SPACE RADIATION DOSIMETRY

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Abstract. The radiation environment in low earth orbital flights is complex. The paper summarises the component of the space radiation, describes the dosimetric methods usually applied for space radiation dosimetry, and gives the typical figures of the measured results. The last part deals with dose limitation system of astronauts.

1 Introduction

Although partly protected from galactic and solar cosmic radiation by the Earth's magnetosphere in **Low Earth Orbit** (LEO) astronauts exposure levels during long-term missions (90 days to 180 days) by far exceed with exposures of up to more than 100 mSv the annual exposure limits set for workers in the nuclear industry, but are still below the yearly exposure limits of 500 mSv for NASA astronauts. During solar particle events the short term limits (300 mSv) may be approached or even exceeded, which certainly would not be life threatening, but raise the probability for developing cancer later in life considerably.

In the **interplanetary space**, outside the Earth's magnetic field even relatively benign Solar Particle Events (SPEs) can produce 1 Sv skin-absorbed doses while the huge SPE observed in August 1972 for example would have resulted in a skin-absorbed dose of 26 Sv behind a shielding of 0.5 g/cm^2 and would have proved lethal had there been any Extravehicular Activity (EVA) during this event. Although new rocket technologies could reduce astronauts' total exposure to space radiation during a human Mars mission, the time required for the mission which is now in the order of years remains still about half of this time. Therefore mission planners will need to consider a variety of countermeasures for the crew members including physical protection (e.g. shelters), active protection (e.g. magnetic protection), pharmacological protection, local protection (extra protection for critical areas of the body) etc. With full knowledge of these facts, accurate personal dose measurement will become increasingly important during human missions to Mars.

2 Space Radiation

2.1 Charged particles

Usual grouping of the charged particle components of the space radiation (Reitz et al. 1989):

- geomagnetically trapped radiation,
- solar-particle radiation,
- galactic cosmic rays.

Trapped radiation. As a result of the interaction of particles coming from outer space or the Sun with the geomagnetic field, there are two belts of trapped radiation, the "Van Allen belts", surrounding the Earth as rings in the plane of the geomagnetic equator. Mostly electrons and protons are present in both belts. These particles gyrate and bounce along magnetic-field lines and are reflected back and forth between the two poles, acting as mirror. At the same time, because of their charge, electrons drift eastward, while protons and heavy ions drift westward. Electrons reach energies of up to 7 MeV and protons up to 600 MeV.

For the majority of space missions in lower Earth orbits, protons make the dominant contribution to the radiation burden inside space vehicles. At lower shielding (in the case of EVA – extravehicular activity) the total absorbed dose will be dominated by the electron contribution. Of special importance for low Earth orbits is the so-called "South Atlantic Anomaly" (SAA), where the radiation belt reaches down to altitudes of 200 km. This behaviour reflects the displacement of the axis of the geomagnetic (dipole) field with respect to the axis of the geoid, with a corresponding distortion of the magnetic field. This region accounts for the dominant fraction of total exposure in ISS, although traversing the anomaly takes less than about 15 minutes and occupies less than 10% of the total time in orbit.

Solar-particle radiation. High-energy solar protons and heavy ions, which are among the most severe hazards for manned space flights, are emitted sporadically during solar-particle events (flares). Flares are observed mainly during the solar-maximum phase. The spectra of solar-flare protons have a large variability in absolute intensity as well as in shape. Doses up to 10 Gy can be reached. On mission outside the magnetosphere, radiation shelters of sufficient thickness must be provided.

Galactic cosmic rays. Galactic cosmic rays (GCR) are charged particles that originate from sources beyond solar system. The GCR spectrum consists of 98% and heavier ions and 2% of electrons and positrons. The ion component is composed of 87% protons, 12% of alpha particles and the remaining 1% heavy ions.
The flux of GCR is affected by the sun's eleven-year cycle. During that period of the solar cycle called Solar Maximum, when solar activity is most intense, the solar wind attenuates a greater flux of the inbound GCR than during Solar Minimum, when solar activity is least intense.

GCR, being composed of charged particles, is also affected by the Earth's magnetic field. Since the geomagnetic field lines are parallel to the Earth's surface around the equator, all but the most energetic particles are deflected away. The geomagnetic field over the North and South Poles points towards the Earth's surface and GCR particles of all energies are funnelled toward the poles at high latitudes. The 51.56° orbit of the ISS is sufficiently highly inclined to receive a substantial exposure from less energetic GCR (Benton and Benton 2001).

2.2 Neutrons

High-energy secondary neutrons produced by interactions of high-energy charged particles (from the trapped belts and cosmic rays) contribute a significant fraction of the total dose equivalent in large human spacecraft as the International Space Station (ISS). The two basic components of the neutron radiation are the albedo neutrons emanating from the Earth's atmosphere and the secondary neutrons from the interaction of high-energy space radiation with spacecraft materials. The neutron energy range of interest for radiation risk assessment is 0.1 to at least 200 MeV. Based on both the modelling results and a few measurements covering a portion of the energy range of interest, it was found (USRA 1998) that secondary neutrons contribute a minimum of additional 30 percent and up to 60 percent of the dose equivalent rates of charged particles.

3 Methods to Determine Dose

3.1 Measurements of dose and dose equivalent of charged particles

Because the radiation field in space is a mixture of different particles, which differ also in energy, and varies with time (all solar cycles are different), it is difficult or all but impossible to calculate doses from earlier measurements.
There are three main methods for the determination of the astronaut's radiation exposure:
1. calculation approach,
2. on-line measurements with active devices and
3. measurements with integrating, passive dosimeters.

Calculation approach. Accumulated dose and dose-rate can be calculated from the information delivered on-line by active devices (tissue equivalent proportional counters, silicon detector systems) used as area dosimeters.

Tissue equivalent proportional counter (TEPC) is simply a spherical or cylindrical detector constructed of tissue-like plastic material and filled with tissue equivalent gas. If operated at low pressure (few percent of atmospheric pressure) this type of instrument allows the simultaneous determination of the absorbed dose to tissue. The pulse height spectra are usually calibrated in terms of the microdosimetric quantity linear energy (which is related to LET) and can be used to assess the effective quality factor (Q) in complex radiation fields including neutrons, photons and diversity of charged particles. The measured absorbed dose and Q are used to evaluate dose equivalent.

Silicon detectors and detector system can be used as solid state ionisation chamber (case of a single detector) or as a LET spectrometer (case of telescopes). One type of such LET spectrometers is the DOSTEL. The

DOSimetry TELescope DOSTEL is based on two identical passivated implanted planar silicon (PIPS) detectors and designed to measure the energy deposit of charged particles (Beaujean 1999). Both detectors have the same thickness (~0.3 mm) and sensitive area (~7 cm^2). The distance of 15 mm between the two detectors yields a geometric factor of 1.2 sr for particles arriving from the front when a coincidence in both detectors is required.

On-line measurements with active devices. Active personal dosimeters such as small silicon detectors or small ionisation chambers may be used. Such devices needs power and are difficult to design small enough. They are well known due to their application in NPPs.

Measurements with integrating, passive dosimeters. Passive integrating detector systems such as thermoluminescent detectors (TLDs) are commonly used for environmental monitoring and for personal dosimetry. Such TLD measurements need to be supported by spectroscopic information about the high LET part of the radiation field from other instrumentation.

The most known advantages of passive detector systems are their independence of the power supply, small dimension, sensitivity, good stability, wide measuring range, resistance to environmental changes and relatively low cost. Therefore, they are commonly used for long term measurements from several hours up to months and years.

TLDs are perfect for recording absorbed doses from radiation up to a LET of 20 keV/µm. Above this value the efficiency decreases rapidly with increasing LET. The response function of different TL materials as a function of LET has already been determined through a series of calibration. But this knowledge is not sufficient to allow the determination of the absorbed dose and the dose equivalent for the complete radiation field. The dose equivalent is the product of a quality factor (defined as function of LET) and the absorbed dose and is a measure of the radiation exposure of the astronaut. The TLD response and the quality factor can be calculated if TL detectors are supplemented by passive plastic nuclear track detectors (PNTDs) for measurement of LET spectra ≥5 keV/µm in water. TLDs and PNTDs are exposed together and the LET spectrum measurements from PNTDs are used to correct the dose measured in TLDs and, using the corrected dose, to determine dose equivalent.

TLDs are regularly used on board spacecraft but because of the large dimension and big mass of the readers they are typically evaluated only after their return to the ground, in special laboratories. On-ground evaluation has the disadvantage that it results in the dose accumulated since the last read-out i.e. the total dose of the whole flight. Long duration space flights (e.g. on board space stations or at future interplanetary missions) requires time resolved measurements, since this information is needed for radiation risk estimates.. A small, portable and space qualified TLD reader suitable for reading out the TL dosimeters on board provides the possibility to overcome the above-mentioned disadvantage.

Since the end of the seventies KFKI AEKI has developed and manufactured a series of TLD systems named "Pille" (Butterfly in English) for spacecraft. The system consists of a set of TL dosimeters and a small, compact TLD reader suitable for on-board evaluation of the dosimeters. By means of such a system highly accurate measurements were and are carried out on board the Salyut-6 (Fehér et al. 1981), Salyut-7 (Akatov et al. 1984) and MIR (Deme et al. 1999a, b) Space Stations as well as the Space Shuttle. A new implementation of the system is and will be placed on several segments of the International Space Station (ISS) (Apathy et al. 1999) as the contribution of Hungary to the great international enterprise.

Extended missions call for a measurement of the time profile of the radiation exposure, which cannot be received from PNTD measurements. Their use is also hampered by the fact that PNTDs cannot be read out on-orbit; they need to be returned to the ground for chemical processing and analysis. The solution is to combine the TLD reader with an active LET spectrometer like DOSTEL (Reitz 1998).

3.2 Neutron dosimetry

The neutron dosimetry on the ISS requests application of a set of different dosimeters. Concerning this question the Predictions and Measurements of Secondary Neutrons in Space Workshop (USRA 1998) gave the following recommendations.

1. Provide crew personal dosimeters that are sensitive to secondary neutrons in the energy range of interest (0.1 to 200 MeV). At present, the best candidate appears to be CR-39 plastic track detectors. This is a minimum requirement in order to document crew exposure adequately.
2. Develop a proportional counter that would be sensitive only to charged particles and fly it with an existing tissue equivalent proportional counter that is sensitive to both charged particles and neutrons (but cannot distinguish between them) to obtain a measurement of the neutron contribution to the total LET spectrum.
3. Develop and fly Bonner spheres with lead (Pb) and iron (Fe) shields to obtain measurements of the high-energy neutron component.
4. Provide direct-reading active and/or passive dosimeters that are sensitive to neutrons in the energy range of interest. Such a device is needed to allow crewmembers to manage their exposures by the principle of *ALARA* during the flight. The minimum sensitivity for such an instrument should be 100 μSv.

Bubble detectors. One of the suitable solutions of the crew personal dosimeter is application of bubble detectors (Ing 1998). The bubble detectors made use of the stored mechanical energy in superheated liquid to amplify the effect of the neutron interactions. It consists of microscopic droplets of superheated liquid – that is, liquid that ought to be in the vapour phase, but is maintained in a liquid phase – dispersed throughout an elastic polymer. When radiation strikes these droplets, the energy from the charged particles triggers the droplets to explode. The resulting gas bubbles, which are visible, are trapped in the elastic medium at the positions of formation to provide a record of interactions. The number of bubbles is a measure of the neutron dose. The usual range of bubble detectors is 20-200 μSv, the energy range covers 0.4-15 MeV. In general, the tests done by user group show that the bubble detector (model BD-PND: bubble detector–personal neutron dosimeter) has no difficulty meeting the requirements of regulatory agencies for personal neutron dosimetry.

4 Results of radiation measurement

A review of radiation measurements on both **U.S. Space Shuttle and Mir orbital station** has been made (Badhwar 2000). It shows that

1. The cosmonaut dose varied from a low of 24.3 mGy to a high of 81.8 mGy.
2. The average cosmonaut dose rates, uncorrected for TLD inefficiency and neutron component, varied from 182 μGy d^{-1} to 397 μGy d^{-1}.
3. During the solar minimum, the quality for GCR varied from 3 to 3.6, trapped from 1.66 to 1.88, and the combined quality factor from 2.14 to 2.51, depending upon the Mir module.
4. Using the quality factor of 2.5 measured in the Core module, where the cosmonauts spent most of their time and assuming the factor applies during solar maximum also, the dose equivalent rates would range from 457 μSv d^{-1} to 996 μSv d^{-1}.
5. If one corrects the TLD dose rate for their inefficiency at high LET and includes the dose from high energy neutrons, these values could be roughly 25% higher; then the skin dose equivalent rates would range from 571 457 μSv d^{-1} to 1,246 μSv d^{-1}.
6. The average astronaut dose rate in the Space Shuttle varied from 0.2 mGy to 32.1 mGy, with the highest dose rate of 3,211 μGy d^{-1} or nearly six times the highest cosmonaut dose rate (468 μGy d^{-1}). This is of course, due to the higher Shuttle flight altitude.
7. Neutron contribute between 15 and 25% of the charged particle dose equivalent but have never been included in astronaut exposures.
8. The east-west asymmetry is a very significant factor in flight with fixed altitude. As such, it would be important for the ISS.

International Space Station. The calculated by Badhwar (Badhwar 2000) dose rate and dose rate equivalent for 400 km of altitude are equal 0.35 mGy d^{-1} and 0.9 mSv d^{-1}.

Gradient of the surface dose. Experiments at the surface of the Mir orbital station were carried out (Schöner et al, 1999). Four stacks of TL-dosimeters of different types were exposed in free space. The stacks contained dosimeters of different thicknesses and were covered with a foil of only 1.26 mg cm^{-2}. Within these stacks the gradient of dose and LET was determined in depths from about 1 mg cm^{-2} to 3 g cm^{-2}. The measured surface dose was in the range of 50 Gy followed by a steep gradient.

Assuming a Maxwellian energy distribution for the cosmic electrons, the initial electron energy can be calculated by Monte Carlo methods to approximately 100 keV. The steep gradient is caused by the electrons absorbed in the dosimeter stack, whereas the cosmic protons penetrate through the material almost unattenuated (Fig. 1).

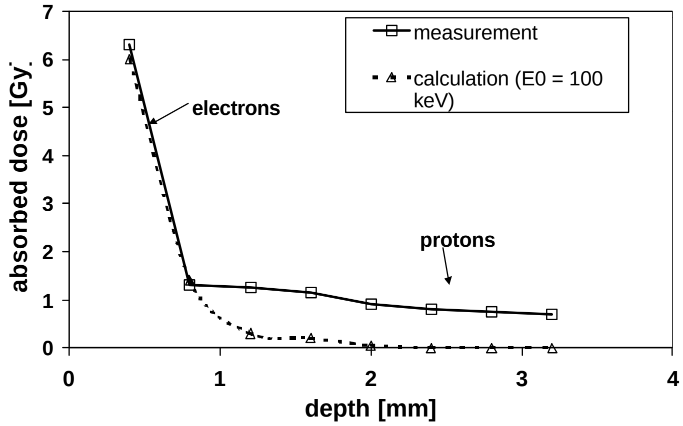

Fig. 1. Gradient of dose measured at the surface of space station MIR (Schöner et al, 1999).

The expected average annual dose as a function of flight altitude. For the same circumstances (inclination**,** wall thickness, orientation, sun activity etc.) the basic component of the dose is the flight altitude. This dependence of the annual dose is given in Figure 2a. For comparison the height dependence of the aeroplane dose is given in Fig 2b.

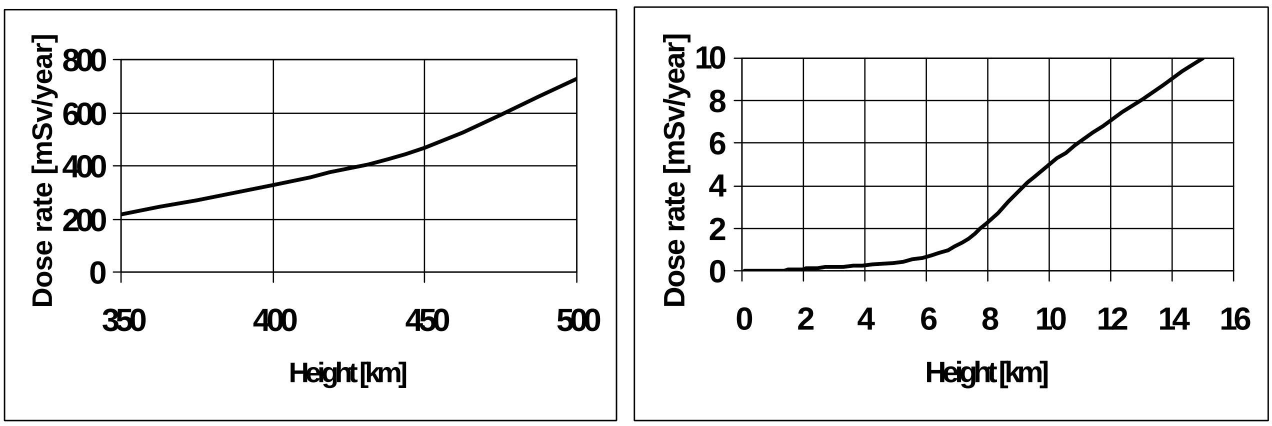

Fig 2. The expected average annual dose as a function of flight altitude for case of orbital stations (a–left) and aeroplanes (b–right).

5 Dose limitation

From the outset of manned exploration of space, it was recognised that exposures of individuals could easily exceed those on Earth unless limiting procedures were adopted. In the low-earth orbit both the inner radiation belt of trapped protons and GCR constitute radiation fields much more intense than on the Earth. Consequently, only limitations on time of exposure could keep exposures to human within reasonable bounds. In addition, solar particle events (SPE) unpredictable in occurrence and intensity could be responsible for large episodic exposures to protons requiring further limitation of exposure conditions.

The new dose limits (Sinclair 2000) for radiation workers correspond to excess lifetime risk of 3% (NCRP) and 4% (ICRP). While astronauts accept the whole variety of flight risks they are taking in mission, there is concern about risks that may occur later in life. A risk no greater than the risk of radiation workers would be acceptable.

The actual recommended values are for 3% excess lifetime (or career) risk are shown in Fig. 3.

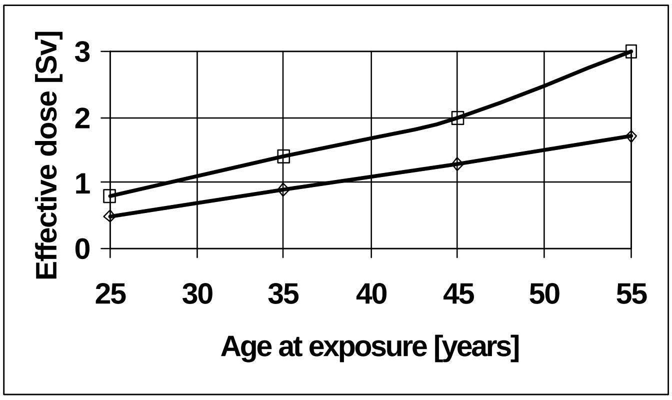

Fig. 3. Career limit (Sv) vs. age at exposure (10 y duration)

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