

The Underwater Spectrometric System Based on CZT Detector for Survey of the Bottom of MR Reactor Pool – 13461

Victor Potapov, Alexey Safronov, Oleg Ivanov, Sergey Smirnov, Vyacheslav Stepanov
National Research Centre “Kurchatov Institute”, Moscow, Russia.
afrosnov@yandex.ru

ABSTRACT

The underwater spectrometer system for detection of irradiated nuclear fuel on the pool bottom of the reactor was elaborated. During the development process metrological studies of CdZnTe (CZT) detectors were conducted. These detectors are designed for spectrometric measurements in high radiation fields. A mathematical model based on the Monte Carlo method was created to evaluate the capability of such a system. A few experimental models were realized and the characteristics of the spectrometric system are represented.

INTRODUCTION

During the decommission of loop-type facilities of the research reactor MR (testing reactor) at Kurchatov Institute a significant increasing of the dose rate (up to 1.6 Sv/h) near the pool bottom was detected. Therefore, it became necessary to survey the bottom of the reactor pool for possible presence of uranium-containing spills and damaged fuel rod elements. To solve this problem the underwater spectrometric system with collimated detector based on crystal CdZnTe was developed and interchangeable detectors with crystal of volume 60 and 20 mm³ and a multichannel analyzer (MCA) InSpector 2000 were used in this system. The survey objective was to find uranium-containing materials (elements of irradiated nuclear fuel) at the bottom of the pool and evaluation of surface activity of Cs-137. The principle of detection of uranium-containing materials is based on the identification of the characteristic peaks in the spectra of uranium radiation measurements in the energy range 95 ÷ 115 keV. As far as the alleged spectrometric measurements at the bottom of the pool would be in high radiation fields, it was necessary to do some works during design of spectrometric system, particularly:

- to carry out a meteorological research of the spectrometric CZT detectors in radiation fields with high dose rate;
- to work out a mathematical model of the spectrometric system based on Monte Carlo method;
- to optimize geometrical parameters of the system;
- to conduct an experiments to determine the capabilities and the characteristics of the system;
- to determine the calibration constants for measurements of radionuclide activity at the pool bottom.

METROLOGICAL RESEARCHES OF SPECTROMETRIC CZT DETECTORS

The loss of registered pulses due to the dead time of the analog-to-digital converter (ADC) occur with increasing of input loading of multichannel analyzer, as well as the collection of the charge of detector during integration time of signal. The dead time of the ADC is defined as the sum of

the time intervals during which the ADC can not handle the other events. The decrease in the number of registered gamma-quanta in the detector is mainly compensated by using live time of analyzer instead a real time. However, the use of live time does not compensate the loss of events due to overlapping pulses at high load of the analyzer.

Count rate in the full absorption peak is the main spectrometric information that is used to evaluate the activity of the radionuclides in the survey of contaminated sites. During measurements of high-level objects analyzer input loading increases. This leads to decrease the number of registered pulses in the full absorption peak in the instrumental spectrum. This may significantly affect to assessment of the activity of the measured objects. Therefore, to assess the influence of input loading the metrological research of detectors was conducted with help of a point source of Cs-137 with high activity. The value of the dead time of the analyzer, the energy resolution (FWHM), the position of the photo peak and count rate in the full absorption peak were determined in relation of the distance between the source and the detector, which is uniquely related to the dose rate of the radiation field where detector was located. Fig. 1 shows the changes of the basic metrological parameters, depending on the dose rate.

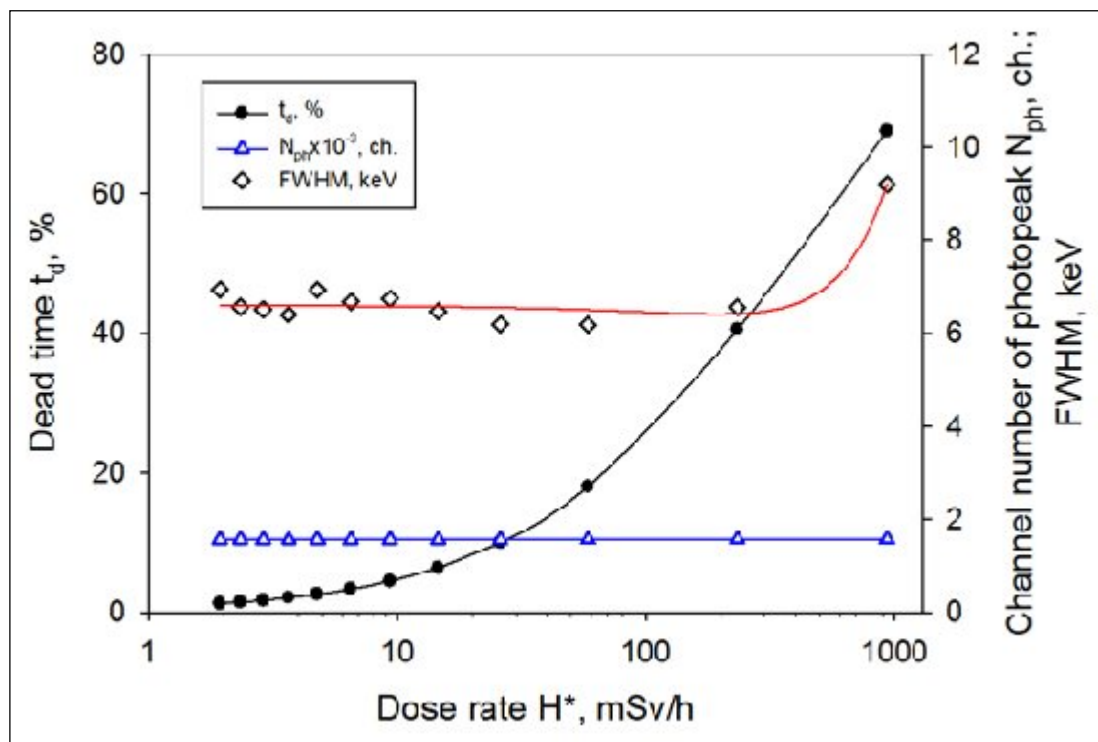


Fig. 1 The behavior of the main parameters of the spectrometric detector versus dose rate exposure.

Looking at the figure shows that the position N_{ph} and FWHM of photo peak virtually unchanged in radiation fields with a dose rate of up to 1 Sv/h, but the dead time t_m increases markedly. It demonstrates that an increase of dose rate has a significant influence on the double coincidence count rate of total absorption peak, which leads to an underestimation of their values. Correction factor K_{cor} which depends on the total load, i.e. total count rate registered pulses n_{tot} was

introduced to compensate for this effect. The relation of the correction factor K_{cor} versus n_{tot} is represented in Fig. 2, which shows that the double coincidence can greatly reduce the count rate in the photo peak (5-6 times or more), and thus lead to a significant underestimation of the measured activity of the radionuclides.

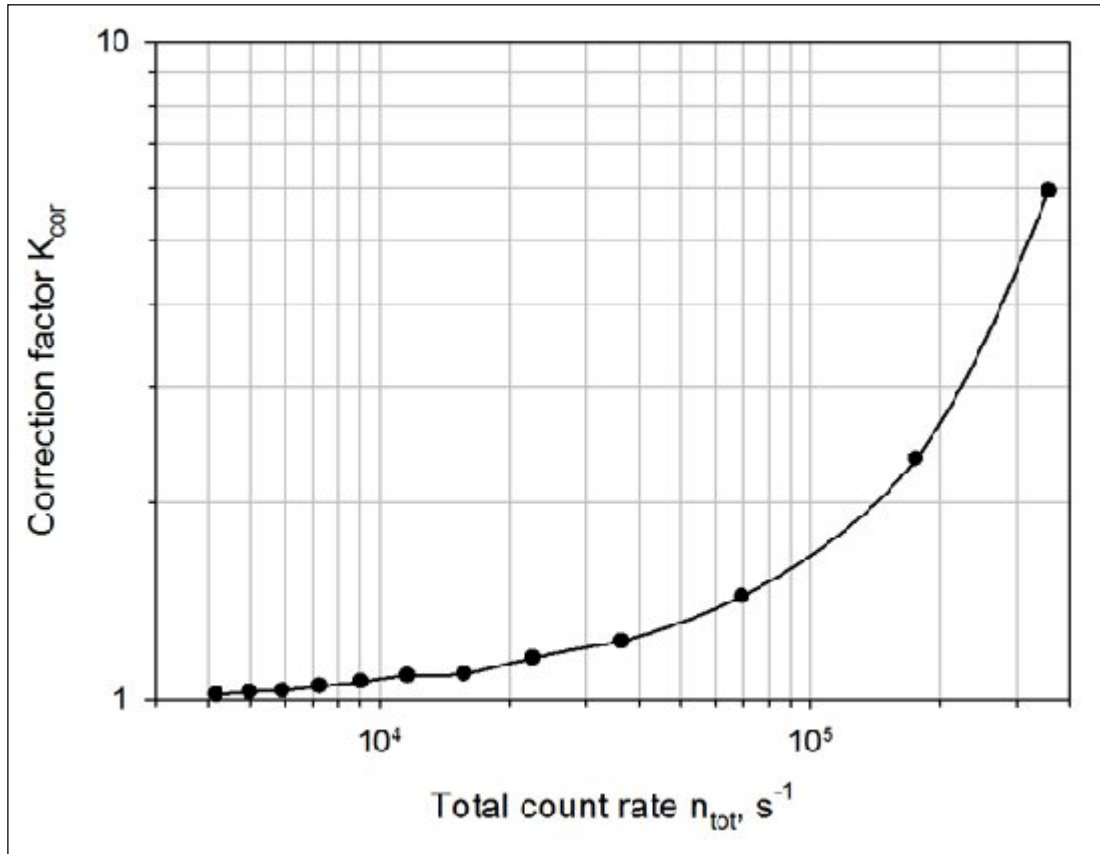


Fig. 2 The dependence of the correction factor K_{cor} on the total count rate of pulses registered with the detector.

These relations were obtained for the CZT detectors with a volume of the crystal 20 and 60 mm³. It should be noted that the dependence $K_{cor}(n_{tot})$ for a particular detector is universal, i.e. does not depend on the nature of the spectrum and is determined only by the total load n_{tot} . Measurements in different environments (in the air and in the water), which varies the ratio of the scattered and unscattered radiation were held for these purposes. Experimental values of correction factor $K_{cor}(n_{tot})$ were placed on a single curve for these two environments. It has been shown that the universal curve is well described by an analytical function (Eq.1) that was obtained in the approximation of a Poisson flow of events. Here Δt is charge collection time (integration time of the current pulse).

$$K_{cor} = \frac{1}{(1 - n_{tot}\Delta t)}. \quad (\text{Eq.1})$$

MONTE CARLO MODEL OF THE UNDERWATER SPECTROMETRIC SYSTEM

To assess the capability and to optimize the geometrical parameters of the spectrometric system the model based on the Monte Carlo method was developed. The spectra of CZT detectors for the geometry of the experiment, which conditional scheme is shown in Fig. 3, were calculated with this model. The model was verified by comparing the calculated and measured detector spectrum of a point source that was located in the water. The results of this comparison are shown in Fig. 4.

The detection of irradiated nuclear fuel was one of the main tasks for survey of the reactor's pool bottom. The detection of uranium-containing materials is based on the identification of X-ray peaks in the spectra of uranium radiation measurements in the energy range $95 \div 115$ keV. This energy region of the spectrum usually has a big contribution of the scattered radiation, so the identification of the uranium X-ray peaks is occurred on a large background substrate. To reduce the influence of scattered radiation lead shielding and collimator detector were used (Fig. 3a). Since the water environment is a good diffuser of gamma-radiation, the option of using additional copper filter with holes like a coded mask aperture (Fig.3b) [1, 2] was considered in order to reduce the contribution of diffused radiation.

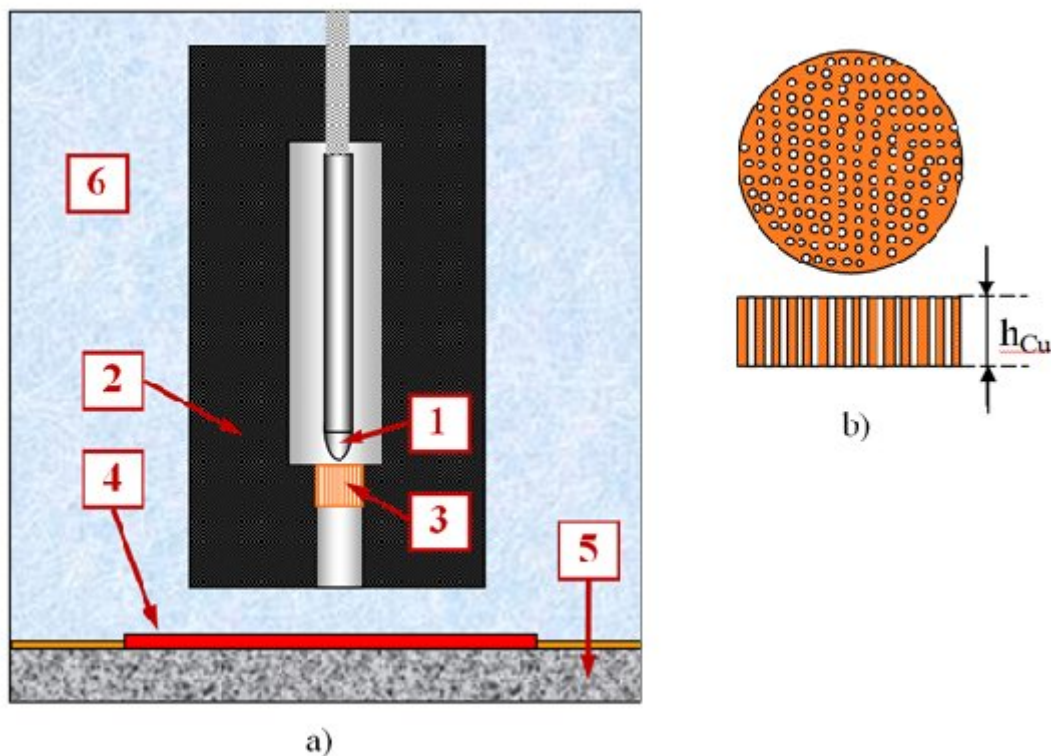


Fig. 3. The conditional scheme for calculation spectrum of collimated detector. (a) 1 - spectrometric detector CZT; 2 - shielding and collimator of detector; 3 - additional copper filter; 4 - source (homogenized layer of irradiated nuclear fuel); 5 - bottom of the pool; 6 - water environment. (b) - enlarged view of the filter structure.

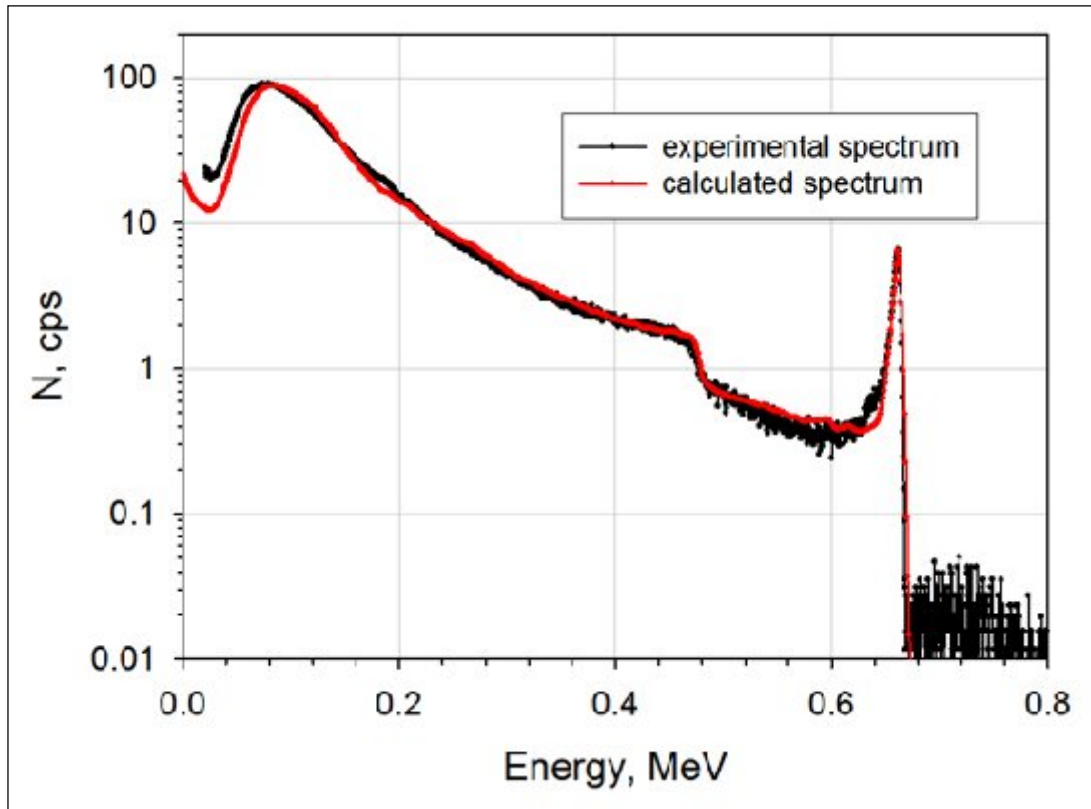


Fig. 4. The apparatus emission spectra of a point source Cs-137 ($A_s = 1.74 \times 10^9$ Bq) that were measured and calculated for water environment. The distance between the source and the detector is 17cm.

The idea of using an additional filter with holes was based on the assumption that the scattered radiation and the characteristic radiation of uranium have different degrees of angular anisotropy, and this may lead to different attenuation of these kinds of radiation. The main characteristics of the filter are its thickness h_{Cu} and geometrical parameter η (0 to 100%). This parameter is defined by the next equation (Eq.2):

$$\eta = \frac{\text{area of the holes}}{\text{the total area of the filter}} \times 100\% . \quad (\text{Eq.2})$$

Instrumental spectra from the source of spent nuclear fuel were calculated for different values of this parameter. These spectra are presented in Fig.5. Looking at the figure shows that count rates in peaks of the characteristic radiation of uranium and the contribution of the scattered radiation in the energy region of interest are reduced when parameter η are decreasing. Therefore, the quantitative criterion of the effectiveness of additional filter can be the value of the signal/noise ratio (Eq.3):

$$S/N = \frac{\text{X - ray peak area of the uranium}}{\sqrt{\text{the variance of the background substrate}}} . \quad (\text{Eq.3})$$

The S/N for five different values of η is shown in the upper right corner of Fig.5. Obviously, the best option corresponds to a larger value of S / N. And as follows from the above data the version without the additional filter provides the greatest value S/N. Therefore such filter was not used in the real device. The Monte Carlo model of the spectrometric system allowed optimizing the geometrical parameters of shielding and detector's collimator. This reduced the influence of the scattered radiation and the adjacent lateral radiation sources. Calibration constants, which needs for measuring the surface activity of Cs-137 at the pool bottom, were also calculated with the mathematical model. This model also allows assessing the possible errors due to the uncertainty of the measurement conditions.

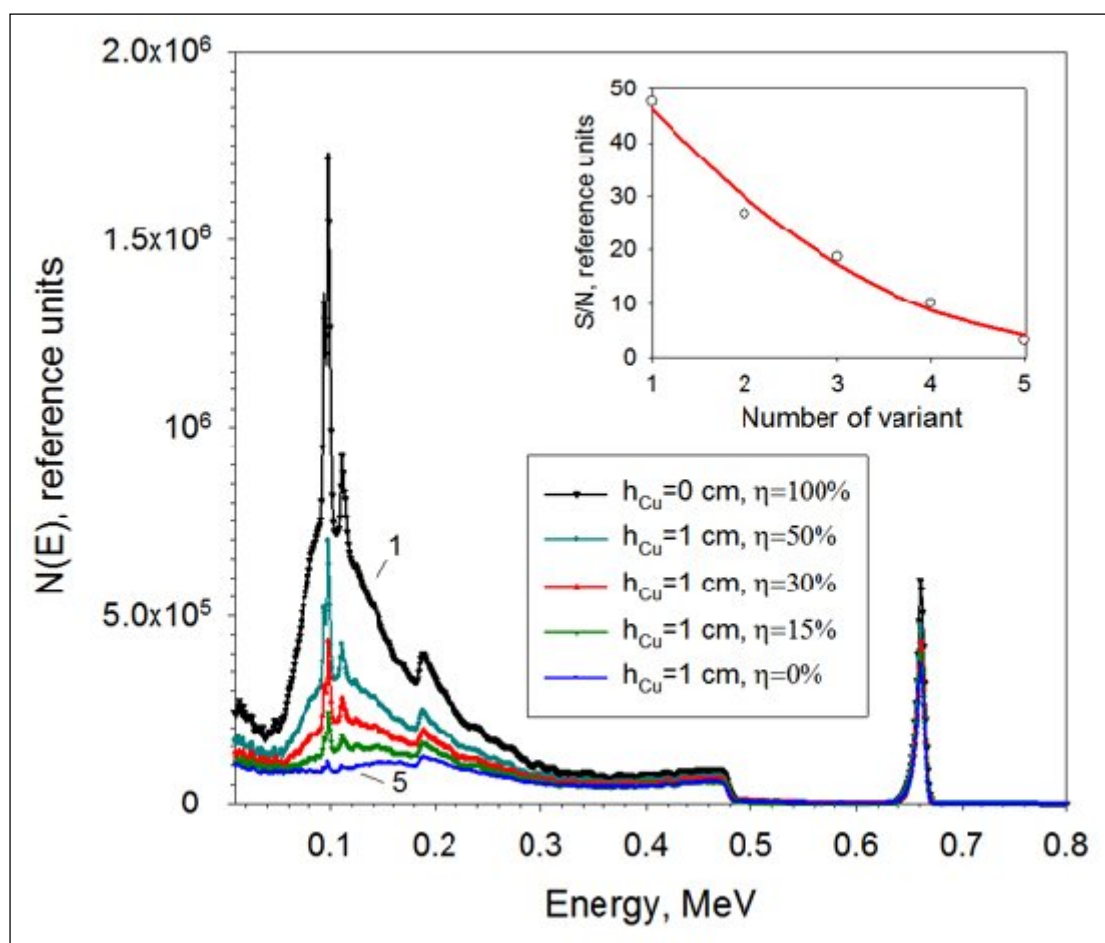


Fig. 5 Calculated spectra for underwater spectrometric system with different parameters of filter (η).

BRIEF DESCRIPTION OF THE SPECTROMETRIC SYSTEM

The general view of the spectrometric installation used for the survey of the MR reactor's pool bottom is shown in Fig.6. The water level in the pool is 9m, so spectrometric system was equipped with a video camera for visualization of measurement conditions on the bottom of the pool.

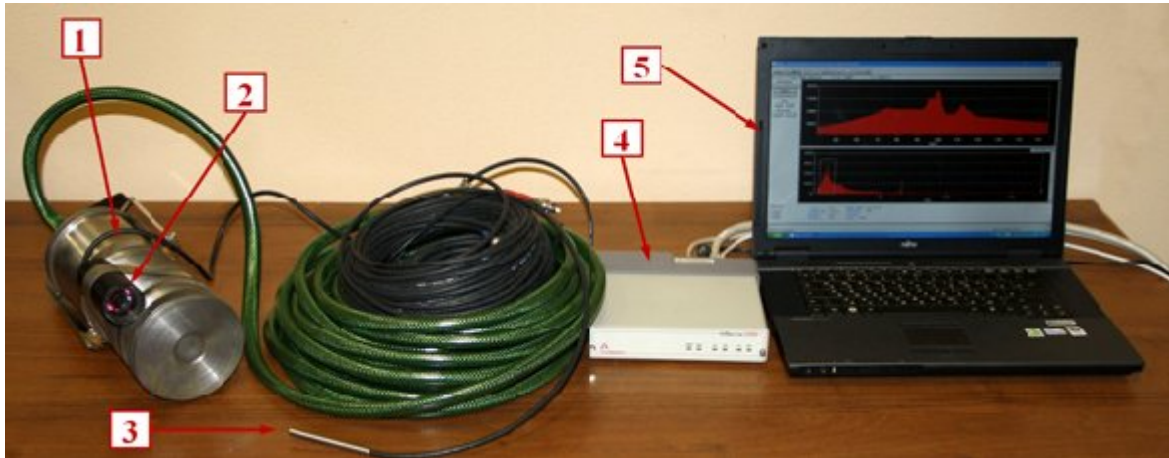


Fig. 6. The general view of the underwater spectrometric system:
1 - the detector placed into shielding with collimator; 2 - video camera; 3 - spectrometric detector; 4 - analyzer InSpector 2000; 5 - computer.

The thickness of the lead shielding of detector is 40mm and the diameter of the collimator channel is 20mm. The inner surface of the collimator channel had a shielding layer of cadmium foil with 2.5mm thick. This shielding layer absorbs X-ray emission of lead, which occurred under the influence of external radiation from radionuclide Cs-137. The angle of view of the collimator (full aperture angle) is about 12 degrees. Total weight of the spectrometric system is 25kg.

MODEL EXPERIMENT

Preliminary modeling experiments with measuring block of the system were conducted. One such experiment was carried out with a real piece of spent fuel, which is located on the bottom of the container with water. The real spectra obtained in this experiment are shown in Fig. 7. This figure shows that the water layer thickness of 4cm between the detector and the source does not attenuate appreciably characteristic radiation of uranium and these peaks are detected in the spectrum.

This modeling experiment was carried out with the detector without shielding, i.e. under more severe conditions of influence scattered radiation.

Experiments with flat and point sources with specified activity allowed determining the calibration constants which will be used to assess the activity of Cs-137 at the bottom of the pool.

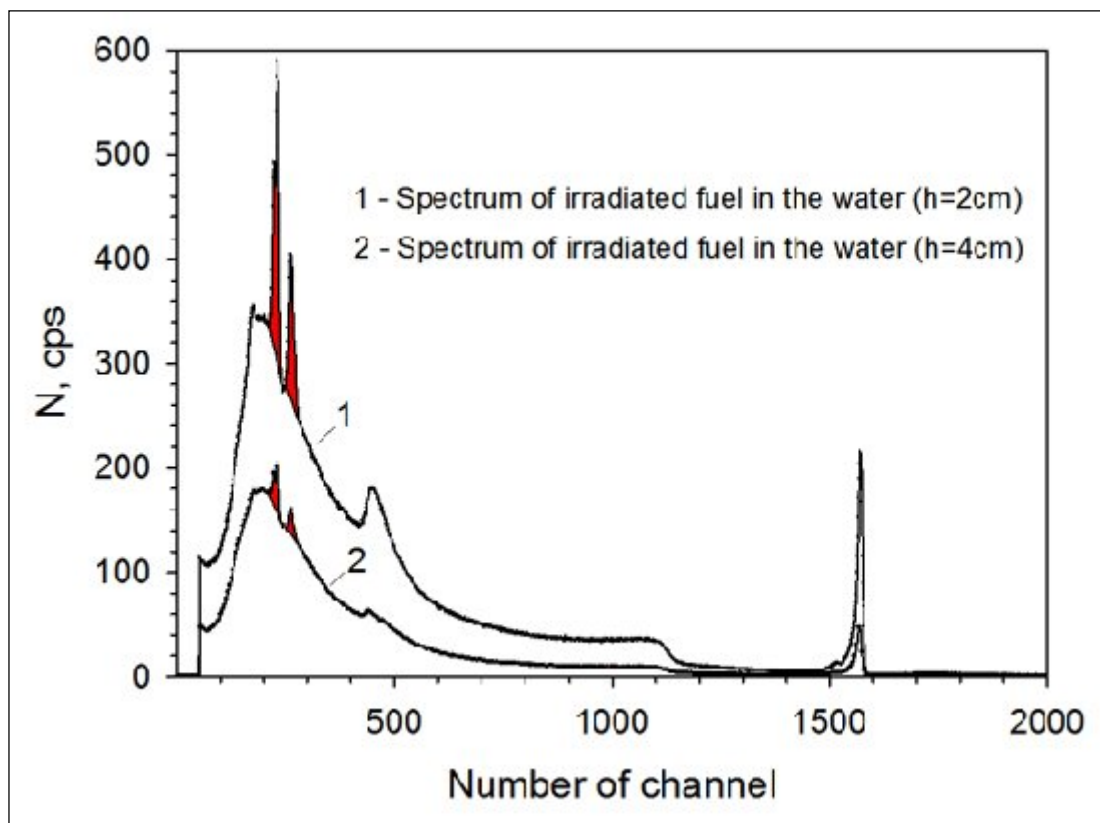


Fig. 7. The emission spectra of the piece of irradiated fuel that was located on the bottom of the container with water. The red areas marked the peaks of the X-ray uranium. The distances between the detector and the source were $h = 2\text{cm}$ (1) and 4cm (2).

CONCLUSIONS

Results of metrological researches of the spectrometric detectors CZT (crystals with volumes 60 and 20 mm³) confirmed the possibility of their use in radiation fields with high dose rate. This allowed using them for the development of underwater spectrometric system designed for survey of the MR reactor's pool bottom. Development of a mathematical model of the system allowed to estimate the optimal geometric dimensions of the detector shielding and collimator and to calculate calibration constants needed for measuring the activity of radionuclides at the bottom of the pool.

REFERENCES

1. M. Gmar, O. Gal, C. Le Goaller, O. P. Ivanov, V. N. Potapov, V. E. Stepanov, F. Laine, F. Lamadie. Development of Coded-Aperture Imaging With a Compact Gamma Camera. IEEE Transactions on Nuclear Science, August 2004, vol. 51, issue 4, pp. 1682-1687
2. V. Stepanov, O. Ivanov, S. Smirnov, A. Danilovich, I. Semin. Portable Gamma Camera with a Rotated Coded Mask for the Remote Measurement of Radioactivity at Nuclear Installation.

WM2013 Conference, February 24 – 28, 2013, Phoenix, Arizona, USA

Proceedings of the [Nuclear Science Symposium and Medical Imaging Conference \(NSS/MIC\), 2011 IEEE](#) 23-29 Oct. 2011, Valencia, Spain, Page(s): 339 – 341

ACKNOWLEDGEMENTS

The authors express their gratitude to employee of the "Rehabilitation" department of NRC "Kurchatov Institute" Ilya Semin for his technical assistance in the development of underwater spectrometer system.