habitats in order to benchmark the simulated characteristics. Research to characterise and develop shielding materials is also needed. While passively shielded temporary shelters for solar events are probably feasible in the near future, it is much harder to foresee an effective system based on passive shielding for galactic cosmic rays during an interplanetary voyage. This consideration, and the important technological advances in the last decade on superconducting magnets, materials and cryostats, prompt the need for a revision of the above mentioned pioneering studies in view of a new combined (active and passive) shielding strategy enabling a long permanence of humans in deep space. In this scenario, active shielding needs further studies to provide feasible implementations.

Proposed investigations and recommendations

- The ISS and free-flying satellites are further considered a basic test bed for estimating the performance of shielding structures.
- New materials and combinations of materials (e.g., multilayers) shall be studied by simulations using transport codes and ground-based testing in accelerators.
- Knowledge of shielding properties of in-situ resources on celestial bodies such as regolith or regolith-derived compounds shall be improved.
- Studies on active shielding in the search for breakthroughs that could make this approach technologically feasible as a complement to the passive strategy shall be resumed.

Trans-disciplinary aspects

This issue is mostly related to the study of radiation effects on humans.

2.2.6. Key Issue 6: Individual radiation exposures

Relevance for space exploration missions

Figure 6: ESA astronaut Thomas Reiter sets up the MATROSHKA phantom on the ISS (Credit: NASA).

This effort partly represents a bridge between the Expert Group on Radiation Dosimetry and the Expert Group on Radiation Effects on Humans. The aim is to work collaboratively to provide all experimental radiation information and relative codes needed to achieve an efficient risk assessment, while also minimising uncertainties in the final risk estimations. One of the most important final goals for radiation dosimetry is the detailed estimation of radiation exposure of inner organs, tissues and/or cells. Today, this is achieved by folding the energy deposition with relative biological effectiveness (RBE) for specific endpoints or appropriate weighting factors (in general, risk coefficients). This can be based on (i) the simulation of the radiation fields (particle type, energy and fluence rate) folded with a human model (particular person if required), (ii) results from surface-position personal dosimeters and algorithms relating these results to organ energy deposition, and (iii) a combination of (i) and (ii) with the calculations and the results of personal dosimeters being used to correct for occupancy in defined radiation fields. An improvement on the use of the risk coefficients mentioned above is the determination and use of a detailed transfer function between advanced personal/area radiation detector readings (and, if needed, simulated radiation quantities) and risk-related quantities. To this end, it is necessary to develop and use adequate active personal radiation detectors with real-time capabilities and to carry out an improved characterisation (input energy, nuclear abundance, fluence rate, direction) of the radiation field both in the environment as well as on the body of the astronaut. A detailed shielding distribution function of the body and proper transport codes will permit the input radiation field to be related to the radiation incident on the organs, tissues and/or cells. In this frame, it is important to provide all the information needed to establish the uncertainties of the organ final risk estimates. An alternative method is to measure the doses at critical organ sites with the help of anthropomorphic phantoms inside and outside the ISS during a full solar cycle. Skin measurements and depth dose distribution in the phantom would be used to determine organ doses using a voxel model and the ratio between skin and organ doses. From a measurement with a personal dosimeter on the astronaut's body, the effective organ doses could be calculated.

Earth benefits and applications

In addition to supporting space exploration, the knowledge acquired will have significant value for terrestrial activities including radiation protection for occupational exposure (hospitals, accelerators, nuclear plants, commercial and military flights) and aircraft crew exposure control. It will also provide contributions to the strategy to set up optimised therapy plans in ion therapy.

Brief review of latest developments

The MATROSHKA experiments provided the first time depth dose distributions in a human phantom in an axtra- and intravehicular activity situation on board the ISS. The detailed analysis of these experiments is the main task of the FP7 project HAMLET (http://www.fp7-hamlet.eu).

Knowledge gaps and research needs

Radiation biology results continually suggest that many interactions with organs/tissues/cells depend on detailed parameters, such as charge and input energy. This dependency propagates into the risk parameters and therefore, there is a need for a much more detailed picture of the radiation environment and the mere folding of energy deposition where RBE appears more and more insufficient to lead to a reliable set of radiation risks. The pattern of energy deposition (timing, local density) should be taken into account.

Figure 7: ESA astronaut Thomas Reiter wearing a European Crew Personal Dosimeter on the ISS (Credit: NASA).

Active personal radiation detectors with alert capabilities and the ability to measure radiation field parameters are still not available. Access to an active real-time personal dosimeter will allow the user to monitor his/her radiation exposure and seek out preferable regions to reduce their radiation risk.

Finally, there is still a lack of an efficient translation between life science issues and experimental data into astronaut radiation protection activities.

Proposed investigations and recommendations

- Further use of human phantoms is mandatory to provide measurements of doses at organ sites in order to benchmark models with these results.
- New small active detector systems need to be developed delivering optimised information of the radiation field parameters.

- Simulation and radiobiology results must be used to determine the transfer function between radiation detector readings and risk related quantities.
- Optimisation of cross-links with human spaceflight operations with strong collaboration between physicists and physicians is needed.

Trans-disciplinary aspects

This issue is mostly related to the study of radiation effects on humans but has also links with medication aspects.

2.2.7. Key Issue 7: Support to mission planning and operation

Relevance for space exploration missions

Improvements in modelling radiation sources, accuracy of radiation transport codes, and radiation monitoring will contribute to improved risk assessments and provide increased confidence that the mission can be carried out as planned. Deviations from the planned mission scenario may require curtailment of planned activities or provide opportunities to enhance or augment planned activities. Astronauts will be especially vulnerable during EVAs, when they are monitored in real-time by a biomedical suite of sensors to assess physiological parameters such as core body temperature, oxygen uptake, skin conductivity and environmental parameters such as the radiation environment. In addition, space weather predictions and remote satellite and areas instrumentation will augment the personal astronaut radiation instrumentation. These real-time measurements will be transmitted to the EVA control node in real time to assess the status of the activity and provide guidance to the astronaut. In addition, radiation exposure assessments made available directly to the astronaut in real-time, with alarms, will enhance the astronaut's confidence in the activity and increase productivity. It is therefore mandatory to use this integrated knowledge for a real-time support of the mission scenarios from the standpoint of radiation risk mitigation. It should also be underlined that most of this support can be made available directly to the astronaut. This would provide a tool that could eventually move the decision-making processes related to radiation towards 'autonomy' of the crew from ground, a mandatory step to be fulfilled to allow deep space exploration.

Earth benefits and applications

The organisation derived from this work will provide significant value to terrestrial activities involving complex operational issues. Nuclear plants design could benefit as well as the design of their operational support strategies. A limited number of extreme Earth activities also could take advantage of the results of these studies.

Brief review of latest developments

The space industry is well aware of the issue of radiation protection and performing independent studies on materials, trying to combine structural requirements and radiation shielding efficiencies of the materials. A new ESA Invitation to Tender on radiation shielding by in-situ resource utilisation (ISRU) and/or innovative materials study has just been released. The ultimate objective of this study is to gather relevant information on radiation shielding for manned spacecraft, habitats, or EVA suits. Radiation risk cannot be considered alone in exploarative missions, therefore there are already activities set up for an integrated risk approach taking into account all risks.

Knowledge gaps and research needs

Until now, spacecraft design has only partly taken into account radiation risk mitigation by special constructive measures. This must and will change in exploration missions. Due to the complexity of such a mission, radiation risk cannot be treated alone and integrated risk models need to be developed. This will be achieved by developing strategies to assess improvements in the relevant mission parameters. Integrated tools based on real-time radiation readings, risk determinations and space weather forecasts, will allow the simulation and support of mission scenarios as well as assessments of the overall mission impacts of uncertainties, provide adequate estimates of astronaut exposure in real-time, and suggest changes in mission scheduling to maintain the total risk below predefined limits.

Proposed investigations and recommendations

- Use this integrated knowledge for a real-time support of the mission scenarios from the standpoint of radiation risk mitigation. This will be achieved by developing strategies to assess improvements in the relevant mission parameters.
- Develop integrated tools based on real-time radiation readings, risk determinations and space weather forecasts that will permit the simulation and support of mission scenarios as well as assess the overall mission impacts of uncertainties, provide adequate estimate of astronaut exposure in real-time and suggest changes in mission scheduling to maintain the total risk below predefined limits.
- Provide the supporting tools needed by the crew to exploit its autonomy in all radiation related decision-making processes.

Trans-disciplinary aspects

This issue is mostly related to the study of radiation effects on humans but has also links with habitat design and management.

2.3. Conclusion

Understanding the sources of space radiation (Key Issues 2 and 3) and the processes behind radiation flux transformation during transport in materials (Key Issues 4, 5 and, with respect to the human body, 6) allows the construction of valuable simulations/models to describe the dynamics of the whole radiation spectra from the sources to almost anywhere in space and time. These models, once benchmarked and validated against proper measurements (performed in space for source models and mostly at ground-based accelerators for transport models), will therefore permit, as an example, the prediction of the radiation environment inside a spacecraft during a Mars voyage or determination of the radiation impinging on human inner organs.

Measurement results and models are already available. However, these are still too few and too incomplete (most of them regarding only a few of the important radiation parameters), while the most recent models still rely on incomplete understanding of the physics of the generation/transport processes and are validated against a very limited set of measurements. New instrumentation, permitting measurements of a larger number of the radiation field parameters with greater sensitivity is mandatory. Further measurements, including, for example, body phantom measurements, and new models, based on the knowledge of improved processes, are therefore required to provide the necessary information for accurate radiation risk assessment in order to reduce these risks to an acceptable level.

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3 Annex: Composition of Expert Groups

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