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IN SITU TESTING OF A PROTOTYPE OF A LASER DOSIMETRY PROBE WITH WIRELESS DATA TRANSMISSION BASED ON THE RADIOCHROMIC PHENOMENON IN AN ORGANIC DETECTION ELEMENT

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Abstract. *In 2023, the Radiochemistry II Department of the Research Centre Rez tested a prototype of a laser telescopic probe with wireless data transmission, based on the radiochromic phenomenon in an organic detection element. This article includes a detailed description of the entire device, documentation of the course of the performed experiments, and measurement results.*

The laser dosimetric probes known so far consist of optical fibers, at the end of which a small scintillation or radiochromic element sensitive to ionizing radiation is attached.

The use of fiber optics makes sense only in cases where the fiber itself carrying the light signal receives such a low dose of ionizing radiation that it does not measurably affect its optical properties. This technology has therefore found application primarily in the field of radiation oncology, where it is necessary to measure doses in units of centigrays (cGy) to grays (Gy), which fiber optics can handle without any problems.

The laser dosimetric probe according to our technical solution eliminates the aforementioned shortcomings. In contrast with the use of optical fibers, there is no Radiation-Induced Attenuation (RIA), nor Cerenkov signal, because the light pipe is filled with air. Despite the loss of flexibility, this constitutes a clear advantage over the use of optical fibers.

The probe is designed and tested for measuring very high doses in the order of units to hundreds of kilograys (kGy) and the corresponding dose rates. It is intended for industrial applications, such as measuring dose rates inside the primary circuit of nuclear reactors, near the core of nuclear reactors, in the bowels of high-activity gamma irradiation plants, hot chambers, potentially also at the site of nuclear or general radiation accidents with difficult access to the source of ionizing radiation (fire, collapse, melting of the reactor core, loss of control over the source, etc.)

The experiments performed have proven the functionality and temporal stability of the constructed device for dosimetry of high dose rates in hard-to-access spaces, such as the channels of a research nuclear reactor, etc.

Pilot measurements of the dose rate directly at the edge of the core during the planned shutdown of the LVR-15 nuclear research reactor have already helped to provide some valuable information on the overall inventory of activity inside the core. From the rate of decline of activity in the active zone during a shutdown, it may be possible in the future to make inferences e.g. also the radioisotope spectrum.

Keywords: *Laser, polycarbonate, research nuclear reactor, optical density, absorbed dose, radiochromic phenomenon, luxmeter, dosimetric probe, optical periscope*

1. INTRODUCTION

The development of a laser dosimetry probe based on the radiochromic phenomenon in the polycarbonate detection element located on the tip of the probe began in May 2020. The laser beam passes through a light pipe formed by an internally polished stainless steel tube with an outer diameter of 10 mm and an inner diameter of 7 mm, at the end of which the beam is reflected at an angle of 90° onto a transparent polycarbonate detection element with a thickness of 10 mm. After passing through the element, the beam is again reflected at an angle of 90° into the second parallel light pipe of the same design, through which it returns, after which it hits the sensitive Sonel LXP 10-A optical detector, which measures and records the intensity of the incident light in its memory in real time.

The probe was developed on the basis of previous long-term research related to the radiochromic phenomenon in polycarbonate, which has been ongoing since 2015 at the Research Centre Rez [1]-[6]. Polycarbonate (PC) is a polyester of carbonic acid, which is produced by the gradual polymerization of bisphenol A with phosgene. It is a transparent polymer with a large index of refraction (n = 1.584) and a large light transmission (at least 80% transmittance for 10 mm thick plate) [7]. It reacts to irradiation by changing the optical density [1] – [6], [8] – [10]. The changes first occur predominantly in the UV region of the spectrum (10–380 nm), for higher doses they extend into the visible region (380–760 nm).

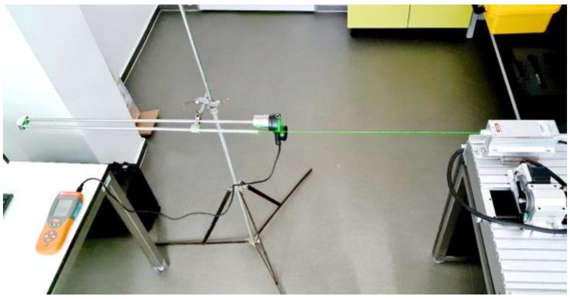

Figure 1. Demonstration of the working principle of the probe

Monitoring of changes in optical density (optical densitometry) is an easily and inexpensively measurable

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parameter that can be determined remotely, in-situ and in real time using a laser beam. Therefore, the use of solid state organic radiochromical dosimeters is much easier and cheaper, than using some other methods.

Thanks to the structural solution of the probe, which also allows for a telescopic design, it is possible to place the dosimetric element at the end of a very long and thin light pipe, and thus measure the dose and dose rate in situ even in narrow and difficult-to-access spaces with a dangerous level of ionizing radiation, such as the active zone of a nuclear reactor. The telescopic design of the probe is an innovation that we would like to test in the future.

The laser dosimetric probes known so far consist of optical fibers, at the end of which a small scintillation or radiochromic element sensitive to ionizing radiation is attached.

The use of fiber optics makes sense only in cases where the fiber itself carrying the light signal receives such a low dose of ionizing radiation that it does not measurably affect its optical properties [11]. This technology has therefore found application primarily in the field of radiation oncology, where it is necessary to measure doses in units of centigrays (cGy) to grays (Gy), which fiber optics can handle without any problems.

A separate class of laser dosimetric probes consists of probes for photodynamic therapy, i.e. the treatment of malignant tumors using visible light or other non-ionizing radiation, delivered by an optical fiber directly to tumor tissue doped with a suitable chemical photosensitizer. In these cases, however, the measurement is of the absorbed dose of light and not of ionizing radiation.

The laser dosimetric probe according to our technical solution eliminates the aforementioned shortcomings. In contrast with the use of optical fibers, there is no Radiation-Induced Attenuation (RIA), nor Cerenkov signal, because the light pipe is filled with air. Despite the loss of flexibility, this constitutes a clear advantage over the use of optical fibers.

The probe is designed and tested for measuring very high doses in the order of units to hundreds of kilograys (kGy) and the corresponding dose rates. It is intended for industrial applications, such as measuring dose rates inside the primary circuit of nuclear reactors, near the core of nuclear reactors, in the bowels of high-activity gamma irradiation plants, hot chambers, potentially also at the site of nuclear or general radiation accidents with difficult access to the source of ionizing radiation (fire, collapse, melting of the reactor core, loss of control over the source, etc.).

2. TECHNICAL PARAMETERS

2.1. Laser source parameters

The energy source of the probe consists of a stabilized solid-state laser pumped by semiconductor diodes GL532T6-1500 with an output power of 1.5 W at a wavelength of 532 nm, with a power stability of 3%, powered by a control and power supply unit ADR-800D, which was supplied by OPTIX s.r.o. (Fig. 2).

Figure 2. GL532T6-1500 laser source together with ADR-800D control and power supply unit

2.2. Optical detector parameters

The digital luxmeter Sonel LXP-10A (Fig. 3) works with a resolution of 0.001 lx and measures within the range from 0 lx to 400 klx with an uncertainty of less than 2%. The semiconductor photosensitive element consists of a silicon photodiode and a spectral filter.

The device contains internal memory for manual storage of up to 999 values, and memory for automatic storage of up to 16,000 values. The auto-save interval can be preset from 1 s to 60 s in one-second increments. The data is stored in the memory together with the time of their acquisition.

The Sonel Reader control program enables wireless data transfer to a remote PC using the OR-1 USB adapter, even through the 500 mm thick steel wall of the hot cell and the 50 mm thick lead shielding of the protective bunker.

The photodiodes and filters used cause the spectral sensitivity characteristic to be suitably adapted to the requirements of the C.I.E. curve. The sensitivity characteristic V (λ) is shown in Fig. 4.

Figure 3. Digital luxmeter Sonel LXP-10A with recording and wireless data transmission

2.3. Parameters of highly active source

As a source of ionizing radiation, a highly active source model IGI-C-8-2 with a content of 7.2 TBq of radionuclide 137 Cs was used. The source was loaned by the Department of Highly Active Waste. The source After being removed from the package in a hot cell, the source was placed in a polyethylene ampoule and then in a prepared resealable can (Fig. 5 right).

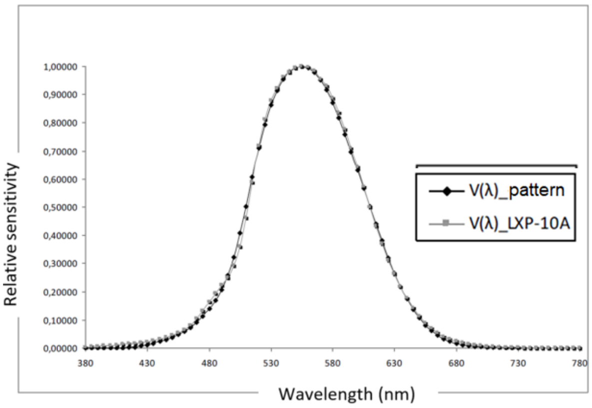

Figure 4. Characteristics of the spectral sensitivity of the Sonel LXP-10A digital luxmeter

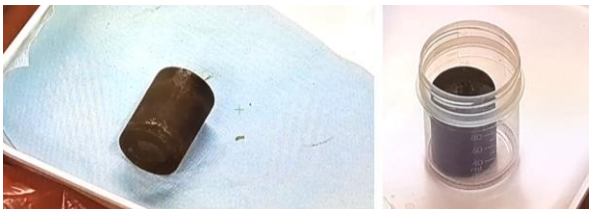

Figure 5. Highly active radionuclide source IGI-C-8-2 with an activity of 7.2 TBq 137Cs

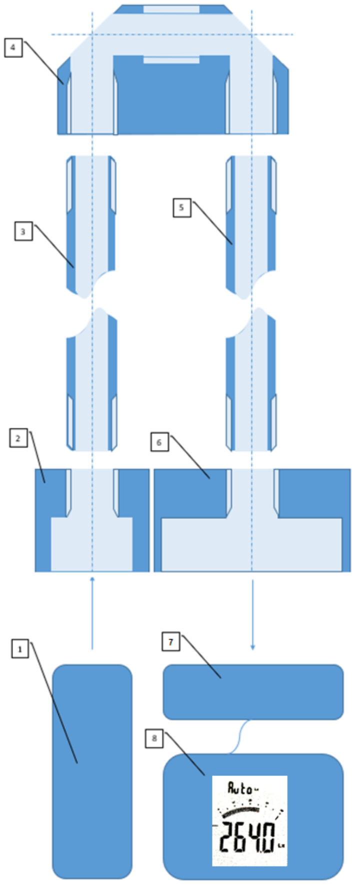

Figure 6. The configuration scheme of probe: 1 – laser source, 2 – reduction element A, 3 – input light pipe, 4 – dosimetric head 5 – output light pipe, 6 – reduction element B, 7 – optical detector of the luxmeter (photodetector) 8 – digital luxmeter

3. DESCRIPTION OF THE DEVICE

The laser source was connected through a custom-made reduction element A to the input light pipe by a screw connection through an M10 thread.

The output light pipe was connected to the Sonel LXP 10-A optical detector at the output of the light beam via a screw connection with an M10 thread through a custom-made reduction element B.

Both the input and output light pipes were connected at their other ends by an M10 threaded connection to an aluminum dosimetric head (Fig. 7) constructed to allow the beam to pass through a transparent polycarbonate detector and then direct the beam into the output light pipe towards the Sonel LXP 10-A detector (Fig. 6).

A clear polycarbonate detection element MAKROCLEAR in the shape of a cube with an edge of 10 mm was inserted into the dosimetric head (Fig. 8).

We determined the uncertainty of MAKROCLEAR detectors in a reasonable range of doses, e.g. in work [6] to about 10%.

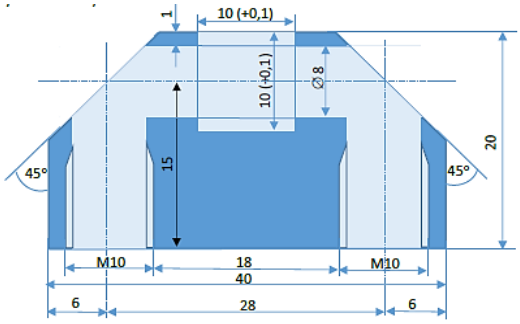

Figure 7. Technical drawing of the dosimetric head

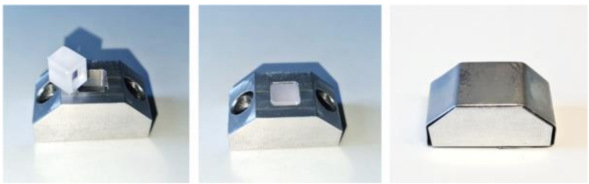

Figure 8. Detail of the disassembled dosimetric head

4. LABORATORY TESTS

After complete assembly, the device was first thoroughly tested in the laboratory, with the length of both light pipes being 3300 mm (Fig. 9).

Figure 9. Laboratory tests of assembled probes with a length of light pipes of 3300 mm

4.1. Experiment preparation

Due to the limited space inside the hot cell, both light pipes had to be shortened to a length of 2600 mm. In the corner of the cell, a shielded bunker with dimensions (w x d x h) of 300 x 400 x 300 mm and weighing approx. 300 kg was built from 50 mm thick lead bricks. All the sensitive electronics were placed in it. Through 2 of the bricks, grommets for both light pipes were drilled.

At the opposite end of the hot cell, a screen weighing approx. 130 kg was built from 50 mm thick lead bricks. The screen also included a storage supporting both light pipes on the side of the dosimetric head. A lead pedestal for a closable can with a highly active source of ^{137}Cs was placed behind the screen (Fig. 10).

Figure 10. A radiation-shielded lead bunker to protect the probe's sensitive electronics from the effects of ionizing radiation (left), a lead screen to shield the highly active source ^{137}Cs (right)

During the experiment, the dose rate on the wall of the bunker was 17.6 mSv/h (measured with a calibrated MDG 04 dosimetric probe) and the dose rate inside the bunker, calculated using the Rad Pro Calculator program, was determined to be 65 μSv/h. During the entire irradiation time (103 hours), the sensitive electronics inside the bunker received a dose of less than 7 mSv.

4.2. The course of the experiment

The Sonel LXP 10-A luxmeter was set to the mode of automatic data saving in the internal memory at intervals of 60 s. At the same time, it was switched to radio mode, where it is possible to communicate with it remotely via a PC in the operator's room of the hot cell and continuously download data in xlsx format. The laser source was started, and the bunker was completely radiation shielded from above with 10 mm thick steel sheets, on which a continuous layer of 50 mm thick lead bricks was laid. A narrow gap was left only in the rear part for the purpose of cooling the internal space with electronics and at the same time a passage for cabling – Fig. 11.

Figure 11. A fully shielded bunker to protect the probe's sensitive electronics from the effects of ionizing radiation

The high-activity source was transported inside the sealed can via loading equipment to the hot cell, where it was set into place on a lead plinth behind a screen by remote manipulators. (Fig. 12).

Figure 12. Camera view of the detail of the storage of the high-activity source can behind the shielding screen

Using the MDG-04 dosimetric probe manufactured by VF Nuclear, calibrated for ^{137}Cs, a dose rate of 501 Gy/h, i.e. 8.35 Gy/min, was measured at the detector site.

Since this is a gas detector, the measured value has been further corrected for pressure p and temperature T in the hot cell, against the reference pressure p_0 and temperature T_0 at which the meter was calibrated:

$$\frac{dD}{dt} = \left(\frac{dD}{dt}\right)_0 \frac{T}{T_0} \frac{p_0}{p} \tag{1}$$

Calculating the above values resulted in dD/dt = 487 Gy/h, which corresponds to a dose rate of 8.1 Gy/min. The measurement took place continuously for 6,174 minutes, i.e. 103 hours, during which the optical density of the polycarbonate detection element gradually increased due to the absorbed dose, and the signal at the output of the probe weakened with time as a result.

After the measurement, the organic detection element was removed from the dosimetric head and photographed - Fig. 13. The radiochromic coloration of the initially clear polymer is very clearly visible on the image, which starts to regenerate towards the edges as a result of interaction with oxygen, as we described, for example, in work [2], [3].

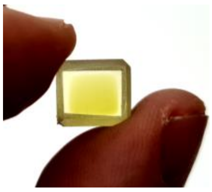

Figure 13. The irradiated detection element after the end of the experiment

4.3. Processing results

In the Fig. 14, we see the course of the signal intensity (in units of lx) with the absorbed dose (in units of Gy), fitted by a second order polynomial (orange curve).

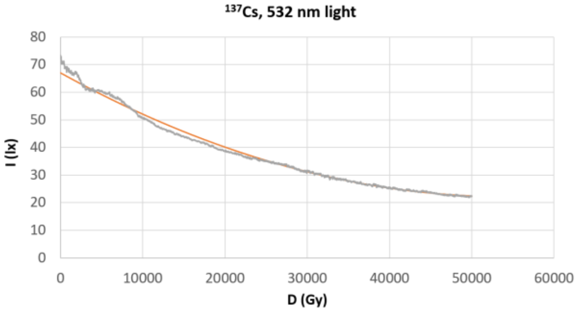

Figure 14. Measured dependence of illumination intensity on dose fitted with a 2nd degree polynomial

Figure 15 shows the conversion to optical density (in inverted centimeters) determined as the ratio of the decimal logarithm of the ratio of radiation intensity incident on dosimeter I_0 and radiation intensity transmitted by dosimeter I, and thickness of blackening area d:

$$OD = \frac{1}{d}\log\frac{I_0}{I} \tag{2}$$

with an uncertainty of approx. 2% mainly due to the uncertainty of determining the signal intensity with the Sonel LXP-10A luxmeter.

The regression curve of the graph can already be used in the given range of doses as a calibration curve of the probe for photons with energy around 662 keV (photopeak ^{137}Cs).

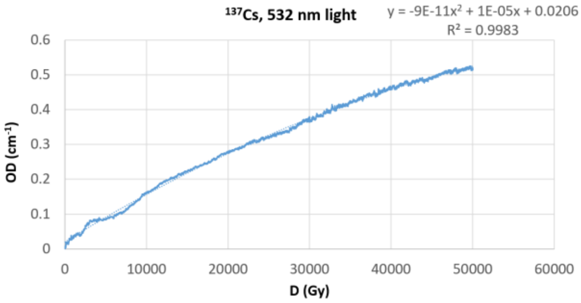

Figure 15. Calculated dependence of optical density on dose, fitted with a quadratic regression function (dotted line)

5. PILOT IN SITU MEASUREMENTS

The pilot in situ measurement was carried out inside the active zone of the research nuclear reactor LVR-15 of the Research Centre Řež. It is a reactor with a maximum thermal output of 15 MW, cooled and moderated by light water - Figure 16. The measurement took place during its planned two-week operational shutdown.

A number of horizontal and vertical channels lead to the active zone of the reactor, which exit outside the reactor space and allow irradiated materials and probes to be inserted directly to the active zone. The pilot measurement took place inside one of the horizontal experimental channels marked HK1.

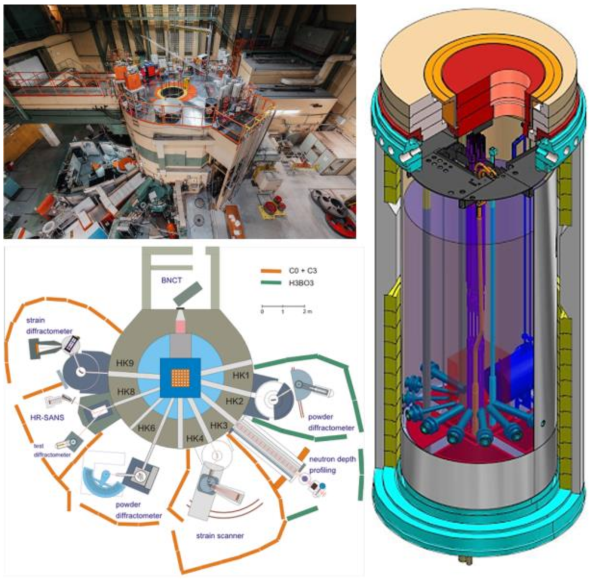

Figure 16. Research nuclear reactor LVR-15

5.1. Protective measures

At the mouth of HK1, a dose rate of 2 Sv/h was detected at the time of measurement. For that reason, the mouth of the channel was shielded with a cylindrical lead plug 90 mm long and 96 mm in diameter, with drilled holes for the laser probe light pipes – Fig. 17.

Figure 17. Lead shielding plug with a diameter of 96 mm and a total height of 90 mm, for shielding the mouth of the horizontal channel of the LVR-15 research reactor

After inserting the probe together with the shielding plug into the horizontal channel of the reactor (see Fig. 18), and pulling out the additional shielding of the channel, a dose equivalent input of only 12 mSv/h was measured at the mouth.

Figure 18. Inserting a 4 m long probe with a lead plug into the horizontal channel of the LVR-15 nuclear research reactor

In order to protect the probe's sensitive electronics from radiation passing through radiation-unprotected hollow light pipes, an optical periscope containing 2 optical prisms capable of changing the path of the laser beam by 90°, i.e. outside the direct beam of ionizing radiation, was installed at the entrance and exit of the beam (Fig. 19). The most exposed electronic elements were thus exposed to a dose rate of only 7 μSv/h and received around 0.5 mSv during the entire measurement period.

Figure 19. Optical periscope changing the trajectory of the laser beam by 90°

The complete assembly of the probe for measuring inside the channel of the LVR-15 research reactor, was photographed during its laboratory testing (figure on the left) and subsequently during its installation in the horizontal channel of the nuclear reactor LVR-15 (Figure 20).

Figure 20. Laboratory testing of the complete laser probe assembly

5.2. *Results processing and final summary*

Measurements inside HK1 of the LVR-15 research reactor took place at a depth of 3.6 m from the outer wall of the reactor, i.e. at the very border of the active zone. The measurement time was 78 hours, during which the probe gradually received a dose of almost 200 kGy. The dependence of the absorbed dose on the OD, calculated as the inverse function of the regression function (Fig. 15), is shown in the Fig. 21.

By interpolating the calculated values with a second-order polynomial regression function, the values lying outside the dose area of the measured calibration curve were also calculated.

By assigning the measured irradiation time to the individual OD values, the dependence of the absorbed dose on time was then obtained - see the Fig. 22. By interpolating these points with a linear regression function, the dose rate at the probe location dD/dt = 42.5 Gy/min, i.e. 2.55 kGy/h with an uncertainty of 10%, was already easily expressed as the directive of this regression function.

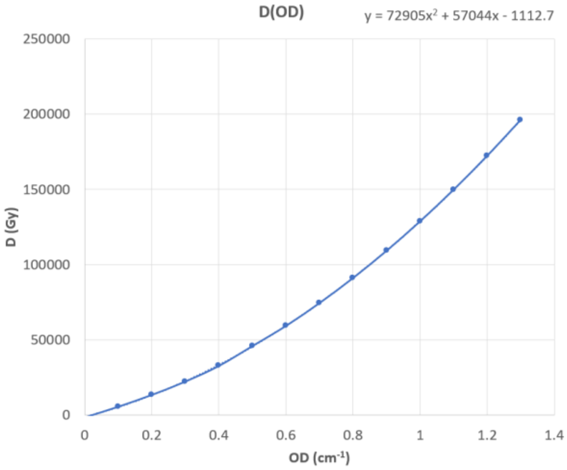

Figure 21. Dependence of the absorbed dose on OD

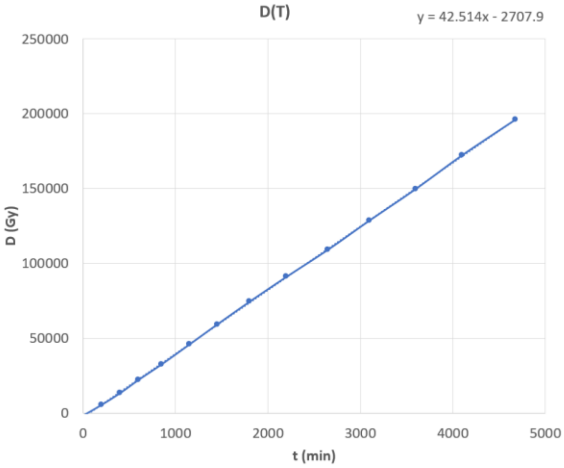

Figure 22. Dependence of the absorbed dose on time

6. CONCLUSION

The experiments proved the functionality and temporal stability of the constructed device for dosimetry of high dose rates in hard-to-access spaces, such as the channels of a research nuclear reactor, etc.

Pilot measurements of the dose rate directly at the edge of the core during the planned shutdown of the LVR-15 nuclear research reactor have already helped to provide some valuable information on the overall inventory of activity inside the core. From the rate of decline of activity in the active zone during a shutdown, it may be possible in the future to make inferences e.g. also the radioisotope spectrum.

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