**ABSTRACT**

One of the many risks of long duration space flight is the dose from cosmic radiation, especially during periods of intensive solar activity. At such times, particularly during extravehicular activity (EVA), when the astronauts are not protected by the wall of the spacecraft, cosmic radiation is a potentially serious health threat. Accurate dose measurement becomes increasingly important during the assembly of large space objects. Passive integrating detector systems such as thermoluminescent dosimeters (TLDs) are commonly used for dosimetric mapping and personal dosimetry on space vehicles.

KFKI Atomic Energy Research Institute has developed and manufactured a series of thermoluminescent dosimeter systems, called Pille, for measuring cosmic radiation doses in the $3 \mu$Gy to 10 Gy range, consisting of a set of CaSO$_4$:Dy bulb dosimeters and a small, compact, TLD reader suitable for on-board evaluation of the dosimeters. Such a system offers a solution for EVA dosimetry as well. By means of such a system, highly accurate measurements were carried out on board the Salyut-6, -7 and Mir Space Stations, on the Space Shuttle, and most recently on several segments of the International Space Station (ISS).

The Pille system was used to make the first measurements of the radiation exposure of cosmonauts during EVA. Such EVA measurements were carried out twice (on June 12 and 16, 1987) by Y. Romanenko, the commander of the second crew of Mir. During the EVA one of the dosimeters was fixed in a pocket on the outer surface of the left leg of his space-suit; a second dosimeter was located inside the station for reference measurements. The advanced TLD system Pille '96 was used during the NASA-4 (1997) mission 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.

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. The paper presents EVA dose
values measured last years on ISS as well.

INTRODUCTION

One of the many risks of long duration space flights is the dose
burden from cosmic radiation, especially during periods of intensive solar
activity. At such times, particularly during EVAs, when the wall of the
spacecraft does not protect the astronauts, cosmic radiation is a
potentially serious health threat. Accurate dose measurement becomes
increasingly important during the assembly of large space objects. On-
board personal dose measurements are mainly based on thermoluminescent
dosimetry.

A small, portable, and space-qualified TLD reader suitable for
reading out the TL dosimeters on board 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" (in English: butterfly). Such systems consist of a set of TL dosimeters
and a compact TLD reader suitable for on-board evaluation of the
dosimeters. By means of such systems, highly accurate measurements were
and are 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
realised and has been placed on several segments of the International
Space Station (ISS).

THE "PILLE" TLD SYSTEM

First versions

This version of Pille was developed for the Hungarian cosmonaut B.
Farkas, and he used it during his flight in 1980 on board the Salyut-6 Space
Station (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 utilizing on-board power, and
several bulb dosimeters containing CaSO₄:Tm thermoluminescent material.
The measuring dose range of the system was from 10 µGy to 100 mGy and
the measured values were displayed and manually recorded.

In 1983, the Pille TLD reader was upgraded to achieve a measuring
range two orders of magnitude wider (10 µGy - 10 Gy) (Fehér et al., 1983).
The upgraded bulb dosimeters were based on CaSO₄:Dy TL material whose
supralinearity beyond 1 Gy was less than CaSO₄:Tm. The system on board
Salyut-6 was replaced by the improved one, and the latter was relocated
to Salyut-7 (Akatov, 1984) and later to the Mir Space Station, having been
used by Soviet cosmonauts. This improved 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).

**New, microprocessor controlled version**

The development of a brand new version containing a microprocessor-controlled reader with automatic dosimeter 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 thermoluminescent dosimeter (TLD) system consists of numerous bulb TL dosimeters and a lightweight, compact portable TLD reader, suitable for reading out and evaluating the dosimeters at the place of exposure, i.e. on board a spacecraft.

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. By virtue of its construction, the reader resists mechanical impacts during launch, and it fulfils space requirements. The mass of the reader is in the range of 1–1.4 kg, depending on the version.

For high sensitivity measurements, CaSO$_4$:Dy is used as the TL material. The measuring dose range of the system with CaSO$_4$:Dy bulbs is from 3 $\mu$Gy to 10 Gy at an accuracy level of <10%; above 10 $\mu$Gy the accuracy of measurements is < 5%.

The new system (Fig. 1) appears first on board the Mir Space Station as part of ESA’s Euromir’95 mission (1995-96) (Deme et al., 1999a) while an improved version was used on the same space station in the framework of the NASA4 experiment (1997) (Deme et al., 1999b) measuring - as far as we know for the first time in the history of NASA – the dose received by astronauts during an extravehicular activity (EVA).

![Fig. 1. Microprocessor version of PIlle TLD system. Mir version](image-url)
MEASUREMENTS

Measurements on board Salyut and Mir Space stations

The Pille dosimetric system was developed in Hungary for use in international collaborations initially within the "Intercosmos" programme, and was first used on the Salyut-6 Space Station in 1980 by the Hungarian cosmonaut B. Farkas and then, by Soviet cosmonauts. 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.

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 dosimeters was fixed in a pocket on the outer surface of the left leg of his space-suit (Fig. 2); a second dosimeter was located inside the station for reference measurements. Out of the EVA period both dosimeters 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 1.

![Image](image_url)

**Fig. 2. Location of EVA dosimeter on Russian space-suit.**

<table>
<thead>
<tr>
<th>Event</th>
<th>Duration of EVA</th>
<th>Time between readout</th>
<th>Dose on space-suit dosimeter</th>
<th>Dose inside Mir [µGy]</th>
<th>EVA dose [µGy]</th>
<th>EVA dose rate, [µGy/h]</th>
</tr>
</thead>
</table>

Table 1. First EVA dose measurements on board Mir (June 12 and 16, 1987)
Pille’ 95, a brand new version of the on-board TLD system of KFKI AEKI, consisting of a microprocessor controlled reader and CaSO₄:Dy bulb dosimeters, was used by ESA astronaut T. Reiter on board the Mir Space Station during the Euromir ’95 mission in 1995-96 (Deme et al., 1999a). The measurements were part of ESA’s space dosimetry experiment D-18, led by G. 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 were left in the TLD-Reader to perform frequent measurements (hourly) in automatic mode.

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) 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.

Using the hourly measuring period in automatic mode for 170 hours, 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 and 4. 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 55µGy, and that the width of the SAA at 1/10 of the dose maximum was about 60° longitude at 30° south latitude. Averaging of all the measurements showed that the mean dose rate inside Mir was 12-14µGy/h, and that half of this value was caused by the SAA components.
Fig. 3. Dose rate (dose/loop) measured in automatic mode

Fig. 4. Dose rate (dose/loop) measured in automatic mode during one week
Out of programme, 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 (Table 2). During the first EVA there were no reference measurements with comparable recording time so at 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 dosimeters of the two astronauts were fixed on their space-suit; a third dosimeter was located inside the core module of the station for reference measurements. Out of the EVA period all the three dosimeters were stored at the same location inside the space station and they were read out before leaving and after returning to it. The difference between the EVA dose rates is due to several reasons, like the effect of the SAA crossings, the different duration of stay of the astronauts in the opened space at the same EVA, the different working location and position of the astronauts during EVA etc. The results obtained are given in Table 2.

NASA measurements

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 CaSO₄:Dy dosimeters.

Before flight, both types of TLD bulbs were calibrated with a standard $^{137}$Cs source beam. The in-flight measurements were made by US astronaut J. Linenger during the Mir23/NASA4 mission.
Table 2. EVA data obtained by the Pille TLD system during the Euromir’95 and the NASA4 missions

<table>
<thead>
<tr>
<th>Mission</th>
<th>Euromir’95</th>
<th>Euromir’95</th>
<th>NASA4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date of EVA</td>
<td>20.10.95</td>
<td>08.02.96</td>
<td>29.04.97</td>
</tr>
<tr>
<td>Total exposure time (h)</td>
<td>11.1</td>
<td>10.9</td>
<td>10.9</td>
</tr>
<tr>
<td>EVA duration (h)</td>
<td>5.2</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Dosimeter readout (µGy)</td>
<td>366</td>
<td>499</td>
<td>420</td>
</tr>
<tr>
<td>Dose rate inside MIR (µGy/h)</td>
<td>(15.8)</td>
<td>15.8</td>
<td>15.8</td>
</tr>
<tr>
<td>Dose accumulated inside MIR (µGy)</td>
<td>93</td>
<td>125</td>
<td>125</td>
</tr>
<tr>
<td>EVA dose (µGy)</td>
<td>273</td>
<td>374</td>
<td>295</td>
</tr>
<tr>
<td>EVA dose rate (µGy/h)</td>
<td>53</td>
<td>125</td>
<td>98</td>
</tr>
</tbody>
</table>

The extra dose of the extravehicular activity was studied during an EVA carried out by US astronaut J. Linenger and Russian cosmonaut V. Tsibliev. For EVA dose measurements, CaSO4:Dy bulb dosimeters were located in specially designed pockets of the ORLAN spacesuits (Fig. 6). The measured extra doses due to EVA (5:10 am. - 10:08 am. on April 29, 1997 - UTC) were compared with the dose measured inside the space station at the same time. During EVAs, on three occasions Mir crossed the SAA (Fig. 6).
To correct the effect of the higher background inside the space station due to the SAA, our results of the Euromir'95 mission were used. The method of correction was based on our hourly automatic TLD readouts by 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 3 and Fig. 8.

![Fig. 7. Orbit of EVA (dark red) and position of SAA](image)

**Table 3.** EVA absorbed doses during the NASA4 mission (5:10 am - 10:08 am 29 April, 1997 - UTC)

<table>
<thead>
<tr>
<th>Dosimeter</th>
<th>User</th>
<th>Readout (µGy)</th>
<th>Corrected by control (µGy)</th>
<th>Corrected with control and SAA influence (µGy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A</td>
<td>Person A</td>
<td>415</td>
<td>349</td>
<td>386</td>
</tr>
<tr>
<td>2A</td>
<td>Person B</td>
<td>373</td>
<td>307</td>
<td>341</td>
</tr>
<tr>
<td>4A</td>
<td>Control (inside)</td>
<td>144</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

*Measurements on board International Space Station*
The Pille TLD system is service instrument of the Russian segment of the International Space Station. EVA dose measurement were fulfilled on board International Space Station by the Russian crew using the Pille TLD system. Results of EVA measurements are given in Figure 9.

**Fig. 8.** Dose rates outside (person A) and inside Mir during EVA, indicating background dose

**Fig. 9.** Summarised EVA dose rate data. Data from 2004.02.26 belong to ISS measurements
CONCLUSIONS

Various versions of the on-board thermoluminescent dosimeter system Pille developed in KFKI AEKI have proven the system's capability and reliability in numerous space experiments during the last two decades. Up till now, not a single space qualified system having similar features is available world-wide.

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 flying across 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.

REFERENCES


