Operational Radiation Protection for European Astronauts

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Abstract. Since the early times of human spaceflight radiation has been, besides the influence of microgravity on the human body, recognized as a main health concern to the astro- and cosmonauts. The radiation environment that the crew experiences during a space flight differs significantly to that found on earth due to particles of greater potential for biological damage. High-energetic charged particles, such as protons, helium nuclei (“alpha particles”) and heavier ions up to iron, originating from several sources, such as galactic cosmic radiation (GCR), energetic solar particle events (SPE) as well as protons and electrons trapped in the earth radiation belts, are the main contributors. The exposure that the crew receives during a space flight significantly exceeds exposures routinely received by terrestrial radiation workers. The European Space Agency’s (ESA) Astronaut Center (EAC) in Cologne, Germany, is home of the European Astronaut Corps. Part of the EAC is the Crew Medical Support Office (CMSO or HSF-AM) responsible for ensuring the health and well being of the European Astronauts. A sequence of activities is conducted to protect astro- and cosmonauts health, including those targeting to mitigate adverse effects of space radiation. All health related activities are part of a multinational Medical Operations (MedOps) concept, which is executed by the different Space Agencies participating in the human spaceflight program to the International Space Station (ISS). This article will give an introduction of the current measures for radiation monitoring and protection of astro- and cosmonauts. The operational guidelines that shall ensure proper implementation and execution of those radiation protection measures will be addressed. Operational hardware for passive and active radiation monitoring and for personal dosimetry, as well as operational procedures that are applied, will be described.

KEYWORDS: Radiation Protection, Space Radiation, Human Space Flight, Crew Personal Dosimetry, European Astronaut Center, Crew Medical Support

1. Introduction

Even after nearly five decades, human spaceflight remains an endeavor with inherent significant risks [1]. The exploration of space exposes the human being to a hostile environment which would, if not mitigated, lead to deleterious consequences. In contrast to impacts on the human body that are soon recognizable, e.g. gastrointestinal-, neurological-, cardiovascular- or musculoskeletal symptoms, radiation in space presents itself usually silent but is a risk for the astronauts at all times of flight and remains so even thereafter [2]. The radiation risk is still not yet fully understood and imperceptible for the human being itself unless immediate deleterious consequences would occur in the unlikely event of extreme overexposure. Understanding, predicting and reducing the potential health detriments is a core task commanding medical attention. This article will introduce the operational approach for radiation protection of astro- and cosmonauts that space agencies are taking, which participate in the International Space Station (ISS) program [3]. It will focus on the European Space Agency’s Medical Operations activities. Radiation Protection within Medical Operations (MedOps) is a joint multilateral activity (in close cooperation with the entire international ISS-medical community) and an interdisciplinary activity (in close cooperation with all other bodies that are dealing with radiation, health and safety on ISS). However, considering the given frame of this article only a brief introduction can be provided with emphasis to ESA’s specific hardware and procedure.

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2. Radiation Environment in Low Earth Orbit (LEO)

The radiation environment in space is unique, complex and dynamic. The main contributors are Galactic Cosmic Radiation (GCR) originating from deep space, solar energetic particle events, as well as particles trapped in the earth magnetic field, plus albedo neutrons and gamma rays from interactions within the atmosphere. Spatial and temporal factors including the solar cycle and changes of the earth magnetic field modulate their intensities [4]. Furthermore the altitude and the inclination of a spacecraft influence the energy distribution of particles. Low Earth Orbit (LEO, commonly defined as the altitude between 300 and 1600 km) presents electrons, protons, and heavier particles as main sources of primary exposure in the ISS orbit between 360 and 440 km altitude [5]. In addition secondary particles produced by interactions with the atoms of the spacecraft material and the human body contribute to the exposure. Among secondary particles, neutrons are of foremost importance [6].

2.1 Trapped Radiation

Toroidal regions of increased abundance for energetic particles, referred as Van Allen belts [7], surround the Earth. Mainly electrons and protons are trapped starting above the atmosphere extending up to a distance of about 6 Earth radii [5]. Electrons and protons form under normal conditions two distinct radiation belts. Relevant for radiation protection in LEO are the inner belts. Charged Particles spiral around the geomagnetic field lines, oscillating back and forth between "mirror points" located in opposite hemispheres [8]. The magnetic axis of Earth is slightly tilted from its spin axis and offset from the center of the Earth by about 600 km. As a result, trapped proton belts reach down to the atmosphere in a region located over South America and the Atlantic Ocean known as South Atlantic Anomaly (SAA). The trapped particle intensity strongly depends on altitude. In LEO, the absorbed dose inside the spacecraft is mainly due to protons during transits through the SAA [9]. This exposure increases with increasing altitude. The particle flux in the SAA is directional. Strong east west anisotropy does exist, since particles coming from east are traversing lower altitudes and experience therefore a higher atmospheric density [10]. Energies usually seen for trapped electrons range from 0.5 to about 6 MeV and will not penetrate spacecrafts hull. During severe Solar Particle Events (SPE) energetic protons and electrons can be injected in the belts, creating even additional transient radiation belts. Under these conditions high skin doses can occur during Extravehicular Activities, EVA, or "Spacewalk" [11].

2.2 Galactic Cosmic Radiation (GCR)

GCR originates form outside the solar system and is approximately isotropic. It consists of fully ionized atomic nuclei ranging from hydrogen (87%) and helium (12%) up to uranium (traces) at extremely large kinetic energies of >50 MeV n-1 up to several thousand GeV [12]. GCR is very penetrating and hard to shield against. Its intensity is solar cycle dependent with highest levels during solar minimum conditions. During periods of maximum solar activity, the GCR intensity is reduced due the shielding by the interplanetary magnetic field which is generated by the sun thereby providing some protection to the inner solar system. GCR particles above 10 GeV are not appreciably attenuated; at lower energies fluence becomes significantly reduced. Highest levels of GCR are found in open magnetic field areas around the poles. The integral GCR dose rate in free space is about a factor of 2.5 higher at solar minimum than at solar maximum [13] Compared to low inclination orbits (e.g. 28 º), at higher inclinations (e.g. 52 º) spacecrafts are exposed to increased GCR levels as they transit higher latitudes. In ISS orbit, the magnetic field provides a factor of 10 reductions in total GCR exposure relative to the free space environment [14]. During geomagnetic storms, higher GCR exposures may be experienced also at lower latitudes. The dependences of GCR intensity on altitude is modest. GCR is the most damaging source of radiation, capable of penetrating the shielding of a spacecraft/ISS and a substantial thickness of human tissues. While nuclear interactions are producing high- and low-energy secondary charged particles, fragments are often of even more penetrating.

2.3 Solar Particle Events (SPE's)

SPE's, i.e. solar flares or Coronal Mass Ejections (CME's) originating from the sun consist of electromagnetic radiation and energetic particles: electrons, protons, alpha- and heavier particles, that are injected into interplanetary space. They are unpredictable in their occurrence, mainly lasting form hours to days, however, may be detectable up to weeks. Energies are ranging from 10 to hundreds of MeV. [15]. Travel time for 1 Astronomical Unit, (AU, average distance Sun–Earth) may last from minutes for relativistic particles over hours for particles of lower energy or can take days for solar plasma emissions presenting themselves with geomagnetic disturbances and/or display of auroras. At maximum solar activity, the frequency and intensity of solar flares is increased. For missions in LEO, SPE's only rarely present a serious hazard, because they are either too small to inject significant numbers of energetic solar particles or they occur at solar longitudinal positions that are unfavorable for the direct transfer to the Earth along interplanetary magnetic field lines. However, large flares or rapid sequences of large flares at orders of magnitude greater in intensity than the majority are of particular concern to the astro- or cosmonauts health. Such large SPE's generally occur only once or twice a solar cycle [15]. However, in particular for less shielded situations outside the sheltering spacecraft during EVA or outside the protection provided by the geomagnetic field e.g. near the earth's poles or beyond LEO and in deep space; solar particle events can contribute most significantly to the radiation burden received by the astro- or cosmonauts in total.

2.4 Neutrons

Neutrons are produced by nuclear interactions in the upper atmosphere (albedo neutrons) or interactions of high energy protons and heavier nuclei with spacecraft shielding or human body tissue. In turn the neutrons interact with nuclei producing highly charged secondary particles. Energies typically range from 0.1 to 500 MeV. Armstrong and Colborn (1992) calculated that up to 20 percent of the total dose equivalent (H) on ISS will be from neutrons with energies >10 MeV [16].

3.0 Radiation protection framework and program for Astronauts and Cosmonauts

3.1 Basic Principles

Radiation in Space is an environmental reality as such inferably associated with space exploration. Astronauts Health and Safety is the number one priority as mutually agreed upon by all ISS participating agencies. In comparison to typical terrestrial radiation workers, astronauts receive higher doses and the types of radiation are different. Notwithstanding, basic principals of earth bound radiation protection remain valid. Justification is one of the first three basic principles that is also applied for human spaceflight. In accordance with the International Commission on Radiological Protection (ICRP) report 60 it is stipulated that: *no practice involving exposures to radiation should be adopted unless it produces sufficient benefit to the exposed individual or to society to offset the detriment it causes.* Second: Optimization, as *...a process or method used to make a system of protection as effective as possible within the given criteria and constraints.* Third: *Limitation, individual dose limits are applied to ensure that the principles of justification and ALARA (as low as reasonably achievable) are not applied in a manner that would result in individuals or groups of individuals exceeding levels of acceptable risks* [17]. The unique set of challenges under which human space exploration is executed is recognized by all ISS partners and the participating agencies are constantly seeking to define and apply most advanced standards and limits to protect their crew to the best of their knowledge and abilities.

3.2 Radiation Limits

Radiation protection concerns in the early phase of human space flight up to the Apollo area were focusing on the avoidance of exposures which might deteriorate the operational performance of astronauts. Correspondingly the mission design exposure limits were rather high. The first genuine radiation protection guidelines were recommended in 1970 by the Space Science Board's committee on space medicine. They were based on a primary reference risk describing an added probability of radiation induced cancer over a period of 20 years that is equal to the natural probability for the specific population under consideration. I.e. these limits allowed a doubling of the natural risk (average mortality for western countries is about 20%) to develop fatal cancer. The Scientific Committee SC-75 of the NCRP instead proposed limits based on an added 3% age and sex dependent lifetime risk for cancer mortality after a 10 year career. This risk was comparable with the risk in less safe but ordinary occupations, such as agriculture and construction. However, it is lower than the 5 % lifetime risk which a terrestrial radiation worker incurs if the present annual protection limits would be exhausted (20 mSv/a x 50a). To limit the risk for deterministic radiation effects per year SC-75 proposed an annual limit 0.5 Sv and a monthly one of 0.25 Sv for the blood forming organs (BFO). Also limits for the eye and the skin were recommended. These recommendations were released in 1989 as NCRP report No. 98 "Guidance on radiation received in Space Activities" The Russians Space Agency operated at this time with an annual limit of 1.5 Sv and a monthly limit of 0.5 Sv. By taking biological recovery processes into account differently to the NCRP, they predicted the same deterministic biological effects, that would be obtained after receiving a single dose of 0.33 Sv. Due the fact that the risk per unit dose for cancer mortality was significantly raised by subsequent UNSCEAR (1988) and NAS/NRC (1990) reports, the recommendations of NCRP report 98 were reappraised and released in NCRP report No. 132. Corresponding whole body exposure limits for life time excess risk of 3% are given in Table 1 and the organ dose equivalent limits for all ages in Table 2. In addition dose limits for all ages and both genders were recommended to avoid deterministic effects due to short term high exposures during e.g. SPE's in three critical organs: bone marrow, eye and skin, Table 3.

Table 1: US Career Ionizing Radiation Exposure Limits for Career, Stochastic Effects

Organ Specific Exposure Limits (Career)			
Exposure Interval	Whole Body (Sv)	Eye (Gy-eq)	Skin (Gy-eq)
Career	0.40 to 3.0 (see Tab. 2)	4.0	6.0

Table 2: US Career Effective Dose Limits (based on 3 % excess lifetime risk for fatal cancer)

Age at Exposure	Effective Dose - Sv	
	Female	Male
25	0.4	0.7
35	0.6	1.0
45	0.9	1.5
55	1.7	3.0

Table 3: US Ionizing Radiation Exposure Short-Term Limits, Acute/Deterministic Effects

	Bone marrow (Gy-Eq.)	Eye (Gy-Eq.)	Skin (Gy-Eq.)
Annual	50	2.0	3.0
30 days	0.25	1.0	1.5

The radiation limits used by the other ISS partners are listed in Medical Evaluations Documents (MED) Vol. A [18]. A short description of differences shall be outlined. The acute BFO limit by the Russian Space Agency was proposed as an upper limit of a single acute exposure, which may occur during a SPE. This exposure will limit the working capacity decrease to about 1 to 2%. The limits are close to those of the US limits, but the Russian Space Agency defined in addition a limit for short term exposure of 0.15 Sv for 1-3 days. The Russians also choose an age independent career limit of 1 Sv which is due to the fact that Russian studies show with increasing age an increase of non-cancer risks due to radiation, which compensates the cancer risk decrease with age. It is stated that this limit equals to a total fatal risk of 10% for cancer and non-cancer risks. It is assumed that the corresponding eye and skin limits are defined by the scaling factors adopted for the short-term limits.

The Japanese Space Agency limits are set so that the attributable lifetime fatal cancer risk equals nearly 3%, assuming the most probable pattern for their space missions but never exceeding 5% even if the astronaut stays in space every year but within the dose limits. This is an approach very close to the US concept. For deterministic effects the thresholds given in ICRP publication 26 are adapted.

The Canadian Space Agency applies for their astronauts the US short-term exposure limits, but has chosen a lifetime limit for the BFO of 1Sv.

The limits applied to European astronauts are based on thresholds for deterministic radiation effects in organs as given by ICRP 60 [17].

Table 4: ESA Ionizing Radiation Exposure Limits

Organ Specific Equivalent dose Limits (Sv)			
Exposure interval	BFO	Eye	Skin
30 days	0.25	0.5	1.5
Annual	0.50	1	3

The maximum allowable lifetime exposure has changed from previously 1 Sv to 600 mSv and is age and gender independent. It is reflected in the European directive EU 96/29 [19], the Basic Safety Standards and conforms to national regulations. Until now there is no recommendation by IAEA [20] or ICRP which explicitly includes the group of astronauts as radiation workers. In 2006 the ICRP has set up the task group 67 to work on recommendation which cover exposures in space activities in low earth orbits and beyond.

Understanding the need for awareness, consideration and integration of current expert knowledge, the Multilateral Medical Operations Panel (MMOP) established Working Groups to provide such expertise to the MMOP. The so called Radiation Health Working Group (RHWG) consisting of experts from each agency and extramural specialist is the primary working level body for radiation protection of the astronauts. Among others, the RHWG develops and revises recommendations to the MMOP about general radiation exposure limits for the space radiation environment and artificial radiation sources. It outlines radiation protection requirements and strategies, defines crew member radiation training contents, operational countermeasures, radiation hardware responsibilities, radiation monitoring requirements, radiation health risk assessment procedures, and operational procedures.

Multilateral consensus is achieved for activities in low earth orbit defining organ specific equivalent dose limits for the BFO. The BFO refers to bone marrow, spleen, and lymphatic tissues. Active “red” bone marrow is a surrogate for BF0. The limit was set to 0.25 Sv for 30 days exposure interval and to 0.50 Sv for an annual exposure. Consensus limits provide guidance for mission assignment, development of in-flight recommendations for crew or mission termination.

Table 5: Ionizing Radiation Consensus Dose Limits adopted by the MMOP

Organ Specific Equivalent Dose Limits	
Exposure Interval	BFO (Sv)
30 Days	0.25
Annual	0.50

Current career limits for reference organs and other agency-specific exposure limits for dose management are stated within ISS MED that also addresses related crew selection criteria [18]. Career limits for stochastic effects are expressed in effective Dose (E), which is the product of the tissue weighting factor and the equivalent dose H in this tissue. The dose equivalent H is defined at a point in tissue and is calculated as product of the absorbed dose, D_T and the radiation quality factor, Q. The quality factor Q is defined in ICRP 60 as a function of the LET, the linear energy transfer of a radiation component which in turn characterizes its radiobiological effectiveness. This procedure has been adopted by the space community and conforms to the recommendation of NCRP 142 [16]. For the complex mixture of high and low LET radiation components, the point quantity H in practice is averaged over the organ of interest by means of computational models to obtain the organ dose equivalent H_T. Doses for deterministic effects are expressed in terms of Gray- equivalent (Gy-eq), where the Gray equivalent is the mean absorbed dose in the organ of interest weighted by an appropriate biological effectiveness (RBE). NCRP has recommended the RBE values as given in ICRP Publication 58 and which are shown in Table 6 below.

Table 6: Table NCRP Recommended RBE's

Radiation Type	Recommended RBE	Range
1-5 MeV neutrons	6.0	(4 – 8)
5-50 MeV neutrons	3.5	(2 – 5)
Heavy ions (Helium, Carbon, Neon, Argon)	2.5	(1 – 4)
Proton > 2 MeV	1.5	-

3.3 Scope of Radiation Protection for Astronauts and Cosmonauts

Assurance of the health and safety of the human being is of foremost concern within ESA and equally so for the other ISS partners. Due to the specific nature of the space radiation environment, radiation protection and consecutive health requirements for LEO have to rely upon continuous active and passive measurements inside and outside the spacecraft as well as personal dosimetry and analytical modeling. During a space mission, the ionizing radiation environment is monitored to provide data that allow to maintain crew doses below legal limits and to practice ALARA actions to minimize levels of exposure, collect and record information to assess crewmembers' critical organ and tissue doses for an individual mission and cumulative career records, initiate immediate countermeasures for transient radiation exposure events, e.g., during EVA, solar particle events, or electron belt enhancements. Guidelines to ALARA practices are provided in the ISS MORD [21]. Detailed real-time rules which govern the crew exposure to ionizing radiation are contained in the ISS Generic Operations Flight Rules, Volume B, Section B14 [22]. It is a comprehensive set of rules reviewed and updated continuously, governing all the procedures and operation on the spacecraft and the ISS. Flight rules are outlined decisions, planned in advance to support necessary actions minimizing the amount of real time discussions needed. They are published to assist the management of crew exposure by defining actions to maintain exposure below legal limits thereby conforming to the ALARA principle. Administrative limits or "action levels" are stated to trigger more stringent actions for a mission if higher than projected accumulated exposures are detected. Analytic models of the external radiation environment in combination with radiation transport codes which take account of detailed spacecraft mass distributions enable the assessment of the radiation environment inside the spacecraft. When in addition the body self shielding is accounted for, organ doses can be predicted which can be compared with appropriate phantom studies thereby furthering the improvement of environmental models and transport codes. Auxiliary terrestrial research encompassing all disciplines involved in radiation protection (Physics, health- and biophysics, medicine and engineering) and including basic as well as applied research at particle accelerator facilities is recommended by the agencies

4. Practice of Radiation Protection for Astronauts and Cosmonauts

4.1 General Exposure Management and Countermeasures

Radiation health is a designated part of the astronaut's annual- and mission related medical examinations at the agencies Flight Medical Clinics. Pre-flight crew radiation exposure histories are reviewed and evaluated in respect to the assignment. Current mission exposures and risks are predicted based on planned mission activities. A minimum buffer dose of 0.1 Sv is included in the projected dose calculations for the assignment of a crewmember to an ISS flight. In-flight radiation exposures and health risk predictions are evaluated in order to minimize exposure. Actions that could typically be chosen by ground- and crew in-flight are: restricting crew location within ISS, rescheduling EVAs, reducing the number of EVAs, terminating an EVA in progress, deferring ISS reboost, shortening crew time in orbit, or returning the crew to Earth. The Space Radiation Analysis Group (SRAG) at NASA, the Radiation Health Officer (RHO), and the flight surgeon and biomedical engineers work with the flight director to determine the best course of action when actions are required. Post-flight radiation exposures from each mission are evaluated by radiation health resident experts of ESA, respectively the other ISS partners and their RHO's. Results, along with the crewmember's cumulative exposure history, will be used for future health risk assessments and are documented in each crewmember's medical record [18,21].

4.2 Exposure Management for Extravehicular Activity

Spacesuits, which are worn by spacewalking astronauts, provide less shielding from radiation than the spacecraft. [11] Consequently, higher radiation levels can be perceived during EVA's. Therefore proper planning of EVA's accounting for all mission parameters, e.g. estimated duration, ISS altitude and inclination, as well as information on space weather conditions (e.g., solar activity, geomagnetic field conditions, proton flux) anticipated for that day, is necessary to ensure ALARA.

4.3 Crew Exposure Records and Health Risk Assessments, Medical Records

The dosimetry records for each crewmember are compiled to aid the protection of crewmembers. These records serve as information to the astronauts about their mission and cumulative radiation doses. They support decision making for crew selection and forecasting for flight planning. They help to evaluate the operational radiation safety program for effective program operation and compliance with action levels and dose limits. Finally they enhance the collection of uniform data sets which are accurate, reliable, confidential and retrievable.

4.4 Personnel and Staffing, Expert- and Team- approach

A team effort is necessary to grant proper radiation protection for human spaceflight. Astronauts, Flight Surgeons, Flight Directors, Radiation Health Officers and other specialists within the ISS participating agencies but also external experts are involved. Flight Directors and Flight Surgeons are directly responsible. They are assisted by the RHO or by resident experts of other ISS agencies. The Flight director is the final decision maker with regard to all aspects of the mission, including, flight-rule interpretation and implementation. The flight-surgeon of a crew ("crew-surgeon") is responsible for the overall health and well being of the crew for all aspects of flight training, mission execution, -recovery and post flight rehabilitation. The Crew Surgeon is member of the Integrated Medical Group (IMG) that is in charge of all medical decisions. The Crew Surgeon briefs the crew pre- and post flight about radiation issues including personal dosimetry. They practice careful attention, specifically to radiation exposure related issues. While typically not directly involved in decision making and policy regarding radiation issues, astronauts however, participate in the final realization of practiced radiation protection in-flight e.g. in making sure to constantly wear their personal dosimeters and choosing well shielded areas on ISS as their designated sleep station. Furthermore ground based members of the Astronaut Corps (often with medical background) do serve as representatives ensuring proper acknowledgement of the astronaut's position vis-à-vis boards and panels that are concerned.

4.5 In- flight Radiation Protection Activities onboard the ISS

To be in accordance with the guidelines [18,21,22], the execution of the subsequent procedures is targeted:

- Passive area monitoring:

- Active radiation area monitoring
- Time-resolved LET or y -Spectrum Monitoring
- Internal Time-resolved Charged-particle Monitoring
- Neutron Monitoring
- External Radiation Area Monitoring
- Radiation Contingency Monitoring & Alarm Capability

Current main pillars of operational radiation protection on ISS are personal dosimetry and area monitoring that shall provide measured data of sufficient accuracy for:

- Dose assessment and record keeping for the Astronauts
- Real-time or near real-time estimates of dose rates for purposes of immediate dose management or ALARA
- Determination of field quantities and organ or tissue doses to be used for normalizing radiation transport calculations

Table 7 gives an overview of the applied active radiation monitoring systems, their provenance, and the radiation field parameters measured by these devices.

Table 7: Operational active and semi-active area monitoring detectors onboard the ISS

Instrument	**Provenance**	**Measured radiation field parameters**
Tissue equivalent proportional counter (TEPC), [23]	NASA Johnson Space Center, Houston, USA	LET spectra, absorbed dose, dose equivalent
Charged particle detector system (IV-CPDS), [24]	NASA Johnson Space Center, Houston, USA	LET spectra, particle energy spectra, Nuclear abundances up to Oxygen
Charged particle detector system (EV-CPDS), [24]	NASA Johnson Space Center, Houston, USA	LET spectra, particle energy spectra, Nuclear abundances up to Oxygen
Ionization Chamber (R-16),[25]	Moscow State University, Moscow, Russia	Absorbed dose, dose rate
Silicon detector units (DB8)[26]	Space Research Institute, Sofia, Bulgaria	Absorbed dose, dose rate
TL – system (PILLE), [26,27]	KFKI, Budapest, Hungary	Absorbed dose, dose rate

The systems applied onboard the ISS are based on the concepts of microdosimetry (NASA Tissue Equivalent Proportional Counter - TEPC), on silicon detector technology (NASA Charged Particle Directional Spectrometer - CPDS and Russian DB 8) and on ionization chamber principles (Russian R-16). A semi-active device is the Hungarian PILLE system, which is an automatic onboard reader for passive thermoluminescence detectors (TLD's), which are also applied on regular bases for dose determination during cosmonauts´ EVA. The main advantage of the active systems lies in the real time data display capabilities as well as in "Radiation Alarm Functions". NASA's TEPC is therefore providing "real time" information on exposure and field changes e.g. in case of a SPE. Although some area surveys are performed with active instruments, the area monitoring data are mostly achieved by passive systems, which are distributed at numerous locations throughout the Russian, the US, European and Japanese part of the Station. These passive systems use a combination of thermoluminescence detectors (TLD's) and nuclear track etch detectors (CR-39) for the assessment of absorbed dose, LET spectra and dose equivalent at the point of interest [28,29]. In addition to data that are obtained in the frame of operational radiation protection, scientific experiments improve the understanding of the radiation environment inside and outside the ISS. These experiments can not be discussed her in detail, which however can be found in reading: "ALTCRISS" [30] "ALTEA" [31]; "BBND" [32]; –"DosMap" [33]; or "MATROSHKA", [34].

4.6 Personal Dosimetry

The personal radiation monitoring of the astronauts is currently achieved by applying a combination of TLD’s and CR-39 detectors. This detector combination is also recommended in the NCRP 142 for the personal dose assessment of astronauts. While for the US astronauts from the personal dosimetry is accomplished by the SRAG at NASA Johnson Space Center in Houston, for the Russian cosmonauts the Institute of Biomedical Problems (IBMP) in Moscow is in charge.

4.7 European Crew Personal Dosimetry

ESA has developed its own Personal Dosimeters for their Crewmembers, the European Crew Personal Dosimeters or EuCPD´s. Similar to the other agencies participating in the ISS, the EuCPD’s serve as the primary measurement device of the crew member’s radiation exposure received in space. The EuCPD is a passive system used to measure the total absorbed dose, neutron contributions, and the heavy ion flux as well as linear energy transfer (LET) spectra applying TLD’s and CR-39 detectors. Each European astronaut is equipped with a suite of 5 EuCPD’s. The EuCPD’s are worn around the torso (belly) and ankle within the Station (IVA) and inside the liquid cooling garment (torso and ankle position) inside the space suit for “spacewalks”, (EVA). An additional reference package is kept together at a fixed position inside the ISS personal kit of the astronaut. Figure 1 shows the explosion view of the internal detector configuration of a EuCPD. Figure 2 gives a view of the hardware of the three currently applied personal detector systems by Russia, the United States and Europe. The EuCPD worn on the blue belt by European Astronauts Thomas Reiter and Christer Fuglesang onboard the Space Station in December 2006 can be seen in Figure 3.

Figure 1: Explosion view of the detector EuCPD configuration

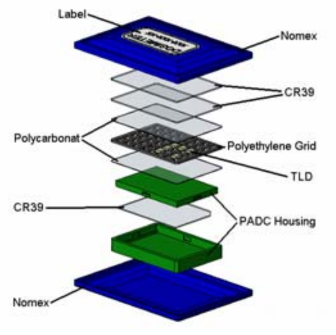


Figure 2: Crew Personal Dosimeters from left to right: Russian, American, European

Figure 3: European Astronauts Christer Fuglesang and Thomas Reiter with their EuCPD´s (blue belts) onboard the ISS in December 2006

Personal dosimetry is executed as a Medical Operations activity for radiation protection. Results of the personal dosimetry for the individual astronauts are private medical data that are going into their medical file.

4.7.1 EuCPD - CR-39 and TLD – Detection principles

When CR-39 nuclear track detectors are traversed by heavy charged particles, the particles induce a latent tracks, which after etching in caustic solution develop into microscopically measurable etch cones. The linear energy transfer (LET) of the crossing particle is obtained from the cone angle by an empirical calibration function which is established from exposures to heavy ions representative for the space radiation environment with known LET at accelerator facilities.

Fig. 4.a: 4He, 20.8 MeV/n, 10.3 keV/µm LET∞H2O, angle of incidence: 90O, picture size: 139 x 111 µm

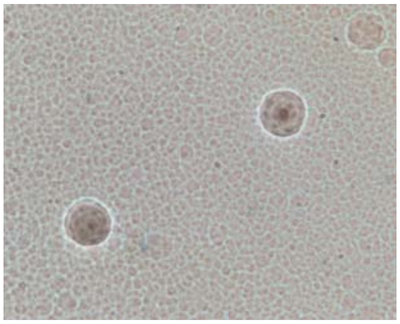
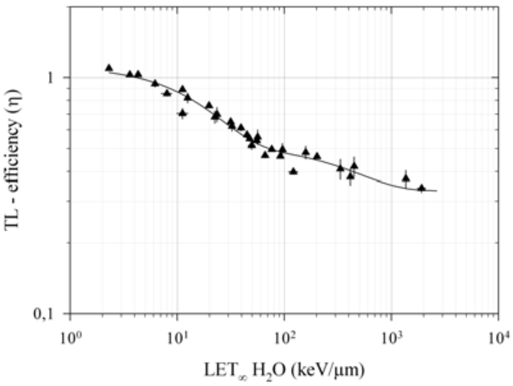


Fig 4.b.: 56Fe, 416.7 MeV/n, 198 keV/µm LET∞H2O, angle of incidence: 45O, picture size: 139 x 111 µm

For example Figure 4 a and b show the tracks of 10.3 keV/µm Helium ions and 198 keV/µm Fe ions obtained during a calibration campaign at the Heavy Ion Medical Accelerator HIMAC at the National Institute of Radiological Sciences, NIRS, Chiba, Japan. The LET registration threshold of plastic detectors for ionizing radiation is somewhat below 10 keV/µm.

Below 10 keV/µm the TLD's are required whose efficiency is approximately equal to 1 in this lower LET range. TLD crystals accumulate energy deposited by ionizing radiation in interstitial energy levels. Upon heating, the stored energy is released as light emitted by the crystals whose intensity is proportional to the absorbed dose. Figure 5 shows the LET dependent TL – efficiency of the TLD detectors applied onboard the ISS based on data gathered from DLR at HIMAC, Chiba, Japan.

Figure 5: The thermo luminescence (TL) detector – efficiency to heavy ions encountered in the space radiation field



Applying a combination of these two detector systems gives a small, robust, and easy to handle passive radiation detector system, however with the disadvantage that the labor intensive data evaluation has to be performed on ground after the exposure.

4.7.2 Detector evaluation and results

After exposure in space, TLD's and CR-39 detectors are evaluated applying standardized readout and data evaluation procedures and systems. The daily absorbed dose rate measured with TLD's (radiation area monitoring distributed to different locations on the ISS) of 160 – 240 µGy/day – reflects the different shielding properties of the ISS. The combination of the TLD absorbed dose data for the low LET component of the space radiation field with the dose equivalent data of the CR-39 detectors for the high LET component of the space radiation field gives (as example from exposure onboard the ISS) a daily average dose equivalent rate of ~ 0.6 mSv, for the year 2007 (i.e. during "Solar-Minimum"). This dose rate can vary – depending on the locations of the detectors onboard the ISS – thereby reflecting the different and varying shielding properties, i.e. mass distributions, of the space station.

4.8 Additional means for estimation of exposure: Biodosimetry

Astronauts returning from missions to the ISS undergo Biodosimetry assessment of chromosomal damage in lymphocyte cells using the multicolor fluorescence in-situ hybridization (FISH) technique. Individual-based pre-flight dose response for lymphocytes exposure in vitro to gamma-rays are compared to those exposed to space radiation in-vivo to determine an equivalent biological dose. We inter-compared the ISS Biodosimetry results.

5. Summary and Conclusion

Human spaceflight exposes space travelers to a hostile environment that encompasses ionizing radiation as one key factor. Radiation environment in space and its biological impact to the human being differs significantly in comparison to exposures that are typical for terrestrial radiation workers.

The designation of personnel, professional astronauts and cosmonauts, as a special occupationally exposed category of radiation workers is deemed necessary. This to identify and acknowledge a) the extraordinary circumstances of their work environment and b) the need to implement a specific radiation protection frameworks within which radiation risks are managed in order not to inordinately endanger the health and safety of these individuals, yet not to limit the extent of the activities that they can undertake.

Ultimate goal for all ISS participating agencies is to accountably safeguard their astronauts and cosmonauts during their entire career and thereafter, to mitigate adverse health effects to the best of their abilities.

Hence - with reference to ionizing radiation - top priority is to ensure compliance with basic principles of radiation protection including ALARA also in space. Furthermore, promotion of research by expanding state of the art scientific knowledge will enable to derive proper operational technologies. It will provide the evidence necessary for a constant advancement of guidelines and procedures, rules and regulations that empower safe operations of humans in space.

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