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## COMPARISON OF PANASONIC'S DOSIMETRIC SYSTEM WITH GAMMA-31 DOSIMETERS

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### Abstract

Equipment being used in medical or industrial institutions is often a source of ionizing radiation with different energies and types, which complicates the detection and assessment of doses. Up until now, for dosimetric measurements of ionizing radiation, Gamma-31 dosimeters have been used in the Central Mining Institute for many years. Now, this system will be expanded by a Panasonic system, for which measurement procedures were developed and comparisons with other dosimeters were held. The method is based on a four-element dosimeters UD-802 Panasonic equipped with CaSO and LiBO detectors additionally sheltered by filters of different surface mass. The use of UD-802 dosimeters, in contrast to Gamma-31 dosimeters, permits measuring radiation doses in a different range of photon energy. Consequently, it is possible to obtain a more accurate analysis of the hazards caused by gamma radiation in underground mines. The publication includes a description of the dosimetry system and presents the results of measurements conducted by means of both types of dosimeters. In order to verify the correctness of the indications of the new dosimetry system a series of measurements were carried out, which allowed examining the behaviour of the dosimeters under different environmental conditions. As a place of exposure, the selected laboratories in the Silesian Centre for Environmental Radiometry were chosen, where the work is connected with (TE)NORM and equipment producing ionizing radiation or containing sources of this type of radiation. Moreover, to observe the dosimeters behaviour in difficult environmental conditions, they were exposed in water treatment plants and an underground potassium salt mine.

### Keywords

*ionizing radiation, thermoluminescence dosimetry, dose assessment*

## 1. INTRODUCTION

With the discovery of the phenomenon of radioactivity and the development of science and industry, previously unknown radioactive nuclides produced firstly in laboratories and then on an industrial scale appeared in the immediate vicinity of man. Radioisotopes or installations intended for radiation production are also widely used in medicine, where they are used for diagnostic and therapeutic purposes.

Over time, people have become more and more aware of the risks associated with the use of artificial or natural radioactive nuclides (the concentration of which have been enhanced by specific technological processes). Such cases demand for monitoring the environment or people and to be regulated by appropriate legal provisions. Radiation protection regulations are becoming more stringent, this requires increasing accuracy and efficiency of the measurement methods. It is necessary to be able to assess doses in more complex fields of ionizing radiation than only photon radiation. Among all the phenomena, the luminescence of solids is commonly used for the detection of radiation (Olko 2010), especially the so-called thermoluminescence dosimetry (TLD), which uses a wide range of materials with properties enabling detection in mixed radiation fields.

The existing legislation based on the recommendations of the Polish Atomic Energy Agency and the relevant ordinances of the Council of Ministers, require both users and operators to use the methods under accreditation (Act 2000). Therefore, in the Silesian Centre for Environmental Radioactivity of GIG, investigations have begun on widening the scope of accreditation with the method allowing the assessment of doses in complex radiation fields. Therefore, a detailed methodology was developed for the measurement and evaluation of doses and measurement uncertainties on the basis of the Gamma-31 and Panasonic UD-802 dosimeter, which was described in the form of standard operating procedures and instructions and is implemented in the analysis software. Furthermore, comparative measurements under laboratory conditions and in water treatment plants were carried out with the Panasonic UD-802 passive dosimeter related to the long-term used Gamma-31 dosimeter.

## 2. GAMMA-31 DOSIMETERS

It is estimated that at the turn of 1999 and 2000, approximately one million people in Europe were subjected to exposure to ionizing radiation (Frasch, Petrova 2007). Within the project EURADOS, a review of the measurement methods

was conducted. They were used in dosimetry control by the facilities located in Europe. It was found that about 70% of the facilities used methods based on thermoluminescent methods (Olko et al. 2006).

This article focuses on the passive methods, using the phenomenon of thermoluminescence: ones which have been used for many years in the Central Mining Institute (Dosimeters Gamma-31) and that which are planned to put into commercial use (Dosimeters UD-802). In general, certain substances glow as a result of radiation exposure (not only ionizing) followed by their heating. This phenomenon, called thermoluminescence, can be explained using a band model (Becker 1973). Substances displaying such properties have a relatively high energy gap, where as a result of various additives there are additional local energy levels located close to the conduction band (electron traps) and valence (hole traps). Ionizing radiation, passing through the material, causes the ionization of atoms and the

release of electrons from the crystal lattice, which are then captured by the “electron traps” in the forbidden band. Energy released during the material heating cause the transfer of electrons from the traps and the emission of photons which is registered in measuring systems called readers. One of the major advantage of thermoluminescent materials is high sensitivity to ionizing radiation, which permits detecting doses below 1 Gy and a linear response up to about several Grey units. What is more, they are characterized by resistance to high humidity and strong magnetic fields and require no power supply.

Until present day, in the Silesian Centre for Environmental Radioactivity’s accredited method, based on thermoluminescent dosimeters, Gamma-31 is used to measure doses from external gamma radiation, especially emitted by natural radioactive isotopes. Such phenomenon occurs in underground mines where the accumulated sediments contain gamma radioactive products of radium disintegration.

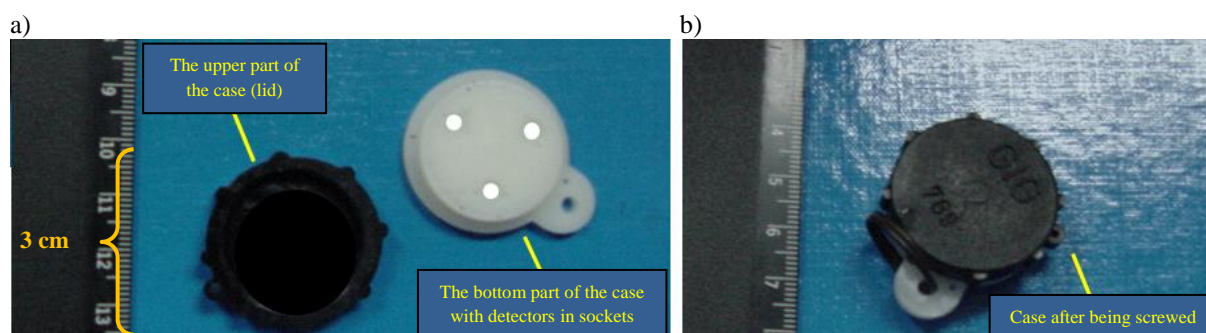


Fig. 1. Elements of the Gamma-31 dosimeter: a – open, b – closed and sealed

Dosimeter Gamma-31 is equipped with three LiF (MCP-N) type detectors, placed in sockets made from a polyethylene base (Fig. 1a). After screwing the case, the detectors are protected from harmful environmental conditions, including water and dust penetration. The recommended measuring period is from one to three months. Exposure does not require power for dosimeters, this makes them very convenient measuring instruments for both individual control as well an environmental control. The measurement analysis consists of heating the detectors up to 240°C in special systems so-called “TL readers” and an assessment of the quanta of light or ultraviolet radiation emitted during this process (Chałupnik, Skubacz 2007). In table 1 the basic characteristics of the readers used in the Central Mining Institute are shown, like the amount of detector per one reading and the kind of gas used during this process.

Table 1. An index of used readers of dosimeters Gamma-31, along with their main characteristics

Reader	Read out efficiency	Reading atmosphere	
		nitrogen	argon
Ra'92 TLD Reader/Analyser	operator is able to read out singular detector	✓	✓
Ra'94 TLD Reader/Analyser	operator is able to read out singular detector	✓	✓
Harshaw 5500	operator is able to read out up to 50 detectors automatically	✓	–

### 3. PANASONIC SYSTEM

Within project MOWITEGRAC POIG 02.01.00-24-045/08 project carried out in 2008-2011, the Silesian Centre

for Environmental Radioactivity of GIG purchased a Panasonic measuring device designed to conduct large-scale dose measurements. The system consists of a set of dosimeters, the UD-794D device to irradiate dosimeters and the UD-7900M reader. Dosimeters UD-802 are composed of four detectors which are permanently placed inside the plastic housing. During the measurements, they are additionally sat inside a protective case UD874ATM (Fig. 2). The cassette, apart from securing dosimeters from adverse environmental conditions, can be easily attached to any item of clothing, or can be hung in a place where the environmental measurement is carried out.



Fig. 2. From the left: UD-802 dosimeter in a protective housing, the case UD-874ATM, dosimeter in a case and the key to open the case

The reaction of the dosimeter to the various types of radiation and its energy depends on the type of detector and filter (Table 2). For example, beta radiation will not reach the fourth one of the detectors, which is covered with a lead layer with a surface mass of 700 mg/cm<sup>2</sup>. In order to read it, a case containing the detectors should be removed from the protective cover and put in the clip. The result is four outcomes, one for each detector. Values and variations for individual

outcomes allow us to come to the conclusion regarding the energy and type of radiation, and then to assess the dose of its individual components separately.

**Table 2.** Characteristics of detectors and filter materials that they are covered with; E: element

Element	Phosphor	Surface mass of filters mg/cm <sup>2</sup>	Surface mass of protective case mg/cm <sup>2</sup>	Total surface mass mg/cm <sup>2</sup>
E1	Li <sub>2</sub> B <sub>4</sub> O <sub>7</sub>	14 (plastic)	3 (plastic)	17
E2	Li <sub>2</sub> B <sub>4</sub> O <sub>7</sub>	160 (plastic)	160 (plastic)	320
E3	CaSO <sub>4</sub>	160 (plastic)	160 (plastic)	320
E4	CaSO <sub>4</sub>	700 (lead)	160 (plastic)	860

Reader UD-7900M Panasonic (Fig. 3) is a fully automated device. After a single loading of clips, a reading of 500 items of dosimeters within 4 hours can be performed (3000/day). The reader operation is controlled by the factory software of the Panasonic. Each dosimeter has its own unique ID, this enables associating the results with the other important parameters and joining them together to a text file. A user can affect the functioning of the reader, changing the steering parameters of work as intended. The heating at about 210°C of detectors takes place as the result of the emission of infrared radiation by Tungsten's lamp within 900 ms (Romero, Rodríguez, Delgado 2004). Each sensor is irradiated three times. Pre-heating enables eliminating the contribution of low-energy signals, and the impulses generated during this period are not included in the final result. The counts obtained during the subsequent heating are a useful signal as it is the basis for the assessment of radiation doses. The aim of the third, in turn, heating of the detector is to remove any information regarding the conducted exposure, which permits reusing the dosimeter for the next measurement. The reader has a built-in microprocessor to control the process of reading and an interface for communication with a PC via the RS-232 port.

All signals generated by the photomultiplier are transmitted digitally to the appropriate (im)pulse counter. The Panasonic reader has two counters: a photon counter and a frequency meter. Both record the signals from the heated detectors. In the case when the number of (im)pulses registered by the frequency meter exceeds the specified value which is equal to 1960 (the so-called *cross-over*) declared in an appropriate parameter, its counts are the basis for the calculation of the dose. Otherwise, the signal from the photon counter is taken into account. Both counters have varying sensitivity that is why it is necessary to calibrate each reader individually. Due to the different sensitivity of the detectors (about 1:60), the *cross-over* value is much more difficult to cross when reading LiBO than CaSO detectors.

The UD-794D (Fig. 3) device is equipped with a high-activity source of Cs-137 and can irradiate dosimeters in a series with a given, user-defined dose. In this way, individual relative correction coefficients can be determined for each of the dosimeters in a series. This is not a method for calibrating the reader in itself. The calibration is performed under different conditions by mean of devices generating radiation and phantoms, where ionization chambers are used for the determination of the reference kerma of ionizing radiation.

On the one hand, the application of different detectors and filters in dosimeters UD-802 facilitates discriminating low-energy radiation. On the other hand, it permits compensating

for the oversensitivity to photon radiation, especially phosphor CaSO<sub>4</sub> (Olko et al. 2006). For the UD-802 detectors, a comparison of the response of elements E1 and E4 is sufficient to determine whether the beta radiation influenced the dosimeter. The relative differences in the signals from the elements E3 and E4 indicate the energy of photon radiation and in particular the presence of its low-energy component (Stanford, McCurdy 1990). Observation of the dosimeters behaviour in different radiation fields makes it possible to develop the algorithms for dose assessment in the case of different types of radiation. By applying the algorithm developed in Physikalisch-Technische Bundesanstalt (PTB, Germany), the individual dose equivalent to  $H_p(10)$  in the field of photon radiation is determined. For these and more complex cases, an algorithm developed by Panasonic can be used, which facilitates assessing such values as:  $H_p(10)$ ,  $H_p(3)$ ,  $H_p(0.07)$  for photon radiation and  $H_p(0.07)$  for beta radiation. It can be also qualitatively assessed whether the dosimeters were influenced by thermal neutrons.



**Fig. 3.** Reader UD-7900M by Panasonic and Irradiator UD-794

#### 4. COMPARISON OF UD-802 AND GAMMA-31 DOSIMETERS IN HANDLING

It was decided to choose a new system from Panasonic due to the advantages which became evident thanks to new design solutions. Table 3 summarizes the main advantages and disadvantages of each system. They show quite clearly the advantage of a more modern system from Panasonic.

**Table 3.** A comparison in handling the UD-802 and Gamma-31 dosimeters

UD-802	Gamma-31
<b>Advantages</b>	
<ul style="list-style-type: none"> <li>- Ability to measure doses in the fields of different energy and type of radiation.</li> <li>- Automatic identification of dosimeters and comparing numbers with the results of the readings.</li> <li>- Fixed location of the detectors in dosimeters, which allows to assign permanent calibration coefficients.</li> <li>- Simple and automated contactless reading of up to 500 dosimeters simultaneously within four hours.</li> </ul>	<ul style="list-style-type: none"> <li>- Phosphors housing provides a high level of protection against mechanical damage and adverse environmental conditions, such as water and dust.</li> <li>- Low cost of a single dosimeter, what is approximately 10 euro.</li> </ul>
<b>Disadvantages</b>	
<ul style="list-style-type: none"> <li>- The relatively high cost of the dosimeter, what is approximately 20 euro.</li> <li>- Applied protective case gives relatively little protection against external factors, which can increase the cost of their use in underground mines.</li> </ul>	<ul style="list-style-type: none"> <li>- The costs caused by the need to perform the reading in a nitrogen atmosphere.</li> <li>- No possibility of automatic identification.</li> <li>- Manual preparation of dosimeters to be read and low efficiency of the system.</li> <li>- For use only in a discrete field of gamma photon radiation.</li> </ul>

## 5. ANALYSIS OF RESULTS OF MEASUREMENTS

### 5.1. UD7900M Reader Calibration

In order to analyse the results, the calibration of the reader UD-7900M was performed at the Central Mining Institute as follows. Selected reference dosimeters were irradiated at a certified source of Cs-137, using the IM6/M-2 device, producing a collimated beam. The apparatus is coupled with an optical calibration bench on which the dosimeters are placed.

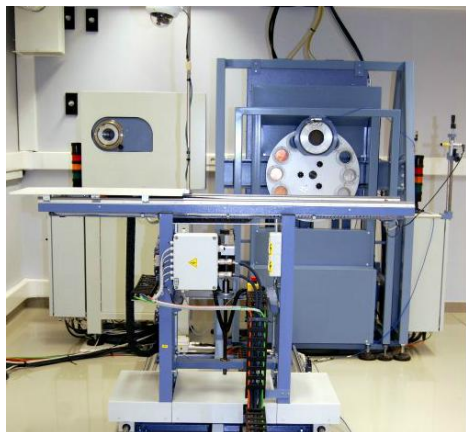


Fig. 4. Irradiator IM6/M2 with calibration bench (left site)

Two distances, 2.32 and 1.82m respectively for lower and higher calibration doses generated by the Cs-137 source of a activity of 100 Ci have been determined, thereby allowing us to obtain doses activating the work of both counters of the reader's signal. In addition, a similar process was conducted, irradiating the dosimeters with the wide panoramic beam of radiation emitted by Cs-137. During this procedure, the dosimeters were irradiated with a cuboid phantom or without any phantom (Table 4).

Table 4. Results connected with calibrations of the TLD Reader

Counter	Irradiation Kerma	Calibration Factor	
		Free in air (without phantom)	Slab Phantom [Hp(10)]
P-Counter	2.45 ±0.03 [mGy]	24.6·10 <sup>-6</sup> ±0.4·10 <sup>-6</sup> [mGy/cnt]	26.8·10 <sup>-6</sup> ±0.5·10 <sup>-6</sup> [mSv/cnt]
F-Counter	28.29 ±0.33 [mGy]	4448.4·10 <sup>-6</sup> ±81.3·10 <sup>-6</sup> [mGy/cnt]	4760.3·10 <sup>-6</sup> ±76.3·10 <sup>-6</sup> [mSv/cnt]

### 5.2. UD-802 and Gamma-31 dosimeters exposure by means of the source Cs-137

As part of the correctness test of the UD-802's and Gamma-31's indications, radiation measurements by use of the certified source Cs-137 under identical conditions were performed where the reference kerma rate was equal to 126.6 μGy/h. Table 5 shows the results of measuring the kerma rate for comparison. The obtained mean values for both groups of dosimeters show differences of about 2%. In the case of UD-802 dosimeters, a greater dispersion of results was observed. This discrepancy of indications can be explained by the fact that the results obtained by Gamma-31 dosimeters are the average of three indicators of identical detectors. In the Panasonic dosimeters, the determination of the dose from gamma radiation of higher energy, comparable with Cs-137 radiation

energy, is carried out on the basis of one detector element (E3), while the indications of the remaining three doses permit evaluating other types of radiation. In addition, each dosimeter Gamma-31 is calibrated separately and in large-scale systems, the calibration coefficient is the average value determined for the particular group of reference dosimeters, which should be eliminated by the individual correction coefficients.

Table 5. A comparison of Gamma-31 and UD-802 dosimeters indications irradiated with Cs-137 source

UD-802		Gamma-31	
identifier	kerma rate, μGy/h	identifier	kerma rate, μGy/h
130	119.49 ±6.09	172	118.91 ±4.15
147	120.99 ±6.11	940	120.62 ±4.22
187	122.17 ±4.75	941	120.28 ±4.21
204	118.23 ±4.55	1023	119.14 ±4.16
239	117.98 ±4.93	1152	119.37 ±4.17
284	124.76 ±5.08		
402	112.78 ±4.48		
783	117.24 ±4.40		
1039	131.59 ±6.08		
1239	126.41 ±8.68		
Average	121.16	Average	119.67
Standard deviation	5.35	Standard deviation	0.74

### 5.3. Measurements carried out in the laboratories of the Silesian Centre for Environmental Radioactivity

A series of measurements aimed to compare the kerma rate calculated on the basis of indications of dosimeters Gamma-31 and UD-802 were performed. On their basis, the radiological risk for various work places and individual control can be analysed.

Figure 5 shows the results of measurements carried out in the Laboratories of the Silesian Centre for Environmental Radioactivity (Polish acronym: BCR). As part of the routine monitoring, both individual and environmental measurements have been carried out. The determined values of kerma rate range from 0.045 μGy/h to 0.107 μGy/h. The average indications for individual measurements were as follows:

- 0.061 μGy/h (in the case of UD-802 dosimeters)
- 0.065 μGy/h (in the case of Gamma-31 dosimeters).

The differences observed in the responses of different types of dosimeters in individual cases can reach a maximum of 20%; however, in most cases they do not exceed 7%. In addition, in monthly periods a series of measurements were performed in different laboratories of the Silesian Centre for Environmental Radioactivity:

- Radiochemistry Unit (Fig. 6), where the studies of water radioactivity are conducted and there is a storage room for liquid samples. Moreover, a few radioactive standard solutions are kept in the laboratory
- Gamma-Ray Spectrometry Unit (Fig. 7), where gamma spectrometric measurements are performed and a storage room for solid samples exists.

Dosimetry Unit (Fig. 8), where facilities for the production of ionizing radiation are located.

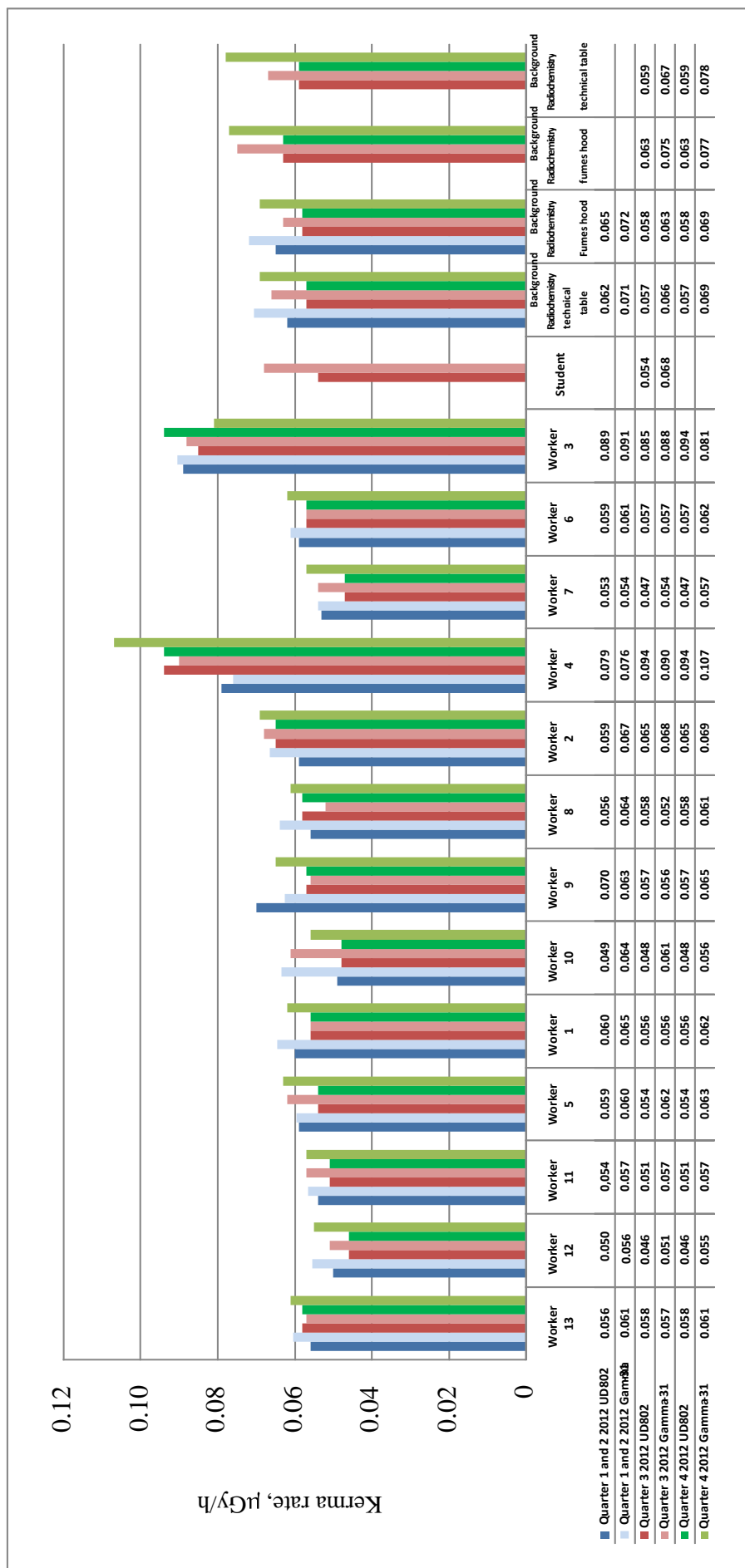


Fig. 5. A comparison of the results given in [µGy/h] of the quarterly dosimetry measurements by means of various thermoluminescence dosimeters in 2012 (workers, students and measurement stands of the Silesian Centre of Environmental Radioactivity)

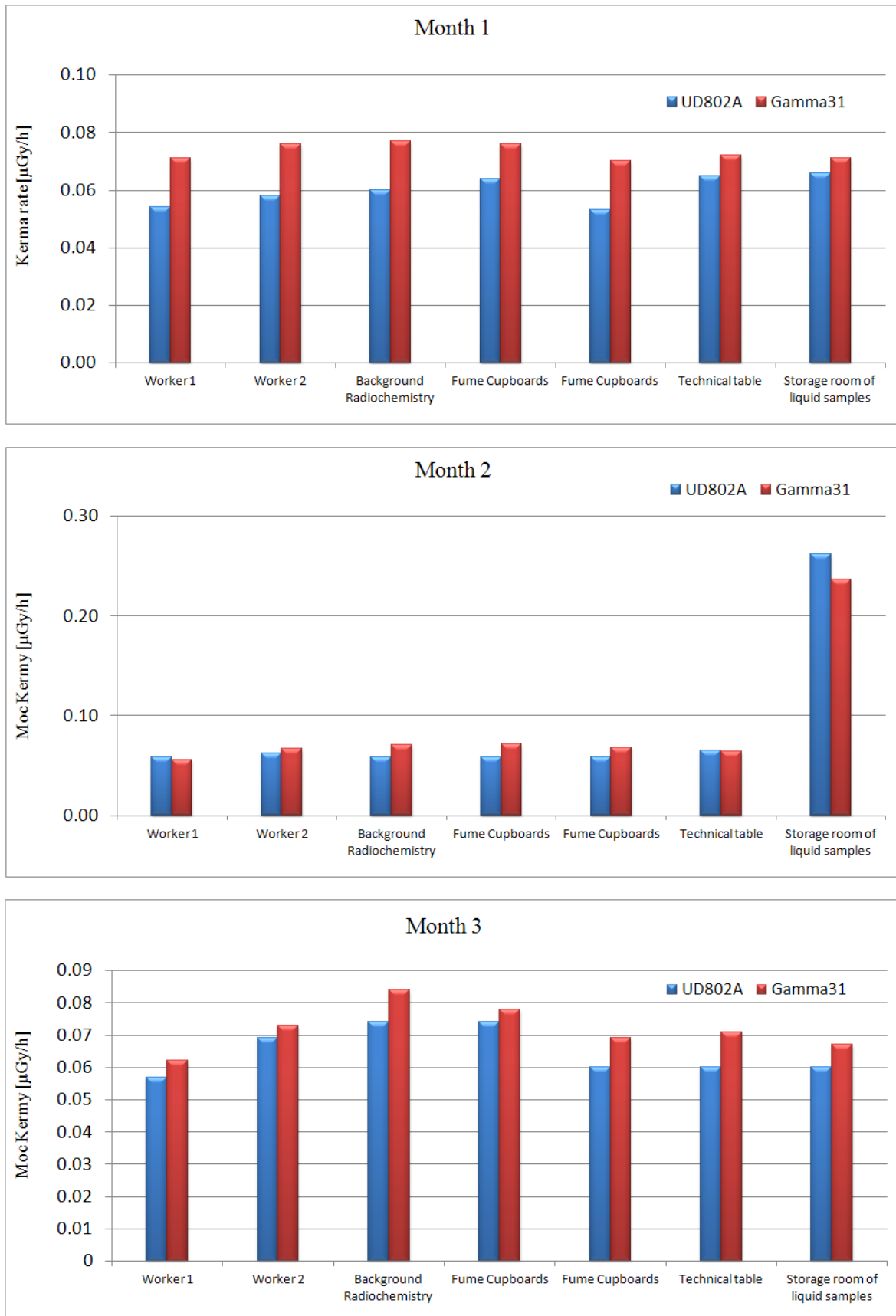


Fig. 6. The results given in [μGy/h] of dosimetric control and comparison of the indicators of Gamma-31 and UD-802 dosimeters carried out in Radiochemistry Unit

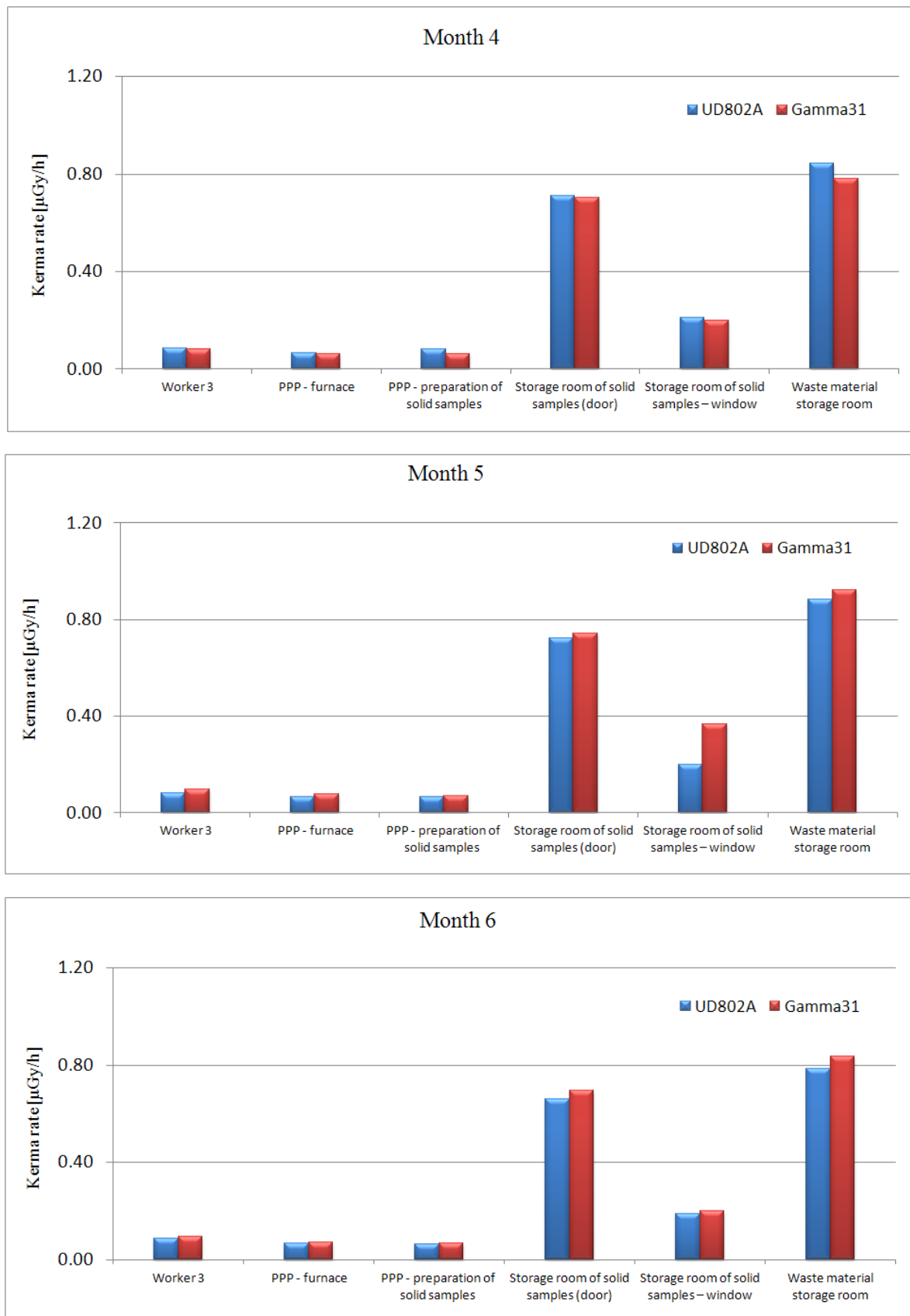


Fig. 7. The results given in [ $\mu\text{Gy/h}$ ] of dosimetric control and comparison of Gamma-31 and UD-802 dosimeters' indicators carried out in the Laboratory of Gamma-Ray Spectrometry

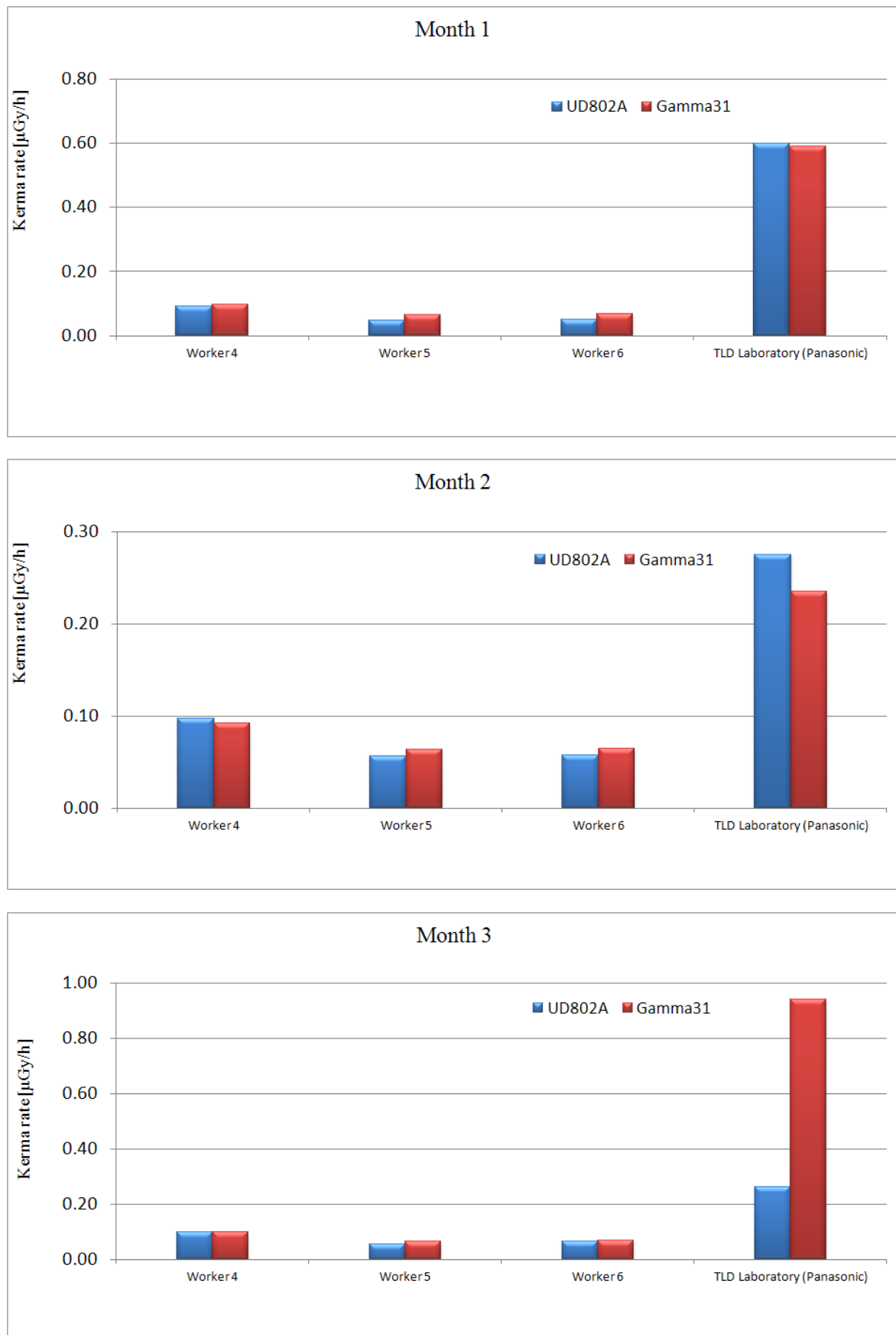


Fig. 8. The results given in [μGy/h] of dosimetric control and comparison of Gamma-31 and UD-802 dosimeters' indications carried out in Dosimetric Laboratory



As a result of the analyses carried out, the increased values of kerma rate were observed in storage rooms intended for various types of environmental samples. These sites are, however, isolated from the offices and the individual control of the personnel performing work, they did not indicate an increase in the doses received. In contrast, significant differences in responses of dosimeters were observed in the case of their exposure in the close vicinity of the apparatus equipped with a high-activity source of Cs-137 (UD-794D). The values at the same time considerably exceed the natural background level, this reflects clearly the increase of doses received by the employees usually staying in this room. The measured doses, however, does not exceed the permissible level of radiation. In all other cases, the kerma rate determined using both types of dosimeters did not exceed the common average level of natural radiation there.

The measured values are characterized by very good compatibility almost in all laboratories with one exception. Near the UD-794D device (Fig. 8 month 2+3: Laboratory Panasonic TLD) they are significantly higher than at the other investigated locations and do strongly fluctuate. The observed differences refer not only to the readings on the various types of dosimeters, but also the specific indications of dosimeters Gamma-31 and dosimeters UD-802 for different measurement periods. This situation indicates a high gradient of intensity of the radiation field on the surface of the device, and the dosimeters in the subsequent measurement periods were not exactly in the same positions.

#### 5.4. Water treatment plants

Exposures of dosimeters were also made in 8 water treatment plants (WTP) such as pumping stations and aerator chambers. Localisation of measuring points is presented below in Figure number 9.

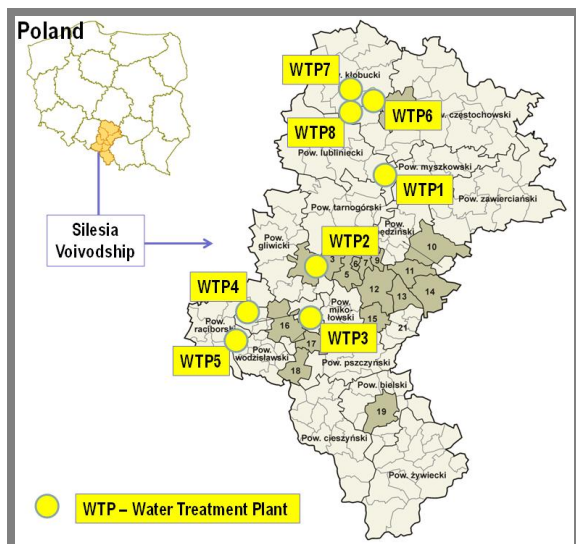


Fig. 9. Localisation of Water treatment Plants (map was derived from the web site: <http://pl.wikipedia.org/wiki/slakieadministracja.png>)

Apart from the assessment of the radiological hazard, it permitted checking dosimeters resistance to difficult measurement conditions when air humidity is much higher than under usual environmental conditions. The obtained results (Fig. 10) are mostly comparable with the level of natural

background and do not usually exceed 0.1  $\mu\text{Gy/h}$ . In WTP number 8, the kerma rates were increased and reached 0.24  $\mu\text{Gy/h}$ . Assuming, however, the appropriate reference level and 2000 working hours per year, the dose above the natural level will never exceed the permissible limit, which is fixed for members of the public at 1 mSv/year (The Regulation 2005). Increased kerma rate of gamma radiation or even radon concentration in the air in WTPs is associated with the presence of natural radionuclides namely radium and progenies. Despite the generally very low concentration of natural radionuclides in the drinking water itself, in rooms or installations like tubes in WTPs, their increasing concentration occurs as a result of treating the water by technological processes in order to fall below the values for other elements (e.g. iron, manganese) given by law.

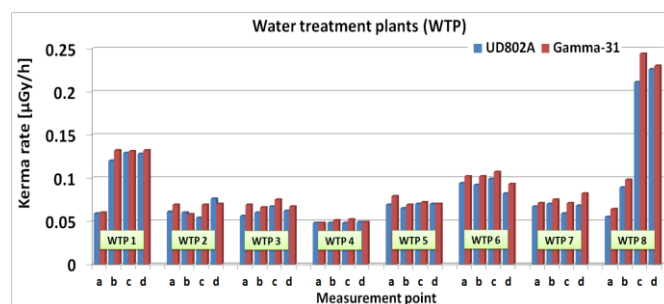


Fig. 10. The dosimetric control results and comparison of Gamma-31 and UD-802 dosimeters' indications conducted at selected water treatment plants

For most cases, the observed differences in the indications of particular types of dosimeters did not exceed 8–10%, and the mean values were 0.076 and 0.085  $\mu\text{Gy/h}$  for dosimeters UD-802 and Gamma-31, respectively.

#### 5.5. Measurements in the potassium salt mine

In addition, both types of dosimeters were exposed for about one month at selected workstations located in the potassium salt mine (Fig. 11).

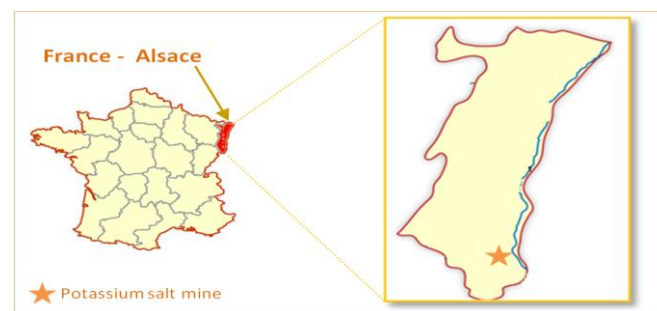


Fig. 11. Localisation of the potassium salt mine (map was derived from the web site: <http://pl.wikipedia.org/wiki/Alzacja>)

One of the measurements was performed on the surface (position: Office-surface), where the dosimeters were left in the office room. All other measuring points were located underground in the mine. The results of the exposures carried out are shown in Figure 12. Places of underground measurements were crucial in terms of:

- the intensity of works carried out (replacement of the girder, anchoring, backfill of the floor's sidewall)

- the time staff spends there (shaft operators, maintenance and repair jobs)
- the possibility of precipitation of radioactive sediments from deep water (sump, settling sump).

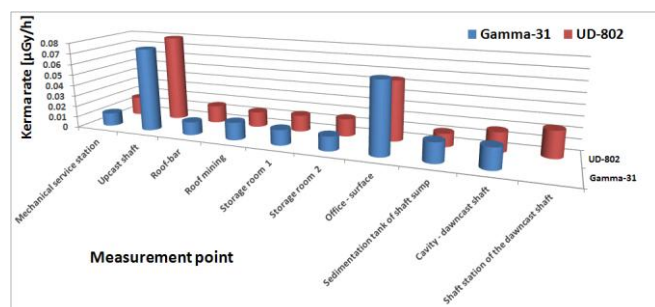


Fig. 12. The results of environmental dosimetric control and the comparison of Gamma-31 and UD 802 dosimeters' indications in underground conditions

All results ranged from between 0.015 to 0.080  $\mu\text{Gy/h}$ , and showed a satisfactory conformity for both types of dosimeters. Such results confirm the correctness of the indications of a new type of dosimeters in the case of registering doses at the natural background level. This fact makes them a reliable dosimetric tool not only in work stands involving the use of radiation sources (industry, medicine), but also the dose measurements resulting from the impact of natural radioactive isotopes (Naturally Occurring Radioactive Materials, Technologically Enhanced NORM). Slightly higher levels of kerma rate can be observed in the case of the uncast shaft of the mine which can be caused by higher concentration of radium nuclides in this area, and in the office room as the result of an influence of cosmic radiation and higher concentration of nuclides in building materials. Nevertheless, these are values at the level of the natural background. This means that in the examined mine, an increased exposure to ionizing radiation does not exist. The carried out underground measurements also confirmed the high resistance of dosimeters UD-802 to changing weather conditions (temperature, humidity) and high dust.

## 6. SUMMARY

The presented dosimetric systems and analysis procedures developed for them, the methodology for dose measurements and their uncertainties allow us to conduct a reliable assessment of radiation exposure caused by mixed ionizing radiation fields. In the case of UD-802 dosimeters, the adopted technical solutions from the Panasonic device create conditions to undertake dosimetric control of large groups of employees or members of the public. In the frame of comparative measurements carried out between UD-802 dosimeters and Gamma-31 (used for years in the Central Mining Institute) a good agreement was obtained, as long as the conditions of exposing dosimeters were comparable. However, in the case of Gamma-31 dosimeters, the use of three indicators of identical detectors results with lower dispersion of results during calibration. In addition, a series of conducted measurements in highly diverse environmental conditions confirmed the high resistance of the UD-802 dosimeters to tem-

perature, humidity and dust. All these properties make the Panasonic system an excellent dosimetric tool both in the research of the natural environment as well as under working conditions. The carried out measurements confirm the usefulness of the newly introduced Panasonic dosimeters for the personnel dosimetry control at the investigated workplaces in water treatment plants and underground mines. That makes it very interesting for all types of industries relying on research, and medical and production procedures where radiation exposure may occur.

## 7. CONCLUSION

The advantage of UD-802 is its high resistance against environmental influences from outside by temperature, humidity and dust and its comfortable handling. Therefore, it is an ideal tool for routine dose measurements in mixed radiation fields.

But Gamma-31 showed better measurement precision than UD-802 in the cases where photon radiation with energy higher than several hundred kiloelectron volts occurred.

## Acknowledgments

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