Radiation Measurements 46 (2011) 1680–1685

Contents lists available at ScienceDirect

Radiation Measurements

journal homepage: www.elsevier.com/locate/radmeas

Comparison of the response of various TLDs to cosmic radiation and ion beams: Current results of the HAMLET project

P. Bilski [a,*], T. Berger [b], M. Hajek [c], G. Reitz [b]

[a] Institute of Nuclear Physics, Polish Academy of Sciences, Kraków, Poland
[b] German Aerospace Center, Institute of Aerospace Medicine, Cologne, Germany
[c] Institute of Atomic and Subatomic Physics, Vienna University of Technology, Vienna, Austria

A R T I C L E I N F O

Article history:
Received 8 November 2010
Received in revised form
1 February 2011
Accepted 23 March 2011

Keywords:
TLD
Cosmic radiation
TL efficiency

A B S T R A C T

HAMLET is an European Commission research project aiming at optimal scientific exploitation of the data produced within the space experiment MATROSHKA. During phase 1 of this experiment a human phantom equipped with several thousands of radiation detectors (mainly TLDs) was exposed outside the International Space Station for 1.5 years. Besides the measurements realized in Earth orbit, the HAMLET project includes also a ground-based program of intercomparison of detector response to high-energy ion beams.

Within the paper, the relative response of main glow-curve peaks of various TLDs (mostly based on LiF) used in frame of the MATROSHKA experiment by three laboratories (DLR Cologne, ATI Vienna and IFJ Krakow) for radiation in space and several ion beams, has been compared. For LiF:Mg,Ti detectors a very good agreement between results obtained by the three laboratories was observed, both for space and accelerator-based exposures. This should be considered a remarkable result, taking into account that the studied TLDs originated from six different batches, manufactured by two producers exploiting different production techniques and were processed by three laboratories, using significantly different protocols (annealing, readout, calibration, glow-curve analysis). Another type of TL detectors, LiF:Mg,Cu,P, was found to show response to cosmic radiation lower than that of LiF:Mg,Ti by 5%–18%.

1. Introduction

Cosmic radiation is one of the main constraints for long duration human space missions. Astronauts working in Low Earth Orbit (LEO) are exposed to a radiation level, which is about hundred times higher than the natural radiation on Earth and will be further increased for travels to Mars. In perspective of the permanent presence of humans in space there is a growing need for reliable estimation of the radiation risk to astronauts.

In response to this need the European Space Agency (ESA) organized the MATROSHKA (MTR) project (Reitz and Berger, 2006), under the science and project lead of the German Aerospace Center DLR. The MTR facility is an anthropomorphic phantom, which mimics a human torso and head, equipped with over 6000 radiation detectors. The majority of them are thermoluminescent detectors (TLD), but also nuclear track detectors and active radiation instruments are used. The facility is dedicated to determine the depth dose and organ dose distribution in the body, for astronauts working at the International Space Station (ISS). MATROSHKA is not only the largest application of TLDs in space measurements, but it is in general the largest international research initiative ever performed in the field of space dosimetry. The project combines the expertise of leading research institutions around the world, thereby generating a huge pool of data of potentially immense value for research.

Aiming at optimal scientific exploitation, the project HAMLET (Human Model MATROSHKA for Radiation Exposure Determination of Astronauts), was funded by the European Commission under the FP7 program, in order to process and compile the data acquired individually by the participating laboratories of the MATROSHKA experiment. Based on the experimental input from the MATROSHKA experiment phases, as well as on radiation transport calculations, a three-dimensional model for the distribution of radiation dose in an astronaut's body will be built up. Further on, the effective dose, as the best available estimation of the radiation risk, will be evaluated.

Up to now three phases of the experiment have been realized: MTR-1 (exposure outside the ISS), MTR-2A and MTR-2B (exposures

* Corresponding author.
E-mail address: pawel.bilski@ifj.edu.pl (P. Bilski).

1350-4487/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.radmeas.2011.03.023

inside the ISS – PIRS and Zvezda modules respectively). The exposure times varied between 1 and 1.5 years. The fourth phase – exposure inside the Japanese Experiment Module Kibo, was started in May 2010. The analyses of the MTR-1 data are now completed and partly published (Reitz et al., 2009), while MTR-2A and MTR-2B are still under evaluation.

Besides the measurements in the Earth orbit, the HAMLET project includes also a large program of ground-based experiments. The most important part of this program consists of the investigation of the detector response to a small, well-defined subset of the space radiation environment, available from high-energy particle accelerators. The HAMLET team was granted with a research project by the National Institute of Radiological Sciences, Chiba, Japan, which enabled realization of several measuring campaigns at the Heavy Ion Medical Accelerator, HIMAC (Chiba, Japan).

The goal of this paper is to compare the response of different TLDs used by the HAMLET co-investigators, both to space radiation within the MTR-1 orbital exposure and to various ion beams.

2. Materials and methods

2.1. MATROSHKA-1 experiment

The MTR phantom is made of commercial phantom parts established in the field of radiotherapy. It consists of 33 slices, each with a thickness of 2.5 cm, and contains natural skeletal bones embedded in tissue equivalent plastics (polyurethane). The density of this plastic is modified spatially in order to account for the differences between the lungs compared to other tissues in the human body. In each slice, special channels were made to accommodate polyethylene tubes containing TL detectors at each 2.5 cm. In this way the whole phantom was filled with over 4800 detectors within a 2.5 cm grid. Additionally at positions of some important organs (eye, lung, stomach, kidney and intestines) packages called "organ dose boxes" were placed (Fig. 1a). In these boxes a larger number of TLDs and nuclear track detectors prepared by various co-investigators, were accommodated. The phantom torso was dressed by a travel jacket ("poncho"), in which further packages with detectors (so called "poncho boxes") were located (Fig. 1b). The whole phantom was covered by a carbon fiber container of average thickness ~ 0.5 g/cm^2, which roughly corresponds to the thickness of a spacesuit (Fig. 1c).

The MTR facility was launched in January 2004 and mounted outside the module Zvezda a month later. The exposure outside the ISS lasted 539 days, whereupon the phantom was transported into the station, passive detectors were dismounted and in October 2005 downloaded to the Earth. The total time spent in space by the detectors of the MTR-1 experiment was 616 days.

2.2. TL detectors

The majority of TLDs used inside the phantom were provided by three laboratories: Institute of Nuclear Physics (IFJ) in Krakow, German Aerospace Centre (DLR) in Cologne and Institute of Atomic and Subatomic Physics in Vienna (ATI). Each of these three participating groups provided TLD types according to their own choice and processed them according to their own procedures. One of the goals of the HAMLET project is to ensure that the results obtained in this way are consistent. Table 1 summarizes the types of detectors used by the three co-investigating laboratories. All groups used ^{7}LiF:Mg,Ti and ^{6}LiF:Mg,Ti detectors and comparison of performance of these TLDs will comprise the main part of this study.

MTS-7, MTT-7, MTS-6 and MCP-7 detectors were manufactured at the IFJ Krakow and have the form of circular pellets with diameter 4.5 mm and thickness 0.6 mm. The remaining TLDs were produced by Thermo Fisher Scientific (Harshaw) and have form of square chips 3.2 × 3.2 × 0.9 mm. MTT-7 detectors are a variant of LiF:Mg,Ti with changed activator concentrations and increased response to high-LET radiation (Bilski et al., 2004).

The selected details of the measurement procedures applied by the three laboratories are compared in Table 2. The gamma calibrations were realized in terms of absorbed dose in water.

Fig. 1. The MATROSHKA phantom. Arrows indicate locations of detector packages. a) View of one of the phantom slices (#20) showing polyethylene tubes with the integrated TLD detectors and an "organ dose" package ("stomach"). b) The phantom torso dressed by the "poncho". c) The phantom covered by the container.

Table 1
TLDs used by different groups in the MATROSHKA-1 experiment.

TL material	Trade name	Groups
^{7}LiF:Mg,Ti	TLD-700	ATI, DLR
	MTS-7, MTT-7	IFJ
^{6}LiF:Mg,Ti	TLD-600	ATI, DLR
	MTS-6	IFJ
^{7}LiF:Mg,Cu,P	TLD-700H	DLR
	MCP-7	IFJ
^{6}LiF:Mg,Cu,P	TLD-600H	DLR
CaF_2:Tm	TLD-300	ATI

Table 3
Ions and energies used at the HIMAC.

HIMAC run	Ion	Primary beam energy [MeV/nuc]
HIMAC-1 May 2008	$^{4}He^{2+}$	150
	$^{12}C^{6+}$	400
	$^{56}Fe^{26+}$	500
HIMAC-2 February 2009	$^{4}He^{2+}$	150
	$^{56}Fe^{26+}$	500
HIMAC-3 February 2010	$^{12}C^{6+}$	400
	$^{28}Si^{14+}$	490

2.3. HIMAC exposures

In the years 2008–2010 four HAMLET/HIMAC runs have been performed. Within this paper the results of the first three runs are presented, as the fourth is still under evaluation. The ion beams used in these experiments are described in Table 3.

Within HIMAC-2 and -3 runs, PMMA filters were additionally used to decrease beam energies and thus obtain higher LET values. The beam dosimetry was provided by the HIMAC team based on ion chamber measurements in terms of absorbed dose in water. The delivered doses were at the level of 100 mGy. The LET values for the used beams were calculated using the SRIM-2008 code (Ziegler et al., 2010). In frame of the HIMAC exposures the relative efficiency of most of the TLD types used within MTR-1 was investigated.

3. TL response

3.1. Space radiation

The relative TL efficiency is usually defined as the TL signal produced per unit dose and mass by a radiation under study, with respect to the TL signal per unit dose produced by a reference radiation. For measurements in space this quantity cannot be determined, as one does not know the true dose values of the cosmic radiation. A quantification of the TL response may be realized only in a comparative way, by determining relative ratios of doses measured by different types of TLDs.

Among the results of the MTR-1 experiment, the data from TLDs distributed in the 3D grid over the phantom volume were not suitable for determining the relative TL response, because in each measuring position TLDs supplied by only one laboratory were placed. As the radiation field inside the phantom is not uniform, a comparison between TLDs would be meaningless and consequently these data were excluded from the present analysis. The comparison of the TLD response was therefore based on the data from: “organ boxes” (five detector packages located inside several slices of the phantom), “poncho boxes” (six detector packages located at the outer surface of the phantom) and two reference packages stored inside the ISS, where all TLDs were located relatively close to each other. In each of these packages 4–5 TLDs of each type were placed. The dose rates measured at all these locations with all TLD types are presented in Table 4.

It can be seen that both packages stored inside the ISS show very good agreement (both values always within 5%). However, for packages placed inside and outside the phantom some scattering of results is present. The reason for this is again the non-uniformity of the radiation field. Packages located inside the phantom had size of about 5 cm (see Fig. 1a). Consequently TLDs positioned in different parts of a box, were actually at different depth into the phantom. Even stronger effects may be observed for the packages outside the phantom. Here, an important role played also distribution of TLDs in two layer. Detectors located in the bottom layer measured significantly lower doses, due to attenuation of weakly penetrating component of the field. This affected mostly DLR detectors.

For that reason for direct comparison between TLD types only the reference packages stored at the ISS, where radiation field was most uniform, were used. For each TLD type the relative response was calculated by dividing the dose values measured by a given laboratory by the mean value of doses measured by ATI, DLR, IFJ with ^{7}LiF:Mg,Ti detectors. The results are presented in Table 5.

Among all results of particular importance are those obtained for LiF:Mg,Ti detectors. For packages located inside the phantom and inside the ISS, all but one ^{7}LiF:Mg,Ti results are within $\pm 5\%$. For ^{6}LiF:Mg,Ti the variation of results is somewhat bigger, but still very low. This indicates that the differences in experimental procedures applied by the three laboratories, have not biased results in

Table 2
Parameters of the measurement procedures applied by ATI, DLR and IFJ.

Parameter	ATI	DLR	IFJ
TL reader	TL-DAT.II	Harshaw 5500	RA’94 (Mikrolab)
Heating method	Contact	Hot nitrogen gas	Contact
Photomultiplier	Thorn EMI 9635 QB with Corning 7-59 filter	Hamamatsu RC095 HA	Thorn EMI 9789 QB with BG-12 filter
Neutral gas flow	Nitrogen	Nitrogen	Argon
Heating rate	5 °C/s	5 °C/s	10 °C/s
Calibration source	Co-60	Cs-137	Cs-137
Pre-heat	120 °C (30 min)*	No pre-heat	120 °C (30 min)
Glow-curve analysis	Main peak height**	Main peak height	Main peak integral
Annealing cycle***:			
LiF:Mg,Ti	400 °C (1 h) slow cooling	400 °C (1 h). 100 °C (2 h) slow cooling	400 °C (1 h). 100 °C (2 h) fast cooling
LiF:Mg,Cu,P	–	240 °C (10 min) fast cooling	240 °C (10 min) fast cooling
CaF_2:Tm	400 °C (1.5 h) slow cooling	–	–

* – TLD-600 and TLD-700 only; ** – for TLD-300 peak 5 height was used; *** – “slow cooling” means cooling of TLDs inside an oven, “fast cooling” means removing of TLDs from the hot oven after the end of the annealing period.

Table 4
Dose rates in mGy/day (in terms of absorbed dose in water) measured with TLD packages at various locations at the MATROSHKA facility and on the ISS during the MTR-1 phase, averaged over the 1.5-year period of exposure. The uncertainties represent only the experimental standard deviation of TLD results.

Location of the package	DLR				ATI			IFJ			
	TLD-600	TLD-700	TLD-600H	TLD-700H	TLD-600	TLD-700	TLD-300	MTS-6	MTS-7	MCP-7	MTT-7
Detector packages inside the phantom:											
Slice 3 (eye)	0.32 ± 0.02	0.34 ± 0.01	0.20 ± 0.01	0.22 ± 0.01	0.31 ± 0.01	0.31 ± 0.01	0.28 ± 0.01	0.32 ± 0.01	0.31 ± 0.02	0.25 ± 0.01	0.27 ± 0.01
Slice 15 (lung)	0.25 ± 0.01	0.23 ± 0.01	0.19 ± 0.01	0.18 ± 0.01	0.28 ± 0.02	0.24 ± 0.01	0.23 ± 0.01	0.29 ± 0.01	0.23 ± 0.01	0.18 ± 0.01	0.23 ± 0.01
Slice 20 (stomach)	0.28 ± 0.01	0.25 ± 0.01	0.18 ± 0.01	0.18 ± 0.01	0.28 ± 0.01	0.23 ± 0.02	0.21 ± 0.03	0.27 ± 0.01	0.22 ± 0.01	0.19 ± 0.02	0.23 ± 0.02
Slice 22 (kidney)	0.22 ± 0.01	0.21 ± 0.01	0.17 ± 0.01	0.16 ± 0.01	0.27 ± 0.01	0.23 ± 0.01	0.22 ± 0.02	0.28 ± 0.01	0.24 ± 0.01	0.19 ± 0.02	0.24 ± 0.02
Slice 27 (intestine)	0.26 ± 0.02	0.22 ± 0.01	0.18 ± 0.01	0.16 ± 0.01	0.25 ± 0.02	0.21 ± 0.01	0.20 ± 0.01	0.26 ± 0.01	0.20 ± 0.01	0.17 ± 0.02	0.21 ± 0.01
Detector packages on the phantom surface:											
Top of head	0.50 ± 0.03	0.54 ± 0.04	0.35 ± 0.01	0.38 ± 0.02	0.48 ± 0.03	0.49 ± 0.02	0.51 ± 0.01	0.50 ± 0.01	0.58 ± 0.07	0.48 ± 0.06	0.48 ± 0.02
Front up	0.60 ± 0.03	0.59 ± 0.03	0.48 ± 0.02	0.44 ± 0.01	0.71 ± 0.04	0.62 ± 0.03	0.56 ± 0.03	0.70 ± 0.05	0.67 ± 0.03	0.61 ± 0.04	0.71 ± 0.06
Front down	0.47 ± 0.03	0.47 ± 0.02	0.40 ± 0.02	0.39 ± 0.01	0.61 ± 0.07	0.55 ± 0.03	0.54 ± 0.06	0.60 ± 0.04	0.61 ± 0.06	0.55 ± 0.04	0.61 ± 0.03
Left side	0.41 ± 0.03	0.40 ± 0.02	0.32 ± 0.01	0.33 ± 0.01	0.52 ± 0.02	0.46 ± 0.01	0.44 ± 0.03	0.50 ± 0.03	0.49 ± 0.03	0.42 ± 0.04	0.50 ± 0.03
Right side	0.44 ± 0.02	0.41 ± 0.02	0.36 ± 0.03	0.33 ± 0.01	0.55 ± 0.02	0.48 ± 0.02	0.48 ± 0.02	0.53 ± 0.03	0.50 ± 0.03	0.44 ± 0.03	0.54 ± 0.04
Back up	0.45 ± 0.03	0.41 ± 0.01	0.37 ± 0.03	0.33 ± 0.01	0.58 ± 0.04	0.48 ± 0.02	0.44 ± 0.02	0.55 ± 0.05	0.49 ± 0.03	0.44 ± 0.03	0.54 ± 0.04
Back down	0.42 ± 0.03	0.40 ± 0.02	0.35 ± 0.02	0.33 ± 0.01	0.53 ± 0.04	0.47 ± 0.02	0.42 ± 0.02	0.52 ± 0.04	0.47 ± 0.03	0.41 ± 0.02	0.52 ± 0.05
Detector packages stored inside the ISS:											
#1	0.18 ± 0.01	0.16 ± 0.01	0.15 ± 0.01	0.15 ± 0.01	0.20 ± 0.01	0.17 ± 0.01	0.19 ± 0.01	0.20 ± 0.01	0.16 ± 0.01	0.16 ± 0.01	0.17 ± 0.01
#2	0.18 ± 0.01	0.17 ± 0.01	0.15 ± 0.01	0.15 ± 0.01	0.21 ± 0.01	0.18 ± 0.01	0.18 ± 0.01	0.19 ± 0.01	0.16 ± 0.01	0.15 ± 0.01	0.17 ± 0.01

a systematic way. This conclusion is very encouraging, considering the need of combining together the datasets produced by different investigators.

The relative response of LiF:Mg,Cu,P detectors is lower than that of LiF:Mg,Ti, but the difference between both types is not that large, as one may expect keeping in mind very low efficiency of LiF:Mg,Cu,P to heavy ions (see paragraph 3.2). This is certainly an effect of dominating contribution of protons and helium ions in the spectrum. Due to the same reason the response of MTT-7 is nearly identical with that of MTS-7, in spite of the much higher efficiency of MTT-7 to high-LET radiation (see Fig. 2). In a similar way may be interpreted the results of TLD-300, which efficiency to high-LET particles exceeds that of LiF:Mg,Ti (Hajek et al., 2008) The difference between results of TLD-700H and TLD-600H is negligible (particularly outside the phantom), what is a result of low intensity of thermal neutrons and low efficiency of these detectors to the products of neutron reaction with ^{6}Li.

3.2. Ion beams

The obtained results, expressed as the relative TL efficiency, are gathered in Table 6. Fig. 2 shows the same data presented as a function of radiation LET. As can be seen, the relative efficiency decreases with increasing LET for all LiF TLD types. The relative efficiency of MTT-7 is higher than that of other LiF:Mg,Ti TLDs, while efficiency of MCP-7 is much lower, as was expected. The efficiency values roughly follow unique trend lines, which is in agreement with the previous observations for this energy range (Bilski and Puchalska, 2010; Bilski, 2006; Berger and Hajek, 2008). It should be mentioned however, that for lower ion energies, the efficiency-LET relationship splits into separate branches. Possibly, the observed lower values of efficiency for 6.9 keV/μm He ions, which are below the trend lines for all TLD types, are caused by this effect. This seems especially probable for LiF:Mg,Cu,P detectors, which are known to be sensitive to any changes of ionization density. On the other hand, the data points for this LET value, may well be just experimental outliers, as for LiF:Mg,Ti and particularly for MTT-7, for which decrease of efficiency seems less probable. The relative efficiency of all LiF:Mg,Ti detectors for low-LET He ions was found to exceed unity, which is again in good agreement with the previous findings.

The main goal of the experiments at HIMAC was checking a consistency of TLD results between different groups. This was particularly important for LiF:Mg,Ti detectors, which were used by all laboratories and which comprised the basis for organ dose evaluation. To quantify the consistency of results, the values of the relative efficiency of all TLD groups were divided by the mean value

Table 5
Relative response of different TLDs to space radiation inside the ISS, with respect to the mean value of doses measured by ATI, DLR, IFJ with ^{7}LiF:Mg,Ti detectors.

Lab/TLD type	Relative response
ATI/TLD-700	1.05 ± 0.05
DLR/TLD-700	0.98 ± 0.04
IFJ/MTS-7	0.97 ± 0.04
ATI/TLD-600	1.24 ± 0.06
DLR/TLD-600	1.08 ± 0.04
IFJ/MTS-6	1.14 ± 0.05
DLR/TLD-700H	0.88 ± 0.05
IFJ/MCP-7	0.92 ± 0.04
DLR/TLD-600H	0.89 ± 0.04
IFJ/MTT-7	1.01 ± 0.04
ATI/TLD-300	1.09 ± 0.05

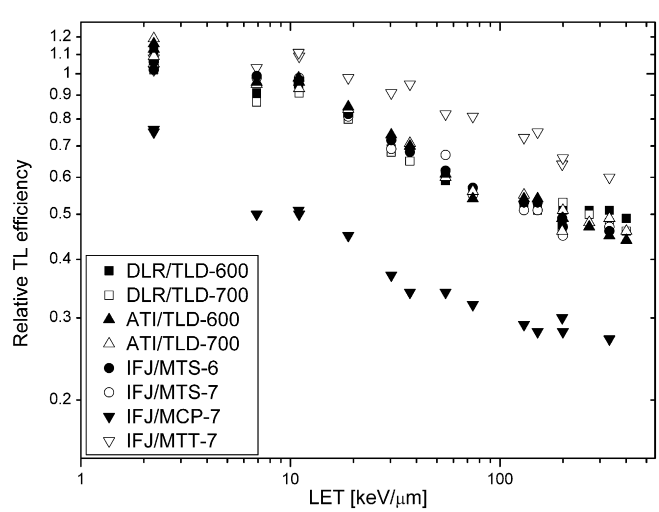

Fig. 2. Relative efficiency of various TLD types vs. LET.

Table 6
Relative efficiency of different TLDs measured for the HIMAC ion beams. The uncertainties represent only the experimental standard deviation of TLD results. The values of uncertainty equal to zero, which are given in some cases, mean that uncertainty is below 0.005.

HIMAC run	Ion	LET [keV/μm]	Relative efficiency							
			DLR		ATI		IFJ			
			TLD-600	TLD-700	TLD-600	TLD-700	MTS-6	MTS-7	MCP-7	MTT-7
H-1	He	2.23	1.12 ± 0.02	1.08 ± 0.02	1.16 ± 0.05	1.09 ± 0.03	1.06 ± 0.02	1.04 ± 0.02	0.76 ± 0.01	1.08 ± 0.03
	C	11.0	0.91 ± 0.03	0.91 ± 0.01	0.96 ± 0.02	0.93 ± 0.02	0.97 ± 0.01	0.98 ± 0.02	0.50 ± 0.01	1.09 ± 0.03
	Fe	198.2	0.48 ± 0.01	0.46 ± 0.01	0.49 ± 0.01	0.46 ± 0.01	0.49 ± 0.01	0.49 ± 0.02	0.30 ± 0.00	0.64 ± 0.02
	Mixed: He(83.3%), C(8.4%), Fe(8.4%)	19.4*	1.03 ± 0.03	1.02 ± 0.02	1.12 ± 0.01	1.05 ± 0.03	1.04 ± 0.02	1.02 ± 0.02	0.70 ± 0.04	1.05 ± 0.01
H-2	He	2.23	1.06 ± 0.03	1.02 ± 0.00	1.13 ± 0.01	1.19 ± 0.02	1.02 ± 0.01	1.07 ± 0.02	0.75 ± 0.04	1.02 ± 0.01
	He	6.9	0.91 ± 0.03	0.87 ± 0.02	0.96 ± 0.03	0.95 ± 0.04	0.99 ± 0.03	0.98 ± 0.01	0.50 ± 0.03	1.03 ± 0.04
	Fe	199.7	0.51 ± 0.02	0.53 ± 0.02	0.49 ± 0.02	0.51 ± 0.01	0.47 ± 0.01	0.45 ± 0.03	0.28 ± 0.03	0.66 ± 0.05
	Fe	332.9	0.51 ± 0.01	0.48 ± 0.02	0.45 ± 0.01	0.49 ± 0.02	0.46 ± 0.01	0.47 ± 0.01	0.27 ± 0.01	0.60 ± 0.05
H-3	Si	55.0	0.59 ± 0.01	0.60 ± 0.03	0.61 ± 0.02	0.60 ± 0.03	0.62 ± 0.00	0.67 ± 0.05	0.34 ± 0.01	0.82 ± 0.01
	Si	74.2	0.56 ± 0.02	0.56 ± 0.01	0.54 ± 0.03	0.56 ± 0.02	0.57 ± 0.00	0.55 ± 0.01	0.32 ± 0.01	0.81 ± 0.02
	Si	130.2	0.52 ± 0.06	0.53 ± 0.04	0.54 ± 0.01	0.55 ± 0.01	0.53 ± 0.00	0.51 ± 0.01	0.29 ± 0.01	0.73 ± 0.02
	Si	151.4	0.52 ± 0.04	0.51 ± 0.05	0.54 ± 0.01	0.54 ± 0.02	0.53 ± 0.00	0.51 ± 0.00	0.28 ± 0.00	0.75 ± 0.02
	C	10.9	0.95 ± 0.01	0.96 ± 0.03	0.98 ± 0.03	0.98 ± 0.02	0.95 ± 0.01	0.96 ± 0.01	0.51 ± 0.01	1.11 ± 0.03
	C	18.9	0.81 ± 0.02	0.80 ± 0.01	0.85 ± 0.02	0.84 ± 0.05	0.82 ± 0.02	0.81 ± 0.01	0.45 ± 0.01	0.98 ± 0.06
	C	30.3	0.69 ± 0.02	0.68 ± 0.00	0.74 ± 0.03	0.74 ± 0.05	0.72 ± 0.00	0.69 ± 0.01	0.37 ± 0.01	0.91 ± 0.02
	C	37.2	0.65 ± 0.01	0.65 ± 0.01	0.70 ± 0.02	0.71 ± 0.01	0.68 ± 0.00	0.68 ± 0.01	0.34 ± 0.01	0.95 ± 0.03

* – dose averaged LET.

for a given exposure. The results are presented as a function of LET in Fig. 3. As one can see, nearly all data points fall into a ±10% band. Only three data points outlie this band by about 1% (what is within the uncertainties range). There is no systematic difference between TLD batches nor between laboratories, with the exception of the ATI/TLD-600 results, which show the highest values for most of exposures. This could be an effect of slightly different properties of this batch, especially that glow-curves of detectors from this batch differed from the typical pattern (peak 4 nearly equal to peak 5). The observed dispersion of results is remarkably low, considering that the data were obtained for six different batches of TLDs, manufactured by two producers and processed by three laboratories, using significantly different protocols (annealing, readout, calibration, glow-curve analysis).

Within the HIMAC-1 run, a mixed ion exposure was realized, with intention to simulate, in a simplified way (with He ions instead of protons), a space radiation exposure. The measured relative efficiency of LiF:Mg,Ti for this radiation field was found to be close to unity in all cases. This is a result of the greater than one relative efficiency for light ions, which compensates the decreasing efficiency for heavier particles. Similar behavior is expected also for the real cosmic radiation spectrum (Bilski, 2011).

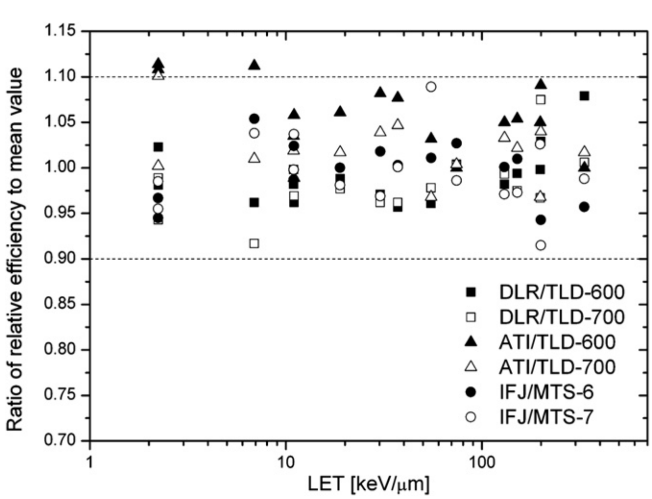

Fig. 3. Ratio of the relative TL efficiency of different groups of LiF:Mg,Ti detectors to the mean value for a given ion exposure.

4. Conclusions

The relative response of the main glow-curve peaks of various TLDs used in frame of the MATROSHKA experiment has been compared for radiation field in space and for several high-energy ion exposures.

For LiF:Mg,Ti a quite good agreement between space results obtained by three participating laboratories was observed, in spite of different experimental protocols applied. This is an important conclusion, in view of the need of combining the datasets produced by different investigators. The relative response of LiF:Mg,Cu,P detectors to cosmic radiation was found to be lower than that of LiF:Mg,Ti (5%–18%), but the difference between both types is not that large, as one may expect keeping in mind very low efficiency of LiF:Mg,Cu,P to heavy ions.

The results obtained with ion beams from the HIMAC accelerator in general agree with the previous findings: relative efficiency for all studied TLDs decreases with increasing LET and the efficiency values roughly follow unique trend lines. Again a very good conformity of LiF:Mg,Ti results was observed. Among 16 exposures of TLDs from 6 different batches, only three data points were found to be slightly outside a 10% limit around the mean value. This should be considered a remarkable result, taking into account that these six TLD batches were manufactured by two producers, exploiting different production techniques, and they were processed by three laboratories, using significantly different procedures (annealing, readout, calibration, glow-curve analysis).

Acknowledgments

The HAMLET project is funded by the European Commission under the Seventh Framework Programme (FP7) under Project Nr: 218817 and coordinated by the German Aerospace Center (DLR) http://www.fp7-hamlet.eu. The HAMLET/HIMAC runs have been performed under the HIMAC project No. 20P240. The authors gratefully acknowledge assistance of Y. Uchihori, N. Yasuda, H. Kitamura and S. Kodaira, as well as the HIMAC operating staff during the ground-based experiments.

References

Berger, T., Hajek, M., 2008. TL-efficiency – overview and experimental results over the years. Radiat. Meas. 43, 146–156.

Bilski, P., 2006. Response of various LiF thermoluminescent detectors to high energy ions – results of the ICCHIBAN experiment. Nucl. Instr. Methods Phys. Res. B 251, 121–126.

Bilski, P., 2011. Calculation of the relative efficiency of thermoluminescent detectors to space radiation. Radiat. Meas. 46 (12), 1728–1731.

Bilski, P., Budzanowski, M., Olko, P., Mandowska, E., 2004. LiF: Mg, Ti (MTT) TL detectors optimised for high-LET radiation dosimetry. Radiat. Meas. 38, 427–430.

Bilski, P., Puchalska, M., 2010. Relative efficiency of TL detectors to energetic ion beams. Radiat. Meas. 45, 1495–1498.

Hajek, M., Berger, T., Bergmann, R., Vana, N., et al., 2008. LET dependence of thermoluminescent efficiency and peak height ratio of CaF_2:Tm. Radiat. Meas. 43, 1135–1139.

Reitz, G., Berger, T., Bilski, P., Facius, R., et al., 2009. Astronaut's organ doses inferred from measurements in a human phantom outside the international space station. Radiat. Res. 171, 225–235.

Reitz, G., Berger, T., 2006. The MATROSHKA facility-dose determination during an EVA. Radiat. Prot. Dosim. 120, 442–445.

Ziegler, J.F., Ziegler, M.D., Biersack, J.P., 2010. SRIM – the stopping and range of ions in matter. Nucl. Instr. Methods Phys. Res. B. 268, 1818–1823.