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TL dose measurements on board the Russian segment of the ISS by the "Pille" system during Expedition-8, -9 and -10

I. Apáthy[a,*], Yu.A. Akatov[b], V.V. Arkhangelsky[b], L. Bodnár[c], S. Deme[a], I. Fehér[a], A. Kaleri[g], I. Padalka[d], T. Pázmándi[a], G. Reitz[e], S. Sharipov[f]

[a]*KFKI Atomic Energy Research Institute, P.O. Box 49, Budapest, 1121 Hungary*
[b]*Institute for Biomedical Problems, Khoroshevskoe Shosse 76a, Moscow, 123007 Russia*
[c]*BL-Electronics, Sport u. 5, Solymár, 2083 Hungary*
[d]*Gagarin Cosmonaut Training Centre, Star City, Moscow Region, 141160 Russia*
[e]*German Aerospace Center (DLR), Linder Höhe, Köln, 51147 Germany*
[f]*Russia's Federal Space Agency, ul. Shepkina 42, Moscow, 129857 Russia*
[g]*S.P. Korolev RSC Energia, ul. Lenin 4a, Korolev, 141070 Russia*

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Abstract

The "Pille-MKS" thermoluminescent (TL) dosimeter system developed by the KFKI Atomic Energy Research Institute (KFKI AEKI) and BL-Electronics, consisting of 10 $CaSO_4$:Dy bulb dosimeters and a compact reader, has been continuously operating on board the International Space Station (ISS) since October 2003. The dosimeter system is utilized for routine and extravehicular activity (EVA) individual dosimetry of astronauts/cosmonauts as part of the service system as well as for on board experiments, and is operated by the Institute for Biomedical Problems (IBMP). The system is unique in that it regularly provides accurate dose data right on board the space station, a feature that became increasingly important during the suspension of the Space Shuttle flights. Seven dosimeters are located at different places of the Russian segment of the ISS and are read out once a month. Two of these dosimeters are dedicated to EVAs and one is kept in the reader and will be read out automatically every 90 min. During coronal mass ejections impacting Earth some of the dosimeters serve for individual monitoring of the astronauts with readouts once or twice every day. In this paper we report the results of dosimetric measurements made on board the ISS during Expedition-8, -9 and -10 using the "Pille" portable thermoluminescent detector (TLD) system and we compare them with our previous measurements on different space stations.

1. Introduction

Astronauts living and working on the ISS are permanently exposed to galactic and solar cosmic radiation, which may have far-reaching health effects, of which the most important is fatal cancer. Although in low earth orbit (LEO) astronauts are partly protected by the Earth's magnetosphere and the spacecraft shielding, they are exposed to far more radiation than is typically encountered on Earth. During solar particle events (SPEs) the radiation exposure might increase to exposure levels which already may cause early radiation effects. During extravehicular activities (EVAs) the astronauts are protected only by the relatively thin space suits; therefore EVAs are scheduled in times where no crossing of the South Atlantic Anomaly—a region where the radiation belt intersects the trajectory of low orbiting spacecrafts—occurs and no increased solar activity is observed, in order to prevent heightened exposures.

* Corresponding author. Tel.: +36 1 3922291; fax: +36 1 3959293.
E-mail address: apathy@sunserv.kfki.hu (I. Apáthy).

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Once they are in space, the health risk to astronauts due to ionizing radiation depends largely on the length of time they are exposed. It should be noted that the astronaut crew of an ISS expedition resides continuously on the ISS for 6 months each time and most astronauts participate in these space flights several times during their career. This is why *general and personal on-board dose measurements have become increasingly important* as baseline data for an accurate health risk estimate.

2. Methodology

Passive integrating detector systems such as thermoluminescent detectors (TLDs) are commonly utilized for *environmental monitoring* and for *personal dosimetry*, for medical dosimetry, for dosimetry in nuclear facilities and in *astronautics*. The most well known advantages of TLDs are their independence of power supply, small dimensions, sensitivity, good stability, wide measuring range, resistance to environmental changes, and relatively low cost.

TLDs are made of (usually doped) inorganic crystal. They "absorb" radiation dose by their valence electrons being excited to a higher energy state. The amount of ionizing radiation the crystal is exposed to is directly proportional to the number of electrons at the higher energy state. When the crystal is heated, these electrons fall back to their resting energy and emit photons, causing the crystal to glow. The emitted light as a function of the temperature is called the glow curve. In a heating cycle the amount of emitted light, i.e. the integral of the resulting glow curve, is proportional to the total dose received by the crystal since the last time it was heated ("annealed").

TLDs need to be read out and evaluated by a TLD reader. Such readers consist of a light-tight cavity in which the TLD is placed to be heated and a photomultiplier tube for measuring the light output. The control of the read-out process and the mathematical function to convert light output to dose is implemented by the reader's electronics.

Although TLDs are regularly used on board spacecraft, because of the large dimensions and mass of the readers, they usually need to be returned to earth for the evaluation. In this case only integrated doses are provided for the whole exposure time. Since for long duration space flights (e.g. on board space stations or at future interplanetary missions) time-resolved measurements are required for risk projection, a small, portable and space-qualified TLD reader was developed and operated in several spacecrafts and now on the ISS.

3. Instrumentation

Since the end of the 1970s KFKI AEKI has developed and manufactured, specifically for spacecraft, a series of TLD systems named "Pille" (the word for butterfly in English). Such systems consist of a set of TLDs and a small, compact 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 [1], Salyut-7 [2] and MIR [3,4] space stations as well as on the Space Shuttle [5]. A new implementation of the system has been first placed on the US segment of the ISS [6]. The current "Pille" is a unique, space-qualified system.

The essential component of "Pille" TLDs is a small vacuum bulb made of glass, containing the TL material ($CaSO_4$: Dy), produced by the Technical University Budapest [7]) laminated to the surface of a resistive metal plate that is heated electrically. Each TLD bulb is encapsulated in a holder. A memory chip inside the holder contains the identification code and the individual calibration parameters of the dosimeter.

The "Pille" TLD reader is a compact, lightweight microprocessor controlled unit for providing the preliminary evaluation of the dose absorbed by the dosimeters. The reader heats the TL material inside the bulb at a defined rate. By measuring the amount of light given off by the heated TL material, the reader can measure the absorbed dose. The measured dose and a series of parameters (dosimeter identifier, date and time of the actual and previous read-out, etc.) are then displayed and stored on a removable flash memory card which can store data of up to 8000 measurements.

TLDs are perfect for recording absorbed doses from radiations up to a linear energy transfer (LET) of 10 keV/μm. Above this value the efficiency decreases rapidly with increasing LET. TLD measurements need to be supported by spectroscopic information about the high LET part of the radiation field from other instrumentation in order to be able to correct the TLD response at high LET values. Therefore, on board the ISS during the DOSMAP experiment [6] three orthogonal stacks of CR-39 passive plastic nuclear track detectors (PNTDs) provided by Eril Research, Inc. (USA) for measuring LET spectra $\geqslant 5$ keV/μm in water were placed on two sides and at the end of "*Pille's*" TLDs. Eleven pieces of such sets were located at different places of the ISS and exposed during the 4 months of the experiment. Average absorbed dose rates from each TLD were corrected for their dose registration efficiency of high LET particles using the LET-dependent efficiency function measured out at

Table 1
Main specifications of the '*Pille*' TLD system

Dosimeters	
Type	Bulb
Material	$CaSO_4$:Dy
Dimensions	ϕ20 mm × 60 mm
Mass	70 g (with carrying case)
Reader	
Measuring range ($s < 10\%$)	3–10 Gy ($CaSO_4$:Dy)
TLD efficiency ($\varepsilon = 1 \pm 10\%$)	LET$\infty H_2O < 10$ keV/μm
Read-out precision	3 digits + exp.
Accuracy (above 10 μGy)	$\delta < 5\%$
Measuring modes	Manual/automatic read-out
Display	8-digit alphanumeric. LED
Displayed information	Dose in μGy (air kerma)
	Date and time of measurement
	Identification numbers
	Mean dose rate
	Error codes
Storage of information	PCMCIA memory card (> 4000 data sets)
Computer connection	RS-232, CAN
Dimensions	70 mm (H) × 190 mm (W) × 120 mm(D)
Mass	1400 g
Power consumption	0.1/1/7 W (standby/ready/readout)

ground-based heavy ion particle accelerators and were then combined with dose and dose equivalent rates from particles of LET $\geqslant 10$ keV/μm in water measured in the PNTDs to yield mean total dose rate, mean total dose equivalent rate and average quality factor. At different locations, the ratio between the total dose equivalent rate and the TLD uncorrected absorbed dose rate varied between 2.1 and 2.5. Subsequently, as an approximation, a factor of 2.3 may be used for specifying the results of the on-board measurements of our stand-alone "*Pille-MKS*" TL dosimeters. The main specifications of the "*Pille*" TLD system are summarized in Table 1.

4. Measurement conditions

The "*Pille-MKS*" TLD Reader (No. 13) and ten dosimeters (Nos. A0301–A0310) were launched on the Progress-12 cargo S/C at the end of August 2003. They were installed as part of the service system in the Russian *Zvezda* module during ISS Expedition 7 by Commander *Yuri Malenchenko.*

Nine dosimeters were placed at different locations in *Zvezda* while the tenth dosimeter was inserted in the reader permanently for automatic cyclic measurements. The nine dosimeters were collected, read out and relocated roughly monthly while the one in the reader was read out automatically every 90 min (in synchronism with the orbital time of the ISS). During specific events such as extreme SPEs and EVAs two of the dosimeters were used as personal dosimeters. In the latter case a third dosimeter served as a reference one; the extra dose due to EVA was calculated by subtracting the reference dose from the EVA dose of the astronauts. The location of the dosimeters and their designation are given in Table 2. The results of the measurements are partly reported in near real-time via radio to the Earth and later—at the time of crew exchange completely transferred on memory card by the Soyuz S/C.

5. Results and discussion

During ISS Expedition 8, in the period up till April 2004, a total of 2822 measurements were completed by ISS Board Engineer *Alexander Kaleri*.

The measurements during ISS Expedition 9 from April until October 2004 (a total of 2290 ones) were carried out by ISS Commander *Gennady Padalka*, and during ISS Expedition 10 from October 2004 until April 2005 (a total of 2244 ones) by Flight Engineer *Salizhan Sharipov*. The chronology of the measurements for these three time periods is shown in Table 3.

The preliminary results of the TL dose measurements fulfilled by the "Pille-MKS" system during ISS Expeditions 8, 9 and 10 are summarized and represented in a series of diagrams.

The average dose rates measured between successive readouts of the nine "*Pille-MKS*" TLDs distributed throughout the *Zvezda* module of the station are displayed in Fig. 1. The mean dose rate for all TLDs attained a maximum in the last months of 2004 due to a considerable altitude correction. The average absorbed dose rates were 6.5 μGy/h (Expedition 8), 7.1 μGy/h (Expedition 9) and 8.2 μGy/h (Expedition 10) while the total average was 7.2 μGy/h during the three Expeditions. There are probably a number of different factors contributing to the changing dose rate measured in different locations within the ISS. The ISS altitude certainly affected the overall dose rate. Changes in the attitude of the ISS relative to its velocity vector also affect the relative particle flux at different locations within the station.

The highest average dose rates were measured by dosimeters A0301, A0302 and A0304 while the lowest ones by dosimeters A0305 and A0306. From these measurements it would appear that the locations at the illuminators in both cabins were the least shielded while the location on ceiling of the lavatory was the most

Table 2
Location and designation of the *Pille* dosimeters on the ISS

Dosimeter No.	Location in *Zvezda* module
A0301, A0302	Cabin of the right board, on both sides of the illuminator
A0303, A0304	Cabin of the left board, on both sides of the illuminator
A0305, A0306	Ceiling, on the system radiometer R-16
A0307	Right board, beside of the cabin, on ceiling of the lavatory *Dedicated for EVA reference measurement inside ISS*
A0308	Inserted in the reader, which is fixed on the floor, right to illuminator No. 9 *Dedicated for automatic measurements*
A0309, A0310	In the transporting case of the reader, left to illuminator No. 9 *Dedicated for EVA personal measurements*

Table 3
Chronology of the measurements during ISS Expeditions 8, 9 and 10

Time ranges	Activities
2003.10.28–2003.11.07 (11 days)	Frequent (daily) readouts because of a coronal mass ejection Nos. A0309, A0310 used as personal dosimeters
2003.11.13–2004.04.24 (5 months)	Regular (monthly) readout of all dosimeters (except No. A0308)
2003.11.13–2004.04.24 (5 months)	No. A0308 dosimeter read out every 1.5 h automatically
2004.02.24–25	Prior and post readouts of EVA (1 EVA during Exp. 8) Nos. A0309, A0310 personal EVA, No. A0307 reference dosimeters
2004.05.14–2005.04.21 (11 months)	Regular (monthly) readout of all dosimeters (except No. A0308)
2004.04.24–2005.04.21 (12 months)	No. A0308 dosimeter read out every 1.5 h automatically
2005.01.17–2005.01.22 (5 days)	Frequent (daily) readouts because of a coronal mass ejection Nos. A0309, A0310 used as personal dosimeters
2004.04.24/06.30/08.03/09.03/ 2005.01.26/03.28	Prior and post readouts of EVA (4 EVAs during Exp. 9, 2 EVAs during Exp.10) Nos. A0309, A0310 personal EVA, No. A0307 reference dosimeters

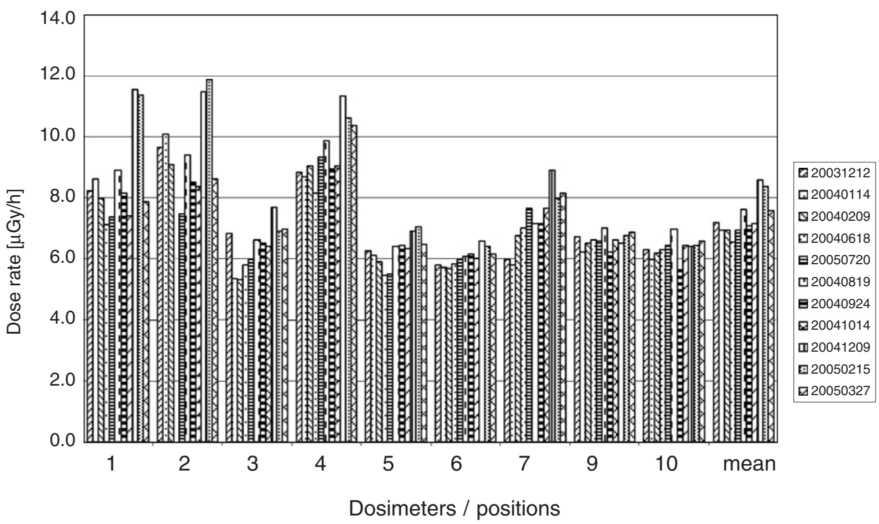

Fig. 1. Dose rates of the single dosimeters during ISS Expeditions 8, 9 and 10.

shielded. The remaining locations were all under similar shielding. The relative low dose rates measured by A0303 located at the same illuminator as A0304 is not yet explained. The sameness of the dose rates measured by A0305 and A0306 located side by side proves the accuracy and reliability of the Pille system.

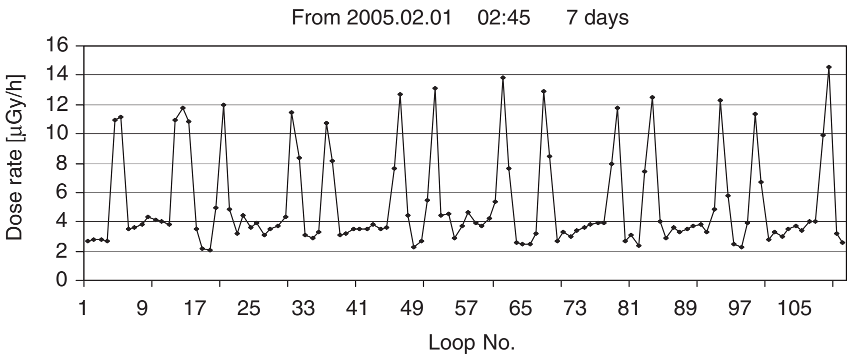

Fig. 2. 7-day sample of automatic measurements (ISS Expedition 10, dosimeter No. 8, average 5.2 μGy/h).

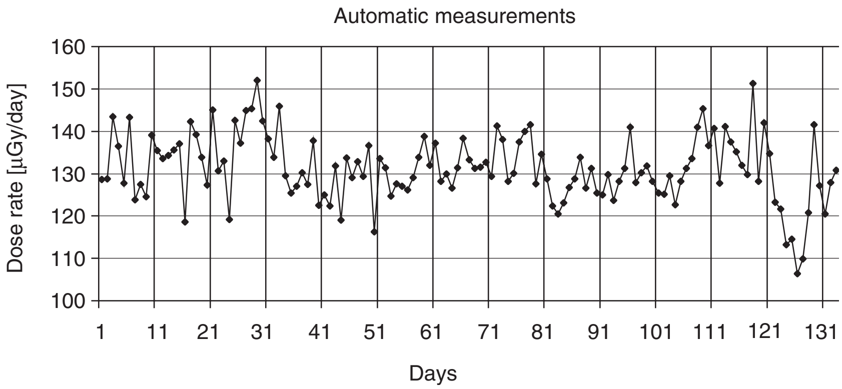

Fig. 3. Daily dose rates (ISS Expedition 9, dosimeter No. 8, average 131 μGy/day).

Fig. 2 shows a 7-day sample of the automatic measurements fulfilled by dosimeter No. 8 every 90 minutes for the period from 02:45, 1 February 2005. The sharp peaks extending from ~ 3 μGy/h up to ~ 14 μGy/h are for orbits that passed through the South Atlantic Anomaly (SAA) twice during every 24 h period and thus received a substantially larger exposure to trapped protons. The reason that all the orbits that passed through the SAA did not receive the same dose is due to the fact that each orbit passes through only a fraction of the SAA and the size of this fraction changes as the ISS orbit processes around the Earth over time.

As a sample as well, the daily dose rates based on automatic measurements during Expedition 8 are displayed on Fig. 3. The daily dose rates are the daily averages of the automatic measurements. Long-term changes in the daily dose rates are due to altitude corrections while short-term changes may be due to attitude changes, changes in the solar activity and passing through different fractions of the SAA. A reason can be as well the slight difference between the period of automatic measurements and the orbital time.

The weekly dose rates calculated in similar way for Expedition 8 can be seen in Fig. 4, where long-term changes can be followed better.

Fig. 5 shows a 4-day sample of high resolution automatic measurements showing the dose accumulated during the Solar Particle Event (SPE) on 2005.01.20. The average dose rate before and after the event including SAA crossings was ~ 5 μGy/h while between crossings ~ 3 μGy/h. During the event, between SAA crossings the average dose rate increased more than four times to a peak value of ~ 13 μGy/h and exceeded 10 μGy/h during several hours.

Results of dose measurements during EVAs are presented on Fig. 6. The differences between the dose rate of the astronauts may be due to their different tasks and consequently their different location and position (“attitude”) around the station during the same EVA. The EVA dosimeters are located in a dedicated pocket of the *Orlan* space suits on the outer side of their legs; in certain positions the dosimeter may be shielded by the body of the astronauts from one side and by the station from the other side at the same time.

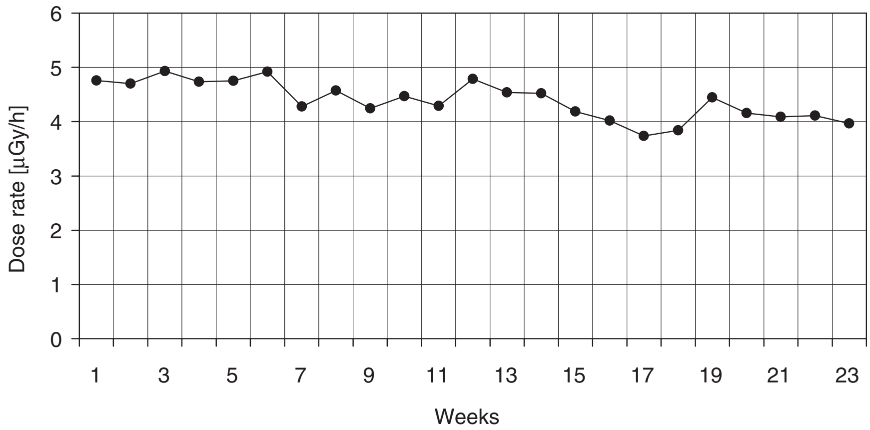

Fig. 4. Weekly dose rates (ISS Expedition 8, dosimeter No. 8, 2003.11.14–2004.04.22, average for period: 4.4 μGy/h).

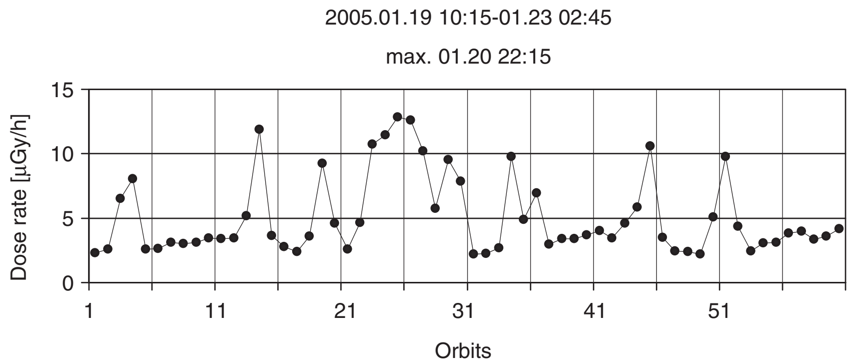

Fig. 5. Sample from an increased solar activity period (ISS Expedition 10, dosimeter No. 8, average dose rate 5.0 μGy/h, maximum dose rate 12.9 μGy/h).

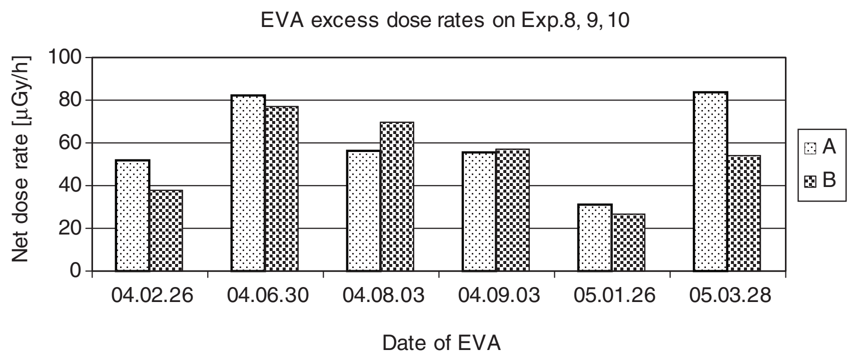

Fig. 6. Net dose rates during EVAs of ISS Expeditions 8, 9 and 10 (Astronauts A and B).

The altitude of the ISS during EVA affects the dose rate as well.

Finally, Fig. 7 compares the dose rate ranges measured on different space stations, in different time periods by "*Pille*" TL dosimeters. The average shielding on the Mir Space Station was probably less than on the ISS and Mir was orbiting sometimes on higher altitudes and in different periods of solar activity than the ISS. The average altitude of the ISS became lower since the Space Shuttle flights were suspended.

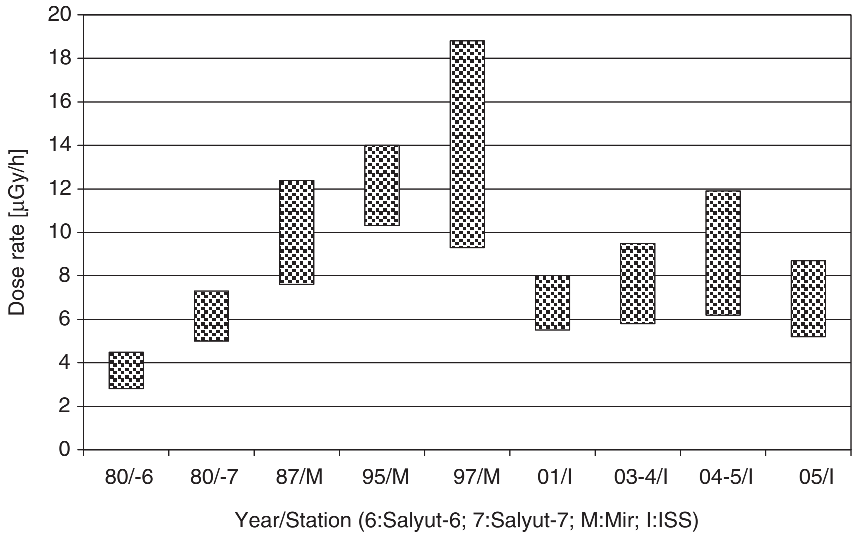

Fig. 7. Comparing dose rate ranges measured by 'Pille's on different Space Stations (Salyut-6, Salyut-7, *M*ir, *I*SS).

6. Conclusions

The "Pille-MKS" TLD system provides unique, high resolution in time, dose and dose rate data at different locations on board the ISS generally as well as during extreme SPEs and EVAs.

Apart from the obviously important contribution to provide dose measurements as basis for the estimation of the health risk of astronauts, another advantage of these long-term measurement series is that by using identical measuring equipment the data obtained on consecutive space vehicles over the last quarter of a century are fully comparable.

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We would like to give special thanks to cosmonauts Board Engineer *Alexander Kaleri*, ISS Commander *Gennady Padalka* and Flight Engineer *Salizhan Sharipov* for operating the "Pille-MKS" TLD system during Expeditions 8, 9 and 10. Our gratefulness is extended to all of our scientific and technical partners who dealt with and were concerned with the various versions of *Pille* systems throughout the work. Acknowledgement and thanks are due to all those government organizations—both national and foreign—for supporting the development and the flights of the "Pille" TLD systems.

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