PERGAMON

Radiation Measurements 35 (2002) 381–391

Radiation Measurements

www.elsevier.com/locate/radmeas

Dose measurements in space by the Hungarian Pille TLD system

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Abstract

Exposure of crew, equipment, and experiments to the ambient space radiation environment in low Earth orbit poses one of the most significant problems to long-term space habitation. Accurate dose measurement has become increasingly important during the assembly (extravehicular activity (EVA)) and operation of space stations such as on Space Station Mir.

Passive integrating detector systems such as thermoluminescent dosemeters (TLDs) are commonly used for dosimetry mapping and personal dosimetry on space vehicles. The well-known advantages of passive detector systems are their independence of power supply, small dimensions, high sensitivity, good stability, wide measuring range, resistance to environmental effects, and relatively low cost. Nevertheless, they have the general disadvantage that for evaluation purposes they need a laboratory or large—in mass and power consumption—terrestrial equipment, and consequently they cannot provide time-resolved dose data during long-term space flights.

KFKI Atomic Energy Research Institute (KFKI AEKI) has developed and manufactured a series of thermoluminescent dosemeter systems for measuring cosmic radiation doses in the 10 μGy to 10 Gy range, consisting of a set of bulb dosemeters and a compact, self-contained, TLD reader suitable for on-board evaluation of the dosemeters. By means of such a system, highly accurate measurements were carried out on board the Salyut-6, -7 and Mir Space Stations as well as on the Space Shuttle. A detailed description of the system is given and the comprehensive results of these measurements are summarised.

1. Introduction

One of the many risks of long duration space flight is the dose burden from cosmic radiation, especially during periods of intense solar activity. At such times, particularly during EVA when the astronauts are not protected by the wall of the spacecraft, cosmic radiation is a potentially serious health threat. Accurate dose measurement as well as the measurement of the radiation-weighting factor becomes increasingly important during the assembly of large space structures.

On-board personal dose measurements are mainly based on thermoluminescent dosimetry. Thermoluminescent dosemeters (TLDs) are usually made of doped inorganic crystals. They "absorb" the radiation dose by their valence electrons being excited to a higher-energy state, a fraction of which remain trapped there for prolonged periods of time. The amount of ionising radiation the crystal is exposed to is directly proportional to the number of electrons trapped in the higher energy state. When the crystal is heated, these electrons fall back to their rest energy and give off photons, causing the crystal to glow. The quantity of light given off over the heating cycle, i.e. the integral of the resulting glow curve, is proportional to the dose received by the crystal since the last time it was heated ("annealed").

TLDs are read out and evaluated by a TLD reader, which is an instrument consisting of a light-tight cavity in which the TLD can be placed and heated, and a photomultiplier

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1350-4487/02/$ - see front matter
PII: S1350-4487(02)00071-9

tube to measure the light output from the TLD. Control of the read-out process and the function to convert light output to dose take place within the electronics of the reader.

Because of the large dimensions and mass of the readers, TLDs used in space activities are generally evaluated in terrestrial laboratories only after their return to the ground. The disadvantage of on-ground evaluation is that it results in the dose accumulated since the last read-out, i.e. the dose of the whole flight, whereas with the increased duration of space flights, periodic and relatively frequent dose measurements are indeed. A small, portable, and space-qualified TLD reader suitable for reading out the TL dosemeters on orbit provides the possibility of overcoming the above-mentioned disadvantage. Such a system offers a solution for EVA dosimetry as well.

Since the end of the 1970s, KFKI AEKI has developed and manufactured specifically for spacecraft a series of TLD systems named "*Pille*" (butterfly in English). These systems consist of a set of TL dosemeters and a compact TLD reader suitable for on-board evaluation of the dosemeters. By means of these systems, highly accurate measurements were carried out on board the Salyut-6, -7 and MIR Space Stations as well as on the Space Shuttle. The newest implementation of the system has been developed and placed aboard several segments of the International Space Station (ISS).

2. The "*Pille*" TLD system

2.1. First version

This first version of "*Pille*" was developed for the Hungarian cosmonaut B. Farkas, and was used during his flight on board the Salyut-6 Space Station in 1980 (Fehér et al., 1981). Subsequently the same system was repeatedly used for on-board dosimetry by Soviet cosmonauts on Salyut-6 until 1983. The system consisted of a small TLD reader utilising on-board power, and several bulb dosemeters containing $CaSo_4$:Tm thermoluminescent material. The measurement dose range of the system was from 10 μGy to 100 mGy and measured values were displayed and manually recorded.

2.2. Improvement of the first version

In 1983, the *Pille* TLD reader was upgraded to achieve a measurement range two orders of magnitude greater than in the first version (10 μGy–10 Gy) (Fehér et al., 1983). The upgraded bulb dosemeters were based on $CaSO_4$: Dy TL material whose supralinearity beyond 1 Gy was less than $CaSO_4$: Tm. The system on board Salyut-6 was replaced by the improved version and the latter was relocated to Salyut-7 (Akatov et al., 1984) and later transferred to the Mir Space Station. This improved version of the system, including a battery-operated version of the reader, was subsequently used on board a Space Shuttle during the 41-G NASA mission in 1984 by astronaut S.Ride (Fehér et al., 1985).

2.3. New, microprocessor controlled version

The development of a brand new version containing a microprocessor-controlled reader with automatic dosemeter identification, logging on a memory card, PC-connection, etc. to provide the basis for an up-to-date TLD system for space dose measurements, started in 1993 (Apáthy et al., 1996). The new system was first used on board the Mir Space Station as part of ESA's Euromir'95 mission (1995–1996) (Deme et al., 1999a) while an other version containing additional improvements was used on the MIR within the framework of the NASA4 experiment (1997) (Deme et al., 1999b) measuring— for the first time in the history of NASA as far as we know—the dose received by astronauts during extravehicular activity (EVA).

2.4. Technical description of the system

The *Pille* TLD system (Apáthy et al., 1996) consists of numerous bulb TL dosemeters and a lightweight, compact portable TLD reader, suitable for reading out and evaluating the dosemeters at the place of exposure, i.e., on board a spacecraft. Fig. 1 shows a cross-section of the TL dosemeter. Its essential component is a small vacuum bulb made of glass (a), containing the TL material (b) glued to the surface of a resistive metal plate (c) that is heated electrically. Each TLD bulb is encapsulated in a cylindrical, pen-like metal holder. In the new version, a one-wire-port integrated electronic programmable memory chip (d), mounted inside the holder, contains the identification code, the individual calibration parameters of the dosemeter, and the date and time of the previous readout. In the latest version, the aperture (e) of the holder is covered by a tube (f) to protect the bulb from light and mechanical effects and to prevent the operator from touching the hot bulb just after read-out. The tube slips backwards automatically when the dosemeter is inserted into the reader. Three gold-plated contains (g) on one end of the holder provide a lead-in for the heating current and access to the memory chip. A milled-edged head (h) at the other end serves for operation during read-out. Except during read-out, the dosemeter is held within a protective metal case. The newest dosemeters have a diameter of 20 mm, a length of 60 mm, and a mass (together with the protective case) of 70 g.

The TLD reader is based on analogue timing circuits and digital integrated circuits operating in sequential logic in the first generation and on a microprocessor controlling all functions in the new generation. The reader heats the TL material inside the bulb at a defined rate. By measuring via a photoelectron multiplier tube the amount of light subsequently given off by the heated TL material, the TLD reader can measure the dose. In the old versions only the measured dose was displayed. In addition to the measured dose,

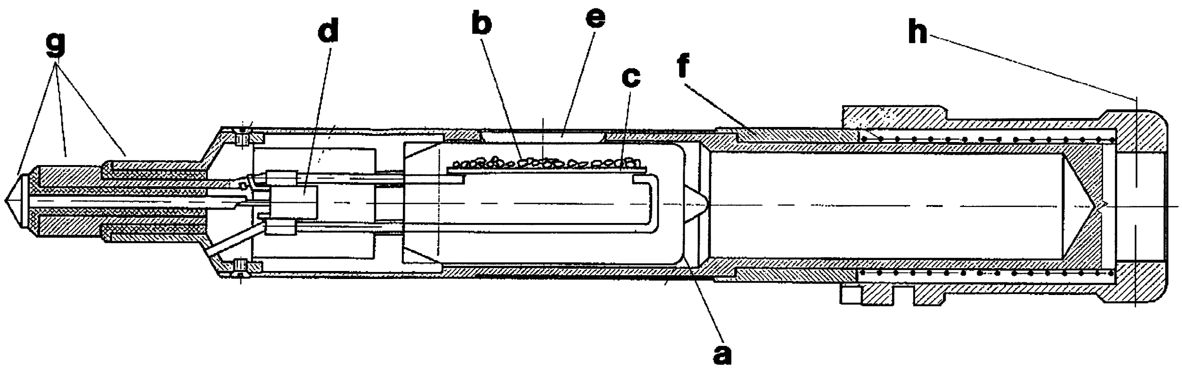

Fig. 1. Cross-section of the *Pille* TL dosemeter.

the newer versions display a series of parameters (dosemeter identifier, date and time of the current and the previous read-out, etc.) and these are stored on a removable flash memory card, up to 8000 measurements can be stored on the flash memory card. The light sensitivity of the reader can be checked by a stabilised electronic light source inserted from outside (old version) or built into the reader (new version). (In the new version) By means of a built in digital thermometer the influence of the environmental temperature is taken into account during dosemeter evaluation. The reader is powered through the central power line of the spacecraft; its maximum power consumption (during the short period of heating) is less than 10 W, its standby power consumption (new version) is less than 1 W.

The reader is a self-contained unit with thin side walls. It is based on an aluminium tube surrounded by printed circuit boards. The longitudinally located tube contains the photomultiplier tube connected to a perpendicular light-proof compartment with a bearing for the dosemeter. By virtue of its construction, the reader resists mechanical impacts during launch and fulfils space requirements. The mass of the reader is in the range of 1–1.4 kg, depending on the version.

2.5. *System operation of the new generation*

The front panel of the reader has an eight-character-wide LED display, memory card slot, aperture for the dosemeter, and five pushbuttons for controlling the reader. The TLD reader has two main modes of operation, manual and automatic. In manual mode, the user can read out the dosemeters, check or set the real time clock, check or set the parameters of the automatic mode, recall the data of any previous read-out, and initiate automatic mode. For manual readings, the dosemeter is inserted into the light-proof compartment of the reader. If one twists the dosemeter, the reading procedure is started automatically. After a measurement, the TL dose in exponential form and the measurement parameters can be displayed sequentially on the front panel. All data, including the glow curve, are stored on the memory card.

The reader can operate in automatic data acquisition mode using a dosemeter that remains in the reader. This dosemeter will be automatically read out periodically on the basis of the previously set parameters. During the time interval between read-outs the reader is in sleep mode. In automatic mode, the reader is switched on by the inbuilt timer only during read-out. The timer is powered by a small stand-by supply during sleep mode; this requires the very low power consumption of less than 0.1 W.

The reader can be connected to a personal computer (PC) via an RS-232 standard serial port. In this way, the parameters can be programmed into the reader and into the dosemeter inserted in the reader, data can be read from the memory card, and service functions can be accomplished. Optionally, the reader can be supplemented by an interface port of any other standard in order to connect it to a local on-board computer network providing remote control and data read-out.

2.6. *Dosimetric characteristics of the system*

For high-sensitivity measurements, $CaSO_4$: Dy is used as the TL material. The measurement dose range of the system with $CaSO_4$: Dy bulbs is from 3 μGy to 10 Gy at an accuracy level of $< 10\%$; above 10 μGy the accuracy of measurements is $< 5\%$. The read-out precision of the reader is 3 digits + exp. LiF:Mg, Ti TL dosemeters with linear heating profile were introduced to ensure linear energy transfer (LET) measurements using the high-temperature ratio (HTR) method (Schöner et al., 1999).

3. Earlier measurements on board Salyut-6, Salyut-7, and the Space Shuttle

3.1. *Salyut-6*

The *Pille* dosimetric system (Fehér et al., 1981) was developed in Hungary for use in international collaborations

Table 1
Results of dose field measurements on Salyut-6 from May 28 to June 2, 1980

TLD no.	Location	Dose rate (μGy/h)
1.	On space suit of Cosmonaut L.I. Popov	3.4
2.	On space suit of Cosmonaut V.V. Ryumin	3.6
3.	On space suit of Cosmonaut V.N. Kubasov	3.5
4.	On space suit of Cosmonaut B. Farkas	3.4
5.	Passage, location no. 1	4.5
6.	Passage, location no. 2	3.9
7.	Passage, location no. 3	4.5
8.	Passage, location no. 4	3.7
9.	Working area, location no. 1	3.8
10.	Working area, location no. 2	2.8
11.	Sleeping place no. 1	4.5
12.	Sleeping place no. 2	4.3

initially within the "Intercosmos" programme and was first used on the Salyut-6 Space Station in 1980 by the Hungarian cosmonaut B. Farkas and later by Soviet cosmonauts (Akatov et al., 1984). The main goal of the dosimetric experiments with the *Pille* TLD system on Salyut-6 and Salyut-7 was to study the dose distribution inside the inhabited sections of the space stations and to determine the personal dose of the crew at various times during the space flight. The dosimetric systems used in the experiments included 16 independent TL dosemeters.

The results of the first experiment on Salyut-6 from May 28 to June 2, 1980 are presented in Table 1. For in-flight calibration purposes, four *Pille* dosemeters were irradiated before lift-off by ^{137}Cs gamma rays to a dose level of 8.7 mGy (in air). When evaluated on board, the readings of these dosemeters were in agreement with the terrestrial calibration of the TLD system to within 3.5%. The next measurement by the *Pille* system on Salyut-6 was performed 350 days later—on May 18, 1981. The integral dose for this period was found to be 35.0 ± 2.0 mGy, i.e. 4.2 μGy/h (Akatov et al., 1984).

3.2. Salyut-7

In the experiments on Salyut-7 the new, upgraded "*Pille*" system was used, with a sensitivity of 1 μGy/digit. An additional on-board control light source was used from time to time for checking the sensitivity of the reader. The complete experimental programme carried out in 1983 included the measurement of the dose field in the inhabited sections of the station at 13 sites and the determination of the individual doses of the two cosmonauts for various periods of the long-term flight. The results presented in Table 2 (Akatov et al., 1984).

3.3. NASA Space Shuttle

The objective of this experiment was to place the *Pille* dosemeters in predetermined locations and to read them out periodically during the mission (Fehér et al., 1985). Three *Pille* detectors were placed on the flight deck and three on the mid-deck of the Space Shuttle during mission 41 G. NASA TLD, were also exposed at the same locations. The

Table 2
Experimental data on the dose distribution measured by the *Pille* system in 1983 in the inhabited sections of Salyut-7

TLD no.	Location	Dose rate (μGy/h)		
		21.07–26.08 (36 days)	26.08–23.09 (28 days)	23.09–11.11 (49 days)
1.	On space suit of Cosmonaut V.A. Lyakov	6.0	6.7	6.0
2.	On space suit of Cosmonaut A.P. Aleksandrov	5.0	6.1	4.9
3.	Passage, loc. no. 1	6.7	8.0	7.2
5.	Passage, loc. no. 3	6.7	9.4	8.8
6.	Passage, loc. no. 4	6.3	7.5	6.5
7.	Working section, loc. no. 1	6.3	7.4	6.6
8.	Working section, loc. no. 2	6.4	7.5	6.9
9.	Working section, loc. no. 3	6.1	7.2	6.7
10.	Working section, loc. no. 4	5.4	6.2	6.1
11.	Working section, loc. no. 5	6.8	8.5	7.3
12.	Working section, loc. no. 6	6.3	7.8	7.0
13.	Sleeping place, no. 1	7.3	8.8	7.7
14.	Sleeping place, no. 2	5.9	7.7	6.6
15.	Work section, location no. 7	6.0	7.1	6.0
16.	Work section, location no. 8	5.4	6.4	5.5

Table 3
Total doses in μGy(air)—corrected by the transport dose—measured at six different dosemeter locations of the Space Shuttle by passive TLDs of the Johnson Space Center (JSC) and by the *Pille* system

Item	Dosemeter location					
	1	2	3	4	5	6
Total dose, measured by JSC (μGY)	776	955	839	824	822	871
Total dose, measured by *Pille* (μGY)	780	967	832	835	829	900
Difference (%)	0.5	1.2	0.8	1.3	0.9	3.3

mission was flown at an inclination of 57° at three altitudes: 352, 274 and 224 km. The mission duration was 197 h. For each of these altitudes, two readings of the *Pille* dosemeters were performed by mission specialist S. Ride. At the end of the mission the dosemeters were returned to NASA JSC and the final readings were completed. The NASA dosemeters were read out independently with a standard commerical reader. The single *Pille* readings for each location were summed and compared with the results of the NASA total dose measurements for the same locations. Table 3 shows the results and the excellent agreement of the two data sets.

Because the shielding at the selected points inside the Space Shuttle was different, different doses were predicted by calculations. Dose was calculated for location #2 the highest and for location #1 the lowest dose, in accordance to the shielding conditions. The ratio of the calculated highest and lowest doses was 1.45.

The dose rate measured at the highest and lowest shielding location at different times is shown in Fig. 2. The main contributors to the dose are the trapped protons of the SAA and galactic cosmic rays. The latter contribution remains constant with decreasing altitude, whereas the SAA proton contribution decreases significantly. The measurements suggest that the cosmic ray contributions seems to be modified only slightly by the different shielding thickness around the detectors, whereas the contribution of the SAA protons to the dose is highly affected. The considerable difference between the dose rates calculated from the two doses measured at the highest altitude is explained by the effect of the SAA during the short period of the first exposure.

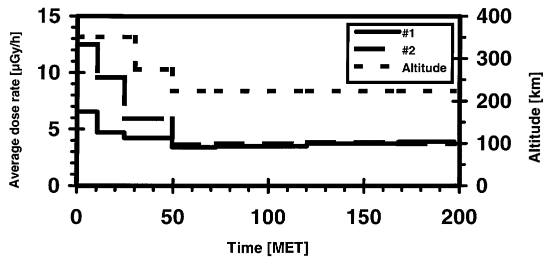

Fig. 2. Dose rates and altitude as a function of mission elapsed time during the Shuttle 41-G mission, in 1984.

4. Russian measurements on Mir

In June 1986, the reader of the *Pille* TLD system previously used on the Salyut-7 Space Station was transported by cosmonauts L. Kizim and V. Soloviev, the very first crew of Mir, from the old space station to the new one. A new set of *Pille* dosemeters arrived to Mir on board the Progress-28 transporting spacecraft in March 1987. During that year, in a period of minimum solar activity, the system was utilised by the second erew for dosimetry mapping the Mir. The results of their measurements are summarised in Table 4.

For the first time in space history the *Pille* system was used to measure the exposure of cosmonauts during their extravehicular activity. Such measurements were carried out twice (on June 12 and 16, 1987) by Y. Romanenko, the commander of the second crew of Mir, during his EVAs. During the EVA one of the dosemeters was fixed in a pocket on the outer surface of the left leg of his space-suit; a second dosemeter was located inside the station for reference measurements. Out of the EVA period both dosemeters were stored at the same location inside the space station and they were read out before leaving and after returning to it. The results of the measurements are presented in Table 5.

5. ESA measurements on Mir

Pille'95, a brand new version of the on-board TLD system of KFKI AEKI, consisting of a microprocessor controlled reader and $CaSO_4$: Dy bulb dosemeters, was used by ESA astronaut T. Reiter on board the Mir Space Station during the Euromir'95 mission in 1995–1996 (Deme et al., 1999a). The measurements were part of ESA's space dosimetry experiment D-18, led by Reitz (DLR, Cologne, Germany) (Reitz et al., 1996). The dosimeters were exposed at six locations of different shielding around them. Five of them were read out manually once a week; one of them was left in the TLD-Reader to perform periodic measurements (24-hourly and, later, hourly) in automatic mode.

Table 4
First dosimetry mapping results on Mir (1987)

Location of dosemeters	Mean dose rate (μGy/h)					
	15.03–23.04 39 days	15.05–22.06 38 days	02.07–30.07 28 days	30.07–10.10 63 days	10.11–01.12 20 days	Average for five periods
Cabin of the commander	14.2	15.0	11.7	10.4	10.8	12.4±2.0
Cabin of the board engineer	13.3	11.7	11.3	8.8	7.9	10.6±2.2
Lavatory	9.2	8.8	8.8	7.5	7.5	8.3±0.8
Passage	12.5	14.2	12.9	10.8	9.6	12.0±1.8
Storage place of photography films	8.3	8.3	7.5	7.1	6.7	7.6±0.8

Table 5
First EVA dose measurements on board Mir (June 12 and 16, 1987)

Event	Duration of EVA	Time between read-out (days)	Dose on space-suit dosemeter (μGy)	Dose inside Mir (μGy)	EVA dose (μGy)	EVA dose rate (μGy/h)
First EVA	1 h 53 m	2.0	982	711	271	144
Second EVA	3 h 15 m	3.0	1596	959	637	196

Table 6
Results of manual readout of dosemeters in the Euromir'95 experiment: absorbed dose rates (October 25–December 3, 1995)

Readout	Dose rate (μGy/h) for dosemeters no.						Mean
	1	2	3	4	5	6	
November 1	12.9	13.0	14.2	13.1	10.2	12.3	12.6
November 8	12.9	12.3	13.4	12.4	9.6	11.3	11.9
November 15	12.8	11.4	14.6	11.5	10.3	10.5	11.8
November 22	12.8	10.4	13.3	12.2	10.2	11.5	11.7
November 29	12.0	11.6	14.2	12.2	10.9	12.2	12.1
December 3	12.4	11.7	14.4	12.2	10.4	11.8	12.1
Mean $\pm\sigma$	12.6 ± 0.3	11.7 ± 0.8	14.0 ± 0.5	12.3 ± 0.5	10.3 ± 0.4	11.6 ± 0.6	12.1

The three main objectives of the experiment were (1) to measure the dose rate distribution inside the Mir Space Station, (2) to record the personal dose of the astronaut, (3) and to fulfil measurements in automatic mode with two different (daily and hourly) time periods to allow the measurement of the contribution of the SAA protons to the dose.

The results received from manual readout are given in Table 6; locations of the dosemeters are listed in Table 7. It can be seen from the data that the lowest dose rate was measured on the astronaut's body; in contrast, the highest dose rate was measured at the usual sleeping places.

Table 7
Locations of the TL dosemeters inside the Mir core module during Euromir '95

TLD no.	Location
1	Floor of the working area at small diameter (panel 132)
2	Ceiling of the working area at large diameter (panel 433)
3	Wall of the sleeping cabin (panel 117)
4	Ceiling of the working area at large diameter (panel 329)
5	Personal dosemeter
6	Overhead cabin of the board-engineer/automatic measurements

Using the hourly measuring period in automatic mode for 170 h, dose components both of galactic (independent of SAA) and SAA origin were determined. The dose rates measured in automatic mode are shown in Fig. 3. The SAA crossings, twice a day, are clearly visible. A computer code developed for our system was utilised for detailed evaluation using data stored on the memory card.

Using Mir Station's orbital data, the extra dose due to SAA crossing was calculated as a function of the longitude of the orbit at 30° south latitude (Fig. 5). It was found that the maximum dose due to crossing the SAA was equal to 55 μGy, and that the width of the SAA at 1/10 of the dose maximum was about 60° longitude at 30° south latitude. Average of all the measurements showed that the mean dose rate inside Mir was 12–14 μGy/h, and that half of this value was caused by the SAA component. Detailed results of the dose value originating from galactic and SAA components are listed in Table 8.

There was an opportunity to measure the exposure during the EVAs carried out by astronaut T. Reiter on October 20, 1995 and February 8, 1996, respectively. During the first EVA there were no reference measurements with comparable recording time so for the calculation of the EVA dose, the results of the reference measurements of the next EVA were taken into account. During the second EVA, the personal dosemeters of the two astronauts were fixed on their space-suit; a third dosemeter was located inside the core module of the station for reference measurements. While not being used for EVA, all three dosemeters were stored at the same location inside the space station and were read out before leaving and after returning to it. The difference between the EVA dose rates is due to several reasons: the effect of the SAA crossings, the different duration of stay of the astronauts in open space during the same EVA (never indicated separately), the different working location and position of the astronauts during EVA, etc. The results obtained are given in Table 13.

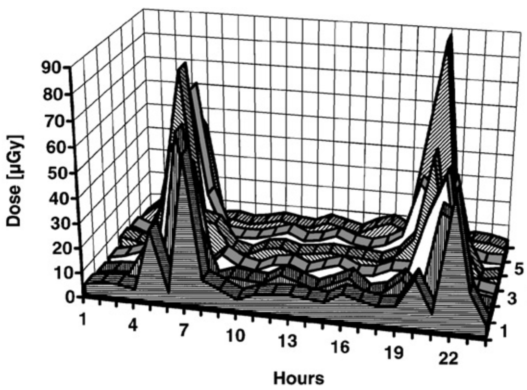

Fig. 3. Dose rate as a function of time, showing SAA crossings, based on hourly dose measurements during the Euromir'95 mission.

6. NASA measurements on Mir

The advanced TLD system *Pille*'96 was used during the NASA4 (1997) mission in the FBI-5 (Fundamental Biological Investigation) experiment (Deme et al., 1999b) to monitor the cosmic radiation dose inside the Mir Space Station and to measure the exposure of two of the astronauts during their EVA activities by means of $CaSO_4$: Dy dosemeters. In addition, LiF:Mg,Ti TLD bulbs were used to measure the mean LET of the radiation field applying the HTR method.

Internal dose mapping using $CaSO_4$: Dy dosemeters gave mean dose rates ranging from 9.3 to 18.3 μGy/h at locations inside Mir with different shielding thickness. Before flight, both types of TLD bulbs were calibrated with a standard ^{137}Cs source and, the LiF:Mg, Ti dosemeters were also calibrated using a thermalised-neutron field. The in-flight measurements were made by US astronaut J. Linenger during the Mir23/NASA4 mission. The memory card of the reader containing all the measured data was returned to Earth at the end of the STS-84 Shuttle flight. The recorded glow

Table 8
Dose values due to the galactic and SAA CR components measured during the Euromir'95 mission (February, 1996)

Day of month	Full dose (μGy/d)	Galactic dose (μGy/d)	Galactic dose rate (μGy/h)	SAA dose (μGy/d)
17	273	128	5.3	145
18	287	151	6.3	136
19	290	149	6.2	141
20	308	169	7.0	139
21	301	154	6.4	147
22	349	155	6.5	194
Total	1808	906		902
Mean (μGy/h)	12.5		6.3	

Table 9
Absorbed dose rates during the NASA4 mission (February 6–May 6, 1997)

Readout	Dose rate (μGy/h) for dosemeters no.							
	1A	2A	2B	3A	3B	4A	5A	Mean
February 13	15.1	12.6	12.6	20.3	21.1	9.9	9.7	14.5
February 27	15.6	11.7	11.5	19.3	19.2	10.0	8.2	13.6
March 15	14.7	12.5	12.5	17.2	18.3	10.2	9.2	13.5
March 24	14.5	10.0	10.4	17.7	19.0	10.1	8.7	12.9
April 7	14.1	10.9	11.0	14.9	15.2	9.9	9.5	12.2
April 24	17.2	10.8	11.0	18.8	18.7	10.2	8.7	13.6
April 29	15.4	12.7	—	—	—	10.2	—	—
May 6	14.2	11.8	13.0	19.8	20.6	9.7	11.4	14.4
Mean	15.1	11.6	11.7	18.3	18.8	10.0	9.3	13.5

Table 10
Locations of the TL dosemeters inside Mir (core module) during the NASA4 mission (February 6–May 6, 1997)

TLD no.	Location
1A	Floor of the working area at small diameter
2A,2B	Ceiling of the working area at large diameter
3A,3B	Wall of the sleeping cabin
4A	Personal dosemeter
5A	Reference dosemeter stored in the reader

curves were evaluated using a computer-based dose- and glow-curve evaluation method.

Measurement environmental radiation by the *Pille* TLDs started before the launch (January 12, 1997) of the STS-81 mission and continued until the last on board readout (May 6, 1997). The measurements constituted eight sessions as described in Table 9. The locations of the TLDs inside Mir are given in Table 10. Locations were chosen to provide comparison with other types of dosemeters and to cover a wide range of shielding conditions. The increased dose from extravehicular activity was studied during an EVA carried out by US astronaut J. Linenger and Russian cosmonaut V. Tsibliev. For EVA dose measurements, $CaSO_4$: Dy bulb dosemeters were located in specially designed pockets on the ORLAN spacesuits. The measured additional doses due to EVA (5:10 a.m.–10:08 a.m.; on April 29, 1997—UTC) were compared with the dose measured inside the Mir at the same time. During EVA on the Mir crossed the SAA three times. To correct the effect of the higher background inside the station due to the SAA, our results from the Euromir'95 mission were used. The method for correction was based on our hourly automatic TLD readouts from the *Pille*' 95 system, producing dose–rate values with very good time resolution over a long time period. From these results each dose during SAA crossings was obtained separately as a function of the crossing latitude. The corrected EVA/inside dose–rate ratio was found to be about 3. The results obtained are given in Table 11 and Fig. 4.

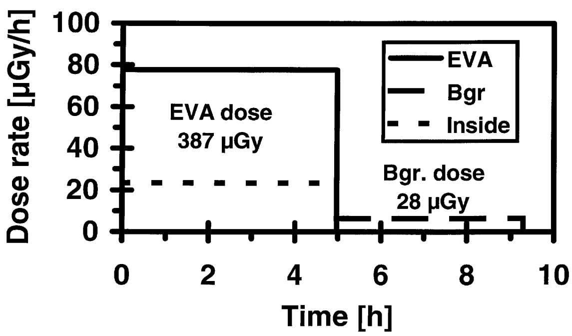

Fig. 4. Dose rates outside (astronaut) and inside Mir during EVA, indicating background dose.

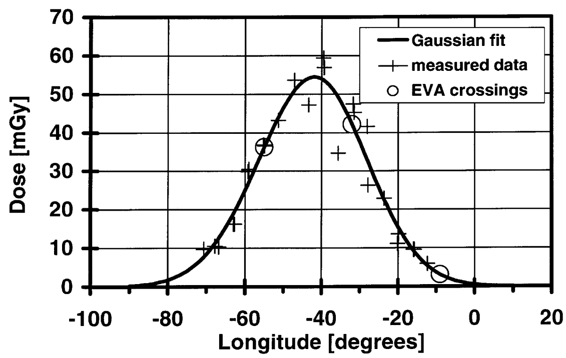

Fig. 5. Dose during SAA crossing as a function of the longitude at 30° south latitude. Circles indicate SAA crossing longitudes during EVA.

The LiF dosemeters were used to estimate the effect of the high LET radiation using the HTR method (Schöner et al., 1999). The glow curves measured on board Mir show some increase of the HTR in comparison with glow curves measured with a gamma beam (Table 12).

Table 11
EVA absorbed doses during the NASA4 mission (5:10 a.m.–10:08 a.m. 29 April, 1997—UTC)

Dosemeter	User	Readout (μGy)	Corrected by control (μGy)	Corrected with control and SAA influence (μGy)
1A	Cosmonaut (C)	415	349	386
2A	Astronaut (A)	373	307	341
4A	Control (inside)	144	—	—

Table 12
Dose and relative ratio of the high-temperature region (HTR) measured with LiF dosemeters placed at different locations inside Mir in 1997

Date of readout	2B		3B	
	Dose (mGy)	HTR ratio[a]	Dose (mGy)	HTR ratio[a]
13 February	4.57	1.27	7.64	1.37
27 February	3.90	1.44	6.45	1.31
15 March	4.87	1.46	7.11	1.51
24 March	2.37	1.63	4.31	1.24
7 April	3.73	1.27	5.16	1.37
24 April	4.48	1.57	7.59	1.62
6 May	3.84	1.36	6.08	1.36
Mean		1.43		1.40

[a]Normalized to HTR at ^{137}Cs irradiation (HTR = 1).

Table 13
EVA data obtained by the *Pille* TLD system during the Euromir '95 and the NASA4 missions

Mission	Euromir'95		Euromir'95		NASA4		
Date of EVA	20.10.95		08.02.96			29.04.97	
Total exposure time (h)	11.1	10.9	10.9	10.9	9.3	9.3	9.3
EVA duration (h)	5.2[a]	3.0[b]	3.0[c]	0[d]	5.0[e]	5.0[f]	0[d]
Dosemeter readout (μGy)	366	499	420	172	415	373	144
Dose rate inside MIR (μGy/h)	(15.8)[g]	15.8	15.8	15.8	6.5[h]	6.5	6.5
Dose accumulated inside MIR (μGy)	93	125	125	172	28[h]	28	60
EVA dose (μGy)	273	374	295	—	387	345	—
EVA dose rate (μGy/h)	53	125	98	—	78	69	—

[a]ESA astronaut T. Reiter.
[b]Russian cosmonaut Y. Gidzenko.
[c]ESA astronaut T. Reiter.
[d]Background dosimeter on board.
[e]Russian cosmonaut V. Tsibliev.
[f]NASA astronaut J. Linenger.
[g]Taken the value of the next (08.02.96) EVA.
[h]See explanation in text and Figs 4 and 5.

7. Conclusions

7.1. Equipment

Various versions of the on-board thermoluminescent dosemeter system *Pille* developed in KFKI AEKI have proven the system's capability and reliability in numerous space experiments during the last two decades. Until now, no single space qualified system having similar features has been available worldwide. TLDs are ideal for recording absorbed doses from radiation up to a LET of 20 keV/μm, but above this value their 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 calibrations, including that for $CaSO_4$: D_y generally used by our system. For the determination of the absorbed dose and especially the dose equivalent detailed information on the contributions of the high LET components is needed. Therefore, in a first experiment on board the International Space Station, KFKI AEKI's TLDs were supplemented by passive plastic nuclear track detectors (PNTDs) provided by Eril Research, Inc. (USA) for measurement of LET spectra $\geqslant 5$ keV/µm in water. TLDs and PNTDs were exposed together and the LET spectrum measurements from the PNTDs were used to correct the doses measured in TLDs and, using the corrected dose, to determine the dose equivalent. The next step will include a real time measurement of LET spectra. This will be achieved by a combination of the TLD reader with an LETspectrometer, namely with the compact, space qualified and well-proven DOSTEL of Kiel University (Beaujean et al., 1999).

7.2. Dosimetry mapping

Dose rates (12–14 µGy/h) measured during the *Euromir*'95 mission on Mir (Deme et al., 1999a) were about three times higher than those measured on board the Salyut-6 Space Station during the flight of the Hungarian cosmonaut in 1980 (Akatov et al., 1984). The main reason for this is the increased flight altitude—about 500 km.

During the NASA4 experiment on Mir (Deme et al., 1999b), three of the *Pille* dosemeters (1A, 2A and 3A) were located at the same places as three NASA Area Passive Dosemeters (ADP, viz. NMA-1, NMA-2 and NMA-3) exposed during the earlier NASA2 mission (see Benton et al., 2002). The dose rate ratios (*Pille* TLDs/APD) were found to be 1.11, 0.96 and 1.08, which is an excellent agreement.

Mean LET estimations were carried out by analysing the glow curves of LiF dosemeters. The mean LET value based on LET-TL signal calibration data published by Schöner et al. (1999) was found to be 7.5 ± 1 keV/µm. Good correspondence with other measurements has proven that the HTR analysis of LiF glow curves is a suitable method for estimating mean LET values following the ICRP-26 recommendation.

7.3. Personal dose

During the *Euromir'*95 experiment, the minimum measured dose inside Mir was that on the body of the astronaut (Deme et al., 1999a). The same was observed during the NASA4 experiment (Deme et al., 1999b), the dose rate measured with the personal dosemeter of the astronaut (10.0 µGy/h) was significantly lower than the mean value of three mapping dosemeters located in the working area and the sleeping areas (15.0 µGy/h). This can be explained by the shielding of the personal dosemeter by the body of the astronaut.

7.4. EVA dose

The dose rate increments measured by the *Pille* system during the two EVAs of the *Soviet* cosmonaut member of the second crew of Mir in 1987 were 144 and 196 µGy/h, respectively. During the *Euromir'*95 and the NASA4 missions, at the orbital inclination and altitude of the Mir Space Station, half of the dose inside the station resulted from the short time intervals passing through the SAA. The extra doses of two EVAs during the *Euromir'* 95 and one EVA during the NASA4 experiment were determined and compared with the reference doses measured inside Mir, and the mean ratio without any correction has been found to be about 4.

Acknowledgements

We should like to give special thanks to all cosmonauts and astronauts for operating the *Pille* TLD system during the experiments on different space vehicles. Our gratitude is extended to all of our scientific and technical partners who dealt with and were concerned with the various versions of *Pille* systems throughout this work. Acknowledgement and thanks are due to all those government organisations—both national and foreign—for supporting the development and the flights of the *Pille* TLD systems.

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