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ScienceDirect
Radiation Measurements 43 (2008) 1231 – 1236
Radiation Measurements
www.elsevier.com/locate/radmeas

Convolution of TLD and SSNTD measurements during the BRADOS-1 experiment onboard ISS (2001)

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Received 3 October 2006; received in revised form 6 March 2008; accepted 28 April 2008

Abstract

The Russian BRADOS experiment onboard the International Space Station (ISS) was aimed at developing methods in radiation dosimetry and radiobiology to improve the reliability of risk estimates for the radiation environment in low-Earth orbit. Experimental data from thermoluminescence detectors (TLDs) and solid state nuclear track detectors (SSNTDs) gathered during the BRADOS-1 (24 February–31 October 2001) mission are reviewed and convolved to obtain absorbed dose and dose equivalent from primary and secondary cosmic-ray particles. Absorbed dose rates in the ISS Russian Segment (Zvezda) ranged from 208 ± 14 to $275 \pm 14\,\mu\mathrm{Gy\,d^{-1}}$. Dose equivalent rates were determined to range from 438 ± 29 to $536 \pm 32\,\mu\mathrm{Sv\,d^{-1}}$, indicating a quality factor between 1.95 ± 0.15 and 2.11 ± 0.20. The contribution of densely ionizing particles ($\mathrm{LET} \geqslant 10\,\mathrm{keV\,\mu m^{-1}}$) to dose equivalent made up between 54% and 64%.

Keywords: Space dosimetry; TLD; SSNTD

1. Introduction

The Russian BRADOS research effort onboard the International Space Station (ISS) was realized under the aegis of the Institute for Biomedical Problems (IBMP) of the Russian Academy of Sciences with Austrian and Hungarian participation. The experiment was aimed at developing methods in radiation dosimetry and radiobiology to improve the reliability of risk estimates for the composite radiation environment of solar and galactic origin prevailing in low-Earth orbit (LEO). Cultures of blood cells and salad seeds were exposed in space and under ground-based reference conditions to investigate the potential correlation between operational physical quantities and radiobiological effects. Radiation sensors used onboard the ISS Zvezda Module comprised thermoluminescence detectors (TLDs) from the Atomic Institute of the Austrian Universities (ATI) of the Vienna University of Technology and solid state nuclear track detectors (SSNTDs) from the KFKI-Atomic Energy Research Institute (AERI) of the Hungarian Academy of Sciences. The experiment was initially scheduled to include the following three phases (but continued later): BRADOS-1 (24 February–31 October 2001, 248 days duration), BRADOS-2 (21 March–10 November 2002, 233 days duration) and BRADOS-3 (2 February–28 October 2003, 268 days duration). This paper summarizes and discusses experimental data gathered during BRADOS-1 which have already been published in part by the cooperating laboratories (Berger et al., 2004; Hajek et al., 2006a, b; Pálfalvi et al., 2004, 2005, 2006) and convolves TLD measurements from ATI with SSNTD measurements from AERI.

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doi:10.1016/j.radmeas.2008.04.094

2. Instruments and methods

The dose determination in space is based on the ICRU 51 (1993) (published also in ICRP 60, 1991; ICRP 74, 1996) quantity "the distribution of the absorbed dose in linear energy transfer" (LET or L) denoted as $D(L)$ in $L + \Delta L$ interval, at a point of interest in a conventionally accepted material (usually in water) and the quality factor, $Q(L)$, defined as a function of the unrestricted LET in liquid water, independent of particle type and analytically expressed in three LET intervals. Then the dose equivalent, $H(L)$ at a point is given as the product of the $D(L)$ and $Q(L)$. To obtain the total absorbed dose (D) and dose equivalent (H) the summation runs over the entire, possible LET range and finally a mean quality factor (Q) can be obtained by dividing H by D.

The acceptance of these quantities for the risk estimation of the astronauts was introduced to the space dosimetry community during the 34th Annual Meeting of the NCRP (Health Physics, 2000) and since the NCRP's recommendations are published (NCRP 2001, 2002, Reports 137 and 142) they are widely used. When passive dosimeters are considered, the dose of particles with LET $\leqslant 10\,\mathrm{keV}\,\mu\mathrm{m}^{-1}$ where $Q(L) = 1$, can be determined by, for instance, TLD technique, while for higher LET particles usually SSNTDs are used and the absorbed dose is calculated from the so-called differential LET spectrum of the incident particles using the following expression:

$D(L) = \bar{L} \times \Phi(L)$, where $\bar{L}$ is the mean LET in the $L + \Delta L$ interval and the $\Phi(L)$ is the fluence of the incident particles in the same interval (see also Eq. (4)).

2.1. Thermoluminescence detectors

Thermoluminescence dosimetry has become a widely used technique for individual monitoring at terrestrial workplaces. Due to the largely unknown thermoluminescent (TL) efficiency to particles of high charge and energy (HZE) its application to space dosimetry has previously been restricted. This limitation was accounted for by substantial ground-based research in heavy-ion beams, resembling the major aspects of galactic and solar cosmic rays. The relative TL efficiency, $\eta_{k,\gamma}$, is defined as the ratio of TL responses per unit mass and dose from the radiation under study (k) and the ^{60}Co reference radiation (γ)

$$\eta_{k,\gamma} = \frac{R_k/D_k}{R_\gamma/D_\gamma} \tag{1}$$

Herein, R_k and R_γ are the TL signals per unit mass at dose levels of D_k and D_γ, respectively. Relative TL efficiency generally tends to decrease with increasing LET which is likely related to microdosimetric track structure effects (Olko, 2004). Close to the ion's path extremely high doses are deposited locally, the TL signal saturates and the particle energy is less efficiently converted into TL light. However, different particles of the same LET can possess essentially different efficiencies (Berger et al., 2006). Horowitz et al. (2001) attributed this behavior to the complex intermediate mechanisms taking place between radiation absorption and TL emission, but pointed out

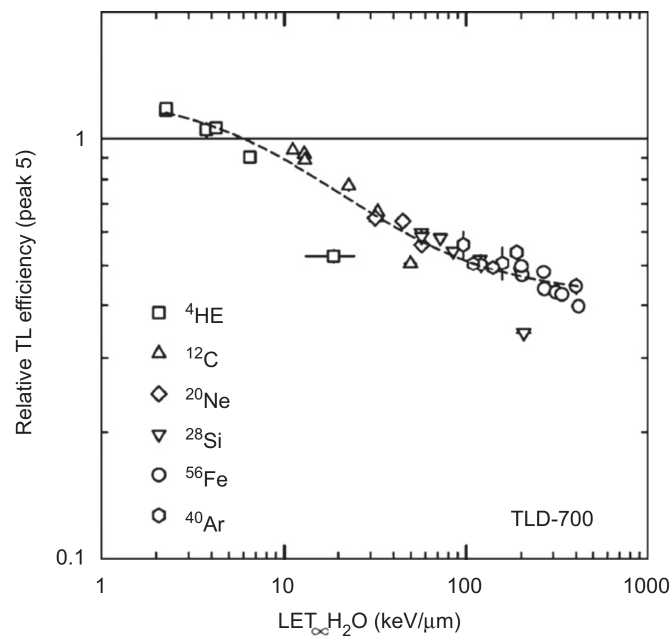

Fig. 1. Relative TL efficiency with respect to ^{60}Co for glow peak 5 in ^{7}LiF:Mg,Ti (TLD-700) for several heavy charged particles.

that a total understanding of the manner in which TL efficiency depends on ionization density was yet to be achieved. For space dosimetry applications, the mean slope of the ^{7}LiF:Mg,Ti (TLD-700) relative TL efficiency, $\bar{\eta}_{k,\gamma}$, as a function of unrestricted LET in water, L, may be approximated by the following three-parameter rational function (Fig. 1) which was derived empirically from experiments at the heavy ion medical accelerator (HIMAC) of the National Institute of Radiological Sciences (NIRS) in Chiba, Japan, for ions with charges from $Z = 2$–28 (Hajek et al., 2006a)

$$\bar{\eta}_{k,\gamma}(L) = \frac{1 + aL}{b + cL} \tag{2}$$

The regression parameters are $a = 0.0144 \pm 0.0043$, $b = 0.8021 \pm 0.0402$ and $c = 0.0456 \pm 0.0092$. TL efficiency values are influenced by the experimental protocol in use, i.e. annealing and readout parameters, method of background subtraction, etc.

The ATI dosemeter stacks accommodated in the BRADOS boxes included commercial TLD-600 (^{6}LiF:Mg,Ti) and TLD-700 (^{7}LiF:Mg,Ti) chips of the dimension $6.4 \times 6.4 \times 0.9\,\mathrm{mm}^3$, all obtained from the same batch. Each stack contained four TL chips per type sealed in polystyrene holders, i.e. a total number of eight chips. Preparation included a 400 °C, 1 h anneal and slow cool. Chip-selective pre-and post-flight calibrations in terms of absorbed dose to water were realized at the ^{60}Co γ-theratron of the Clinic for Radiotherapy and Radiobiology, Vienna Medical University. Detector read-out was accomplished in inert nitrogen atmosphere at a heating rate of $5\,°\mathrm{C\,s}^{-1}$.

2.2. Solid state nuclear track detectors

SSNTDs offer several advantages to gather information on the type and energy of particle radiations. A simple