Measurement of prompt gamma field above the VR-1 water level

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Abstract— **Pool-type reactors are an excellent source of high energy photons without neutrons because the water above fuel acts as an outstanding neutron shielding, whereas for high energy photons, it is nearly transparent. The absence of neutrons is a valuable property essential for testing semiconductor detectors because they are sensitive to neutrons, which might cause their damage. The high energy gammas are worth studying because they are responsible for radiation induced heating of reactor internal components in energy producing reactors, which might lead to their radiation induced damage by void swelling. At this effect, the helium produced in (n,α) reactions influenced by locally increased temperature clusters into bigger bubbles, which are increasing material volume, and therefore changing the geometry of internals. The referred method could be utilized e.g. for resource exploration by detecting prompt capture gammas. The prompt gamma field was measured at the VR-1 reactor with two different cores and water levels. The stilbene measurements showed relatively good agreement with the spectrum shape computed by MCNP6.2. An important result is a confirmation that the stilbene deconvolution matrix can be used with a rotated crystal. The testing measurement with HPGe detectors showed a possibility for measurement in such type of geometry.**

Keywords **—Capture gammas, Scintillation detectors, HPGe detector, Prompt gamma**

I. Introduction

The pool-type reactors have a special benefit for scientific research – they can serve as an excellent source of high energy photons with absence of neutrons. The neutrons are absent due to the shielding by water present above fuel assemblies, whereas water is poor shielding material for high energy photons.

The proper knowledge of the gamma spectrum in the vicinity of the reactor core is essential in the characterization of the radiation field. It is important for ensuring radiation safety. The high energy gammas are responsible for radiation induced heating of reactor internal components, which might lead to their radiation induced damage. In this void swelling effect, the helium produced in (n,α) reactions influenced by locally increased temperature clusters into bigger bubbles, which are increasing material volume, and thus changing the geometry of internals [1].

On the other hand, prompt gamma radiation has several benefits - a well-described gamma field can be used for testing of radiation measuring devices, it can be used for the measurement of the reactor power [2]. Another application is the Earth crust exploration since the capture gammas are an important signature of the presence of materials present in Earth crust [3].

The field in the vicinity of the reactor core is interesting for testing because in contrary to commonly use gamma fields formed by common gamma sources, in the reactor fields, there are high energy gammas formed by neutron interactions with reactor structural components (prompt gamma capture reactions, inelastic scattering). Due to this mechanism, the gammas in the reactor field are mostly accompanied by the presence of neutrons.

An interesting situation may occur in deep penetration problems in water because a deep-water slab is an excellent fission neutron absorber but relatively weaker gamma absorber. Behind the deep-water slab, one can expect high energy capture gamma field with a negligible share of neutrons. This criterion is well filled above the water surface of the VR-1 research reactor.

The paper deals with the results of different measurements – both with nominal and reduced moderator height. The experiment with reduced water level was extended by additional measurement with a lower position of the detector.

II. Measurement

A. VR-1 reactor

The measurements were performed at the VR-1 reactor operated by Czech Technical University in Prague. It is a zero-power pool-type reactor. The reactor core consists of IRT-4M tubular fuel assemblies (19.7% ^{235}U in the form of UO_2-Al, active length approximately 68 cm) moderated and shielded by light water. The height of the water column above the assemblies is usually about 300 cm (see Fig. 1). The core is also equipped with several dry vertical channels, radial channels, and other experimental equipment.

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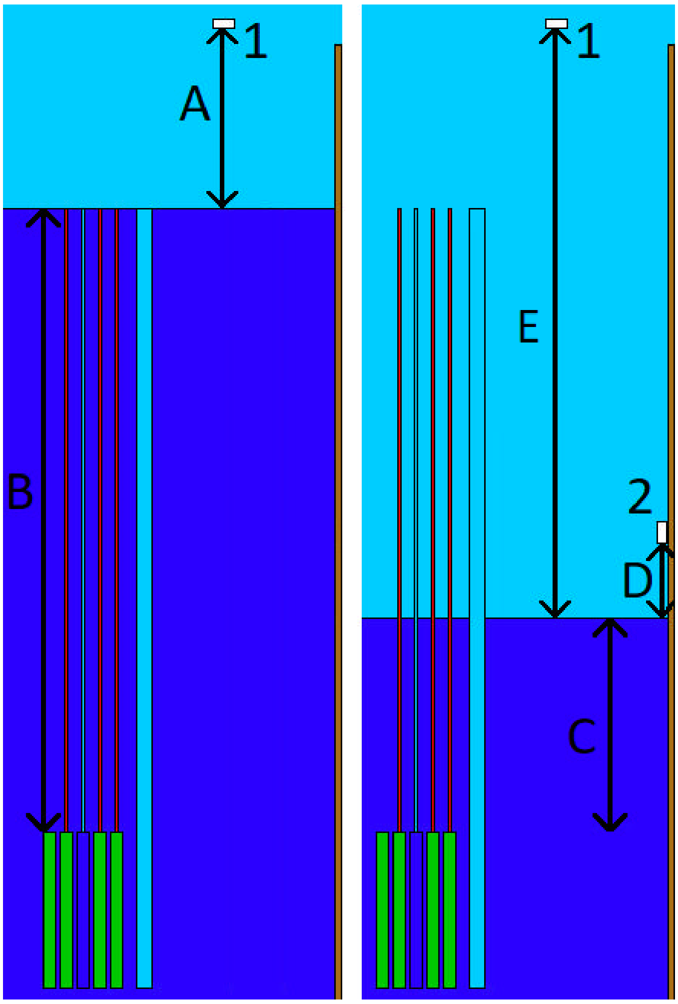

Fig. 1 Visualized axial position of detectors- Position 1 - detector in upper position, position 2 - detector in lower position, distance A is 86 cm, distance B is 306 cm, distance C is 95 cm, distance D is 34 cm, distance E is 291 cm

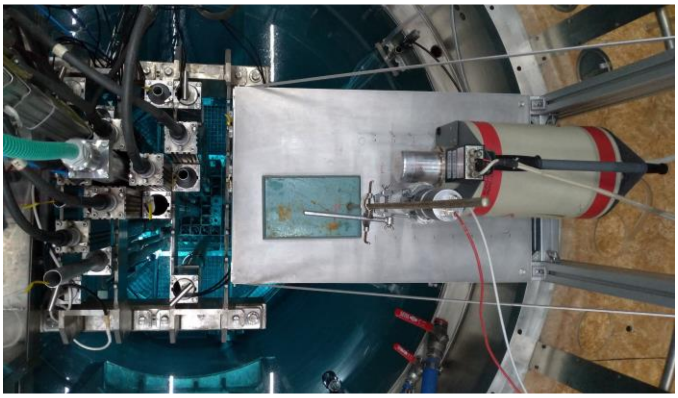

Fig. 2 Photography of measurement geometry

B. *Stilbene measurement apparatus*

The measurement was performed using the spectrometric system NGA-01 [4]. A 45 x 45 mm cylindrical stilbene organic scintillator was used as a detector. An innovative active high voltage divider is used for the measurement (Fig. 3). The divider was developed to compensate for the nonlinearity caused by the high frequency of pulses and their amplitude (Fig. 4). We use an internal negative high voltage source as a bias for the Hamamatsu R329-02 photomultiplier. The negative voltage allows fast pulse processing up to frequencies greater than 1E6. The NGA-01 system uses parallel processing of differently amplified inputs from several fast ADC converters at a resolution of 12 bits and a sampling frequency of individual ADC converters of 500 MS / s. The online data processing is taken care of by the field programmable gate array (Virtex 6), which communicates via a network interface located on the measuring card FD-17 (Fig. 5). A server is located inside the device. Subsequent processing and transfer of stored data are realized by remote connection to a server with the Linux operating system. The instrument spectra are stored on a RAID disk array inside the NGA-01 device for possible reprocessing or further evaluation. Using measured data and data from calibration sources (Cs-137, Co-60) we convert the apparatus spectrum by unfolding to flux density. We use response matrices calculated and validated in PTB Braunschweig for these calculations [5].

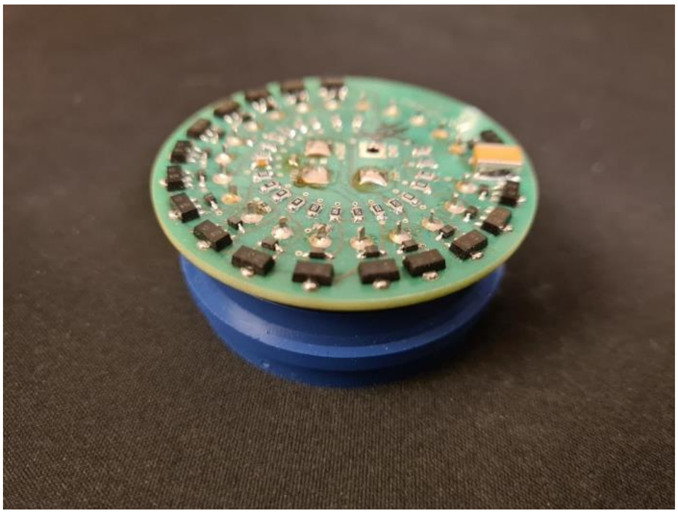

Fig. 3 Implementation of a linearized active divider for high pulse frequencies

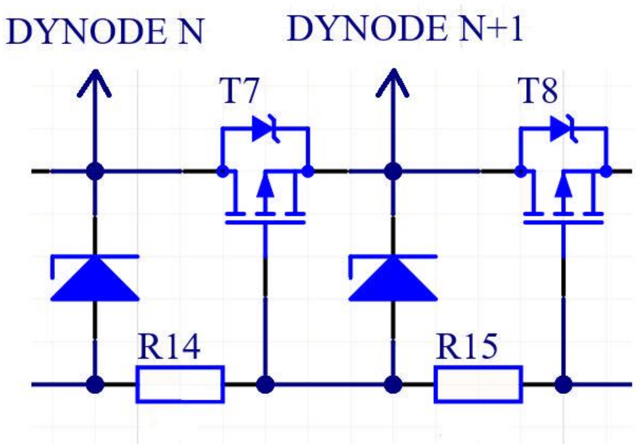

Fig. 4 Connection of a linearized active divider for high pulse frequencies

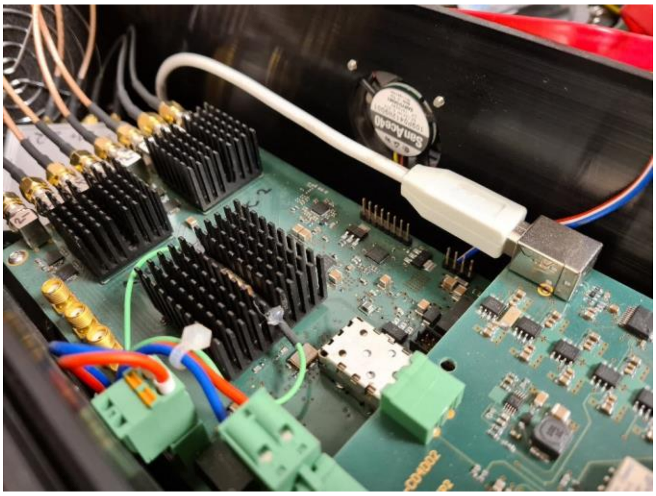

Fig. 5 Digitization card FD-17 with the FPGA (Virtex 6) and two ADC converters with a resolution of 12 bits and a sampling frequency of 500 MS/s containing four differential pair inputs and Ethernet output

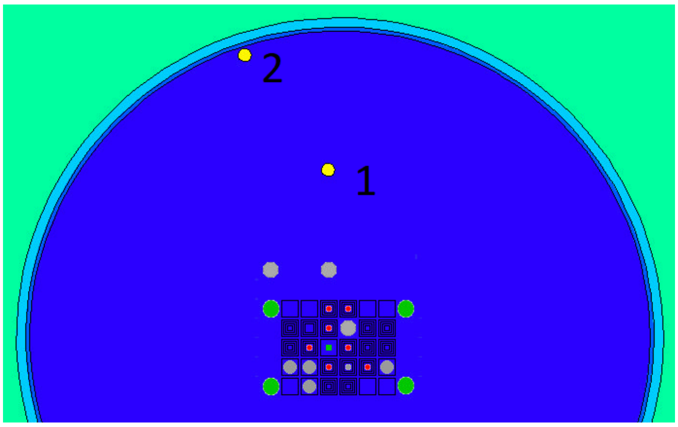

Fig. 6 Visualized position of detectors compared to the core in center of core horizontal plane. Position 1 - detector in upper position, Position 2 - detector in lower position

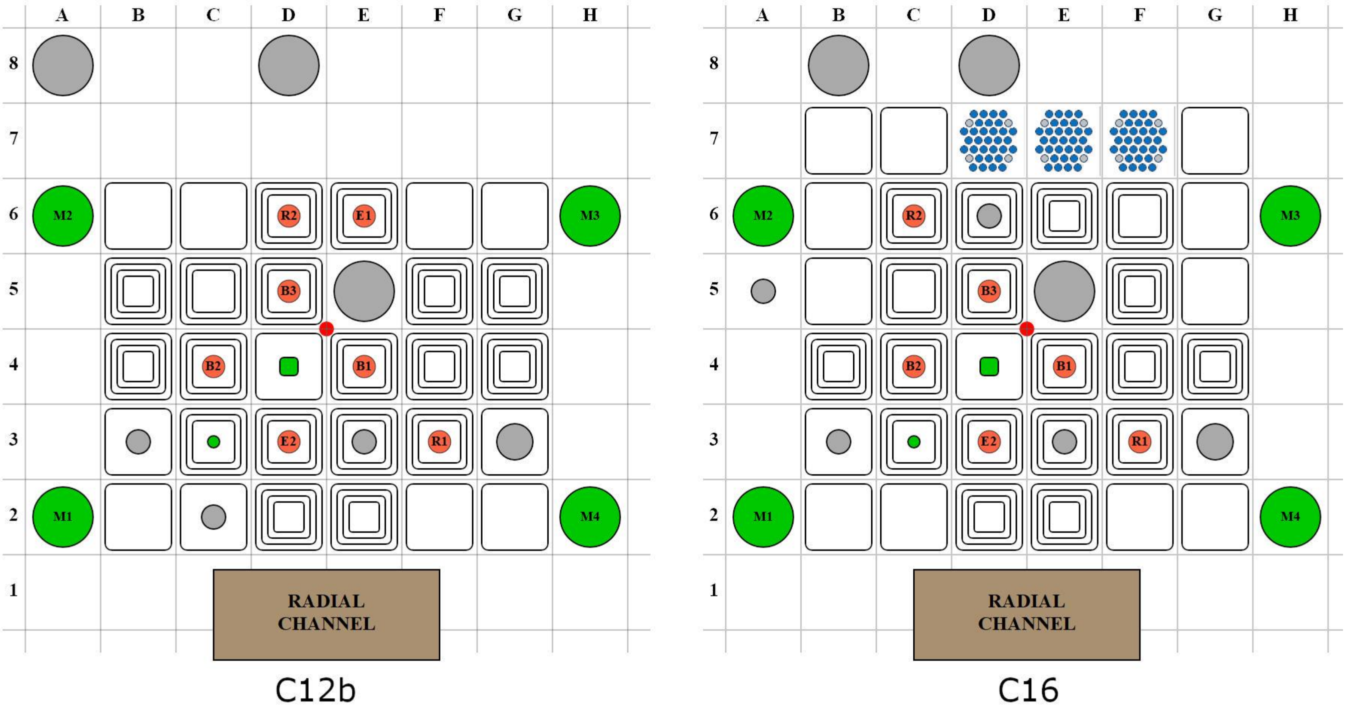

Fig. 7 Comparison of C12b and C16 core configurations. Stainless steel reflector is composed of three blue assemblies

C. Measurement geometry

The measurements were carried out at different times; therefore, two different cores were in the experiment. The experiment with nominal and reduced moderator height was performed with the core C12b. Later, the measurement with the nominal moderator level was repeated with the core C16. The main difference between the cores is a presence of stainless-steel reflector (see Fig. 7)

During experiments with the nominal and reduced moderator height, the detector was placed on the manipulation platform fixed in the reactor vessel above the water surface (same position in both cases). The detector center was 88.6 cm above water and its position was shifted to 48.3 cm from the nearest fuel assembly (see Fig. 1 and Fig. 6). The nominal and reduced water level is 306 cm and 95 cm, respectively, above the upper end of the active part of fuel.

The experiment with reduced water height was also performed with the stilbene detector center placed 36.5 cm above the water level. The detector was placed next to the reactor vessel and its position can see in Fig. 1 and Fig. 6.

During the measurement with nominal moderator level, the possibility of measurement with HPGe detector was tested. Portable HPGe coaxial detector Canberra Big MAC (GC2518 type with the 2002C preamplifier) was fixed next to the stilbene detector at the same height (see Fig. 2).

III. Calculations

Calculations were performed in MCNP6.2 Monte Carlo code [6] using ENDF/B-VIII.0 library [7] for neutrons and MCPLIB84 library for photons. Due to the deep transport problem, it was necessary two split the calculation to two parts. The first part was determination of photon source in critical mode. The photon spectrum was computed in the cell comprising the fuel assembly closest to the detector position. Since it was needed to obtain photon spectrum coming dominantly from fission, neutron capture, and inelastic scattering, the physics settings for photons and electrons were optimized to suppress bremsstrahlung and fluorescence.

It was also necessary to determine photon source distribution. This was determined based on the assumption that most of the photons are produced during nuclear fission and during reaction close to the fuel. Therefore, the tally F7 (fission energy deposition averaged over a cell) was scored in fuel assembly. Additionally, tally F7 was also scored in segments of each tube in the z-direction (per 2.5 cm).

Based on the scored photon spectrum, axial and radial distribution, the photon source was determined in a fixed source model with variance reduction techniques. Each part of fuel assembly has the same spectrum, but its photon emission probability (from tally F7) and own axial distribution (from segmented tally F7). Using the developed fixed source model, the photon spectrum in the detector volume was computed. The obtained spectrum was adjusted by Gaussian broadening with parameters for used stilbene detector.

This experiment was performed as an initial study; therefore, it was decided to focus on the spectrum shape. Thanks to that fact it was not necessary to deal with scaling the calculation to absolute values. Nevertheless, the experiment with focus on absolute value comparison is planned. The compared spectra from measurement and calculation were normalized in the 1 - 3 MeV range for a clear spectrum shape comparison.

IV. Results

Fig. 8 shows results for the stilbene measurement with different detector positions and different moderator height. The effect of water on photon flux attenuation is well visible in comparison of measurements with nominal and reduced water level. This additional 2.5 m of water decreases the flux by factor of 120 in 8 MeV region and of about 530 in 2 MeV region. The measurement uncertainties are within 7% in 1 – 5 MeV energy range and within 10 % in energies above 7 MeV.

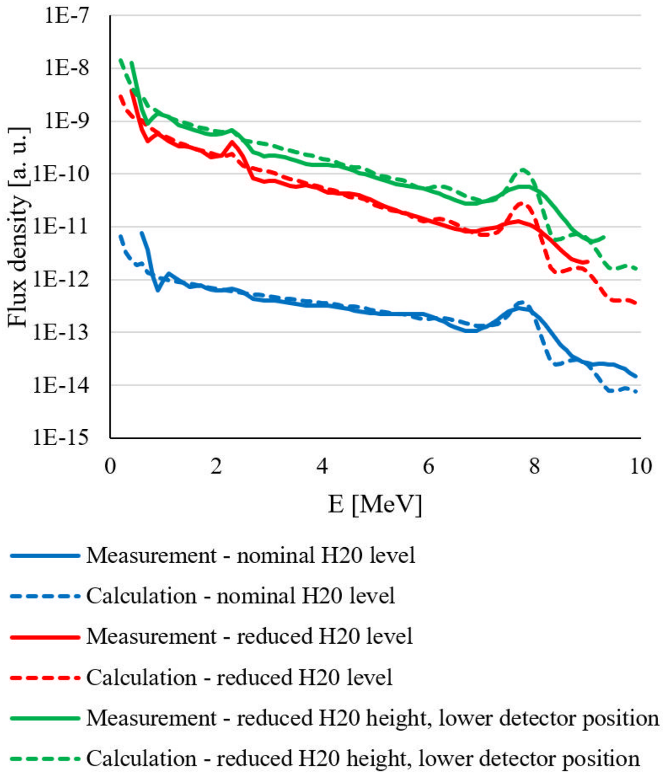

Fig. 8 Comparison of measured and normalized calculated gamma spectra for different moderator levels and detector positions

The comparison for measured gamma spectrum with the different core is visualized in Fig. 9. The C16 core configuration is equipped with the stainless-steel reflector. Its influence is clearly visible in higher energies. The main sources of high energy gammas in stainless-steel are ^{53}Cr (9718.8 keV and 8884 keV), ^{54}Fe (9297.8 keV), and ^{58}Ni (8998.6 keV and 8533.7 keV) peaks. In the 6-8 MeV region, the additional gammas compared to C12b configurations come from ^{56}Fe peaks (7645.6 keV, 7631.2 keV) [8]. On the other hand, the spectra in lower energy regions (bellow 3 MeV) are almost identical.

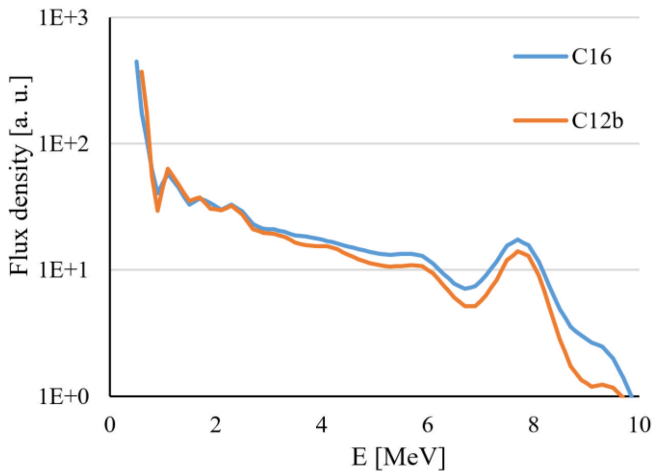

Fig. 9 Comparison of measured gamma spectrum above water level for two different core configurations

In another measurement, the influence of the measurement geometry was assessed. The stilbene detector is usually used in the optical axis parallel to the direction of the neutron field and the deconvolution matrix is derived for this measurement geometry. With advantage, the stilbene detector could be used in different applications if the evaluated photon spectrum would be independent of the crystal orientation. Therefore, the validity of measurement with the perpendicular optical axis was tested. During the test, the gamma spectrum was measured with the same geometry and neutron flux, only with a rotated stilbene axis.

The result of this experiment is visualized in Fig. 10. The presented results correspond to maximum reactor power during irradiation experiment. It is apparent that the results are almost identical and therefore the deconvolution matrix can be used with rotated stilbene.

The test measurement with HPGe detector was performed and the obtained spectrum is depicted in Fig. 11. The figure shows results from measurement in C16 core configuration. The spectrum is shown only in the most interesting energy range between 6 – 10 MeV. This energy range allows identification of important peak.

The most dominant peak in this energy range is 7724 keV ^{27}Al peak and its single and double escape peaks (single and double escape peaks were not identified in Fig. 11). One can also see peaks coming from stainless steel reflector and from other structural components. The effect of stainless steel reflector was also visible in stilbene core comparison (see Fig. 9).

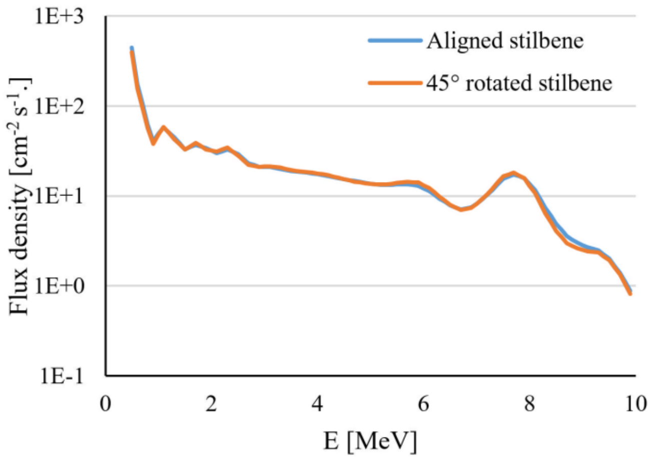

Fig. 10 Measured gamma spectrum with stilbene detector aligned with reactor axis compared to spectrum with rotated stilbene

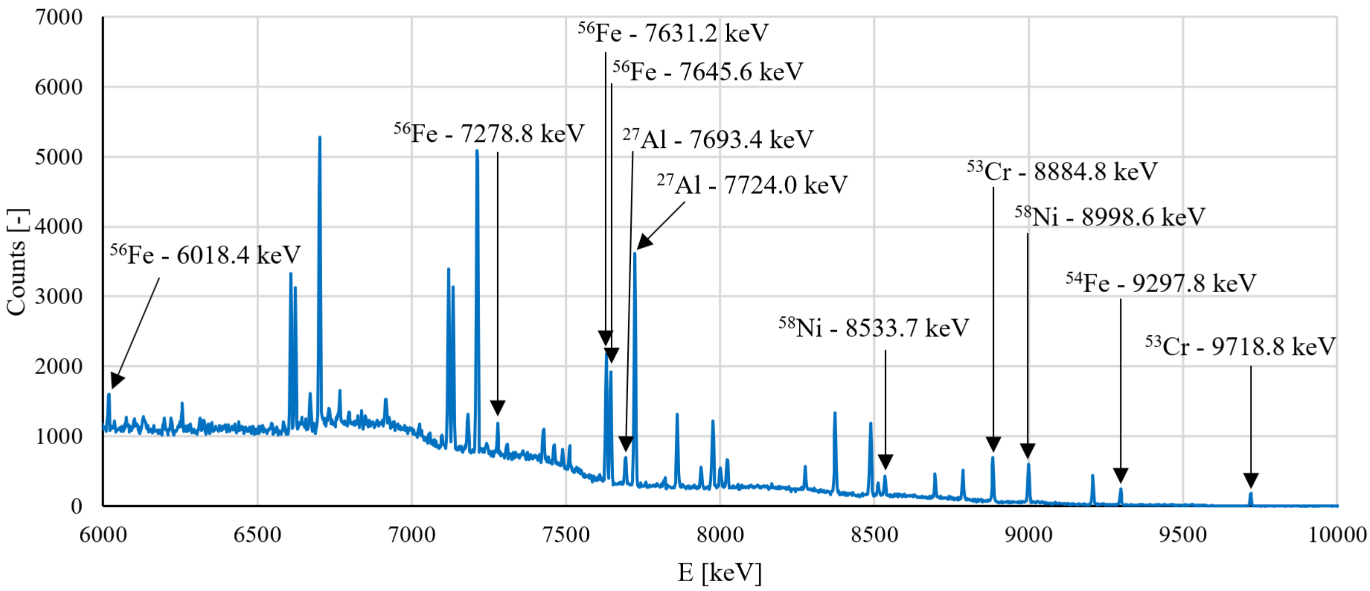

Fig. 11 Measured HPGe gamma spectrum with identification of important peaks, other visualized peaks are mostly single or double escape peaks

Taking into account the fact that the broad peak in scintillation detector measured spectra (see Fig. 8) in 7 – 9 MeV is formed by capture gammas from Al, Fe, Ni, Cr (see Fig. 11), it can be concluded that the magnitude of this broad peak is proportional to thermal neutron flux in the core, because the capture dominates in thermal region. Due to the fact that the VR-1 core is driven by thermal neutrons [9], it can be concluded the broad peak magnitude is proportional directly to reactor power, and such scintillation detector can be used as an independent power monitor.

V. CONCLUSIONS

The gamma field above the reactor pool is suitable for detector testing using high energy gammas. Thanks to the absence of neutrons, the methodology is simplified and allows testing of detectors also sensitive to damage by neutron field. This fact is important especially for semiconductor detectors, or detectors with sensitive volume which might be activated by neutrons.

The experiments prove the usability of organic scintillation spectrometry of high energy gamma rays for independent monitoring of zero power pool type reactors , which is based on the fact, that well distinguishable broad high energy peak magnitude is proportional to the number of thermal neutrons absorbed in structural components and the reactor power is also proportional to the thermal neutron flux.

The experiment proved the possibility of measurement of the prompt gamma field using the HPGe detector. The obtained spectrum shows well separated peaks. Thanks to that, the comparison of the measurement with a calculation for selected peaks is planned.

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REFERENCES

1. D. Harutyunyan, I. Mirzov, M. Košťál, et al, "Estimation of Void Swelling in VVER-1000 Baffle Using Benchmark in LR-0 Reactor". In: Reactor Dosimetry: 16th International Symposium. ASTM International, Santa Fe, NM, USA, 2018, pp 321–334

2. M. Jalali, M.R. Abdi, M.M. Davati, "Prompt gamma radiation as a new tool to measure reactor power". Radiat. Phys. Chem., vol.91, pp. 19–27, October 2013, 10.1016/j.radphyschem.2013.05.033

3. M.-L. Mauborgne, R.J. Radtke, C. Stoller, F. Haranger, "Impact of the ENDF/B-VIII.0 library on modeling nuclear tools for oil exploration". EPJ Web Conf., vol.239, pp. 20007, September 2020, 10.1051/epjconf/202023920007

4. M. Pavelek, Z. Matěj, O. Herman, et al, "Fast digital spectrometer for mixed radiation fields". In: 2017 IEEE SENSORS. IEEE, 2017, pp 1–3

5. F. Cvachovec, J. Cvachovec, P. Tajovsky, "Anisotropy of light output in response of stilbene detectors". Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip., vol.476, no.1–2, pp. 200–202, January 2002, 10.1016/S0168-9002(01)01431-0

6. C.J. Werner, J.S. Bull, C.J. Solomon, et al, "MCNP Version 6.2 Release Notes". February 2018, Los Alamos, NM (United States)

7. D.A. Brown, M.B. Chadwick, R. Capote, et al, "ENDF/B-VIII.0: The 8th Major Release of the Nuclear Reaction Data Library with CIELO-project Cross Sections, New Standards and Thermal Scattering Data". Nucl. Data Sheets, vol.148, pp. 1–142, February 2018, 10.1016/J.NDS.2018.02.001

8. H. Choi, R. Firestone, R. Lindstrom, et al, Database of Prompt Gamma Rays from Slow Neutron Capture for Elemental Analysis, STI/PUB/12. International Atomic Energy Agency, 2007, Vienna

9. M. Košťál, E. Losa, Z. Matěj, et al, "Characterization of mixed N/G beam of the VR-1 reactor". Ann. Nucl. Energy, vol.122, pp. 69–78, December 2018, 10.1016/j.anucene.2018.08.028