MINIATURE CdZnTe DETECTORS FOR APPLICATION IN HIGH INTENSITY RADIATION FIELDS

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Abstract–**Presently room-temperature CdZnTe (CZT) nuclear radiation detectors of various designs and sizes are widely used for spectrometric measurements of X and gamma-radiations. In most cases the spectrometric detectors with highest efficiency are required1. But there are tasks where good spectrometric detectors with a low efficiency should be applied. Those are tasks connected with spectrometric measurements in strong radiation fields where small size quasi-hemispherical CZT detectors can be used. Now the quasi-hemispherical CZT detectors with a very small volume of about 0.5 mm^3 are available. These detectors have energy resolution (FWHM) of 1÷2% at a 662 keV.**

The possibilities and limitations of the miniature detection probes with CZT detectors for application in strong radiation fields are discussed in the report. Some results of these probes application for irradiated spent fuel assemblies and other high-level objects spectra measurements under water in a NPP cooling pond are presented.

I. INTRODUCTION

Today CZT detectors of different designs are widely and successfully used for various applications due to its favorable detection properties. It is a result of great effort of the researchers and designers focused on improving the performance of these detectors.

Because of the poor holes transport some special techniques and detectors design were developed. These techniques and detectors are based on a single polarity charge collection method [1]. There are various detectors based on this method. Among them there are coplanar grid detectors [2], [3], hemispherical or quasi-hemispherical detectors [4], [5], [6], various Frisch-grid and Frisch-ring detectors [7], pixellated detectors [8] and some others.

The most simple (by) design, but very good by spectrometric performance are hemispherical or quasi-hemispherical detectors. Progress in improvement of CZT crystals characteristic and technology of detector fabrication allow fabrication of high quality detectors. The high and uniform level of electron transport ($(\mu\tau)_e = (3÷5)*10^{-3}$cm^2/Vs [9]) and allows fabrication hemispherical detectors with volumes up to 1.5 cubic centimeters [10].

But also there are many applications where the detectors of large volumes are not required. Moreover even vice versa the spectrometric detectors of small volumes with a low efficiency are required. These are applications are connected with measurements in the strong radiation fields, for example, the verification of high-level irradiated nuclear fuels and high-level radioactive waste.

CZT detectors can be successfully used for these applications also. Nowadays very small CZT quasi-hemispherical detectors of volumes $\leq$ 0.5 mm^3 are available. These detectors have good spectrometric characteristic. Energy resolution (FWHM) at the 662 keV of Cs-137 is about 6÷10 keV. Thanks to low registration efficiency the small size detectors do not overload spectrometric measuring chain on measurements in strong radiation fields. On the basis of these detectors we produce small sized spectrometric detection probes type SDP310 (Ø8x90 mm) and type SDP312 (Ø6x65 mm) [10].

Small external dimensions of these probes allow its application in out-of-the-way places where other detectors cannot be used. The SDP310 with detectors of volume 15÷60 mm^3 are already extensively used for safeguards [11] and other applications.

In the presented paper we have done estimation of extreme available radiation fields where our CZT detectors and probes type SDP310 maintain its operation capacity. Also we have shown an example of its application for spectra of nuclear spent fuel measurements.

II. CZT DETECTORS AND PROBES

CZT detectors of sizes 1x1x0.5 mm^3, 2.1x2.1x1.05 mm^3, 3x3x1.5 mm^3, 4.5x4.5x2.2 mm^3, with volumes about 0.5 mm^3, 5 mm^3, 14 mm^3 and 40 mm^3 correspondingly, placed inside of Spectrometric Detection Probes type SDP310 were used for tests.

The detectors of volumes up to 10 mm^3 also can be placed inside the detection probes type SDP312, having cases of 6 mm in diameter.

The measurements with Large Volume Detector CZT/500S with volume of 500 mm^3 were done for the comparison. These detectors are used with an external miniature charge sensitive preamplifier type PA101C.

The applied detection probes type SDP310 were consisted of the quasi-hemispherical detector, charge sensitive preamplifier, watertight case and connecting cable.

Fig. 1. Photographs of the Spectrometric Detection Probes SDP310 and SDP312

All CZT detectors have optimized quasi-hemispherical structure with the sizes of rectangular sensitive volume $a \times a \times d$, where a is the cross size of the detector, d is the detector thickness, $d=a/2$.

Typical energy resolutions (FWHM) of the Super Grade probes with the detectors volume of 0.5÷20 mm^3 at a 662 keV line are no more than 10÷12 keV, for the probes with detectors volume of 50÷60 mm^3 are no more than 15 keV. Fig. 2 shows the spectrum of Cs-137 obtained with the detector of volume 0.5 mm^3 at normal conditions and count rate of 1000 cps.

Energy resolution of this detector is 6.1 keV at 662 keV line.

Peak-to-Compton ratios for Super Grade probes with the detectors of volumes 5÷60 mm^3 are 3÷4, for probes with detectors volumes 0.5÷1 mm^3 are about 1.5÷2.

The decreasing of the peak-to-Compton ratio for small size detectors is connected with the decrease of the number of total absorbed gamma-quantum inside the detector’s sensitive volume.

The detector’s registration efficiency is defined by the gamma-radiation absorption efficiency and by charge collection efficiency in the detector. For small detectors volumes the total absorption peak efficiency is mainly defined by the photoelectric absorption. For larger volumes the Compton absorption gives additional contribution too.

Our earlier measurements with the detectors of different volumes [11] have shown that a ratio of the total absorption peak area at 662 keV line to whole spectrum area is much smaller for the small volumes detectors. Approximately 16÷20% of the total registered pulses are in the total absorption peak for the detectors of 500 mm^3 and only ~2% for the detectors of 0.5 mm^3. Significant decreasing of ratio with the reduction of detector volume is defined by the decrease of Compton absorption.

III. HIGH COUNT RATE MEASUREMENTS

A. Measuring equipment.

High-count rate measurements have been done at the Latvian Radiation Metrology and Testing Centre having calibrated irradiator with Cs-137 source of 740 GBq activity. This equipment has provided measurements at various distances between the detector and irradiator in a dose rate (by Cs-137) from 1.3 mGy/h to 500 mGy/h.

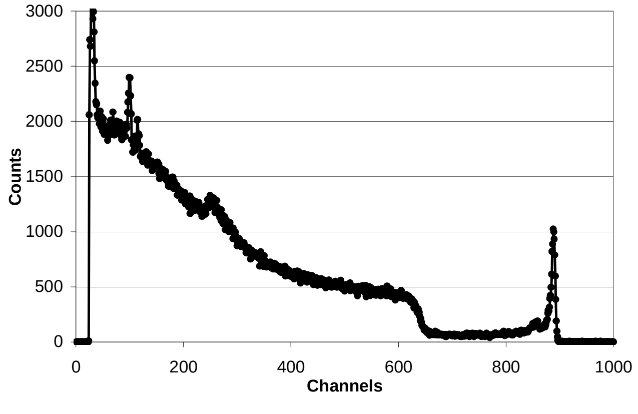

Fig. 2. Spectrum of Cs-137 measured by detection probe SDP310/Z/005 with CZT detector of volume 0.5 mm^3

The main goal of the measurements was evaluation of the extreme possibilities of CZT detectors for the operation in high-level gamma-radiation fields. For such type of measurements it is necessary to take into account the possibilities of applied spectrometric equipment, which may exert great influence on the final results. The spectrometers usually involve the following main units: charge sensitive preamplifier, shaping spectrometric amplifier, ADC and appropriate software.

The preamplifiers count rates ability is mainly defined by the output pulses rise and decay times and output dynamic range. For operation at high-count rates it is necessary to optimize the parameters of preamplifier’s feedback and increase its dynamic range. Modern preamplifiers can operate up to 1000 kcps.

The shaping amplifier high-count rate ability depends on the value of shaping time and correctness of a pole-zero compensation adjustment. Moreover the methods of pulse shaping, base line restoration, pile-up rejection play an important role too.

High-count rate ability is higher for the shaping amplifiers with shorter shaping time, but at the same time a noise level may not be optimized. CANBERRA Fast Spectroscopy Amplifier Model 2024 at shaping time of 0.25 μs may operate up to input load 500 kcps [12].

Digital Spectrometers are the most suitable for the high-count rate measurements. All signals processing there are performed in a digital form. Flexible setting and adjusting systems of these spectrometers allows a fine control for the operation at high input loads. Digital Spectrometers are operable up to input load of 1000 kcps and even higher.

We have used high-precision, ultra-fast all-digital spectrometer Polaris from XIA Inc. [13] for our measurements. Battery powered high performance analog spectrometer MCA-166 from GBS GmbH [14] was used too.

Both spectrometers allow the input count rate measurement and dead time correction.

B. Measurements

Fig. 3 shows the measured input count rate as a function of absorbed dose rate for various detectors.

Detectors worked normally up to count rates of 280 kcps. These count rates were reached in the radiation field with dose rate about 200 mGr/h for the detector with volume of 40 mm^3 and in radiation field with dose rate about 480 mGr/h for the detector with volume of 14 mm^3. In these range the input count rate is directly proportional to dose rate.

Large volume detector CZT/500S of volume 500 mm^3 applied with the preamplifier PA101C could work in higher input load up to 800 kcps. This count rate was reached in rather weak radiation field of dose rate about 50 mGr/h.

Relation between count rate and detectors volume measured in the identical radiation field of 46 mGr/h is a nearly linear, fig. 4.

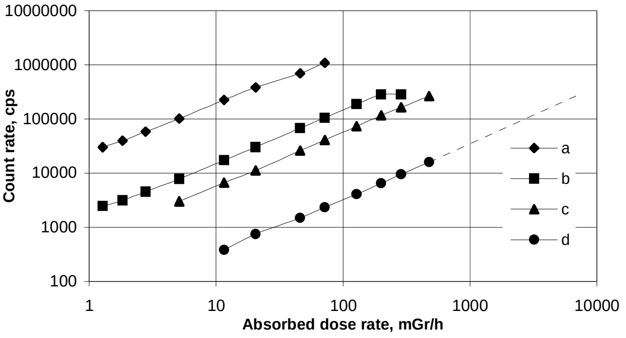

Fig. 3. Input count rate depending on radiation rate for various detectors of volume 500 mm^3 (a), 40 mm^3 (b), 14 mm^3 (c) and 0.5 mm^3 (d)

Fig. 5 shows dependence of energy resolution (FWHM) at 662 keV line, peak-to-Compton ratio, peak position and value of leakage currents on radiation field intensity. At higher input load the detector spectrometric performance is degraded dramatically.

This degradation was observed both with operation with analog spectrometer MCA-166 and with operation with digital spectrometer Polaris. But the detector CZT/500S with the external preamplifier and digital spectrometer could normally work worked up to 800÷1000 kcps. It may testify that the degradation of the spectrometric characteristics of probes SDP310 with detectors of volume 14 and 40 mm^3 is not connected with the limitation of the analog spectrometers and can be results of probe's preamplifiers limitations.

These probes use preamplifiers of a simplified design due to small inside space and for consumption power reduction. They have only a single charge sensitive amplifier section. Such preamplifier has a constant output DC level.

Some serial spectroscopy shaping amplifiers cannot work with the presence of constant DC level on the input. Therefore for the cutoff of DC level we use an output capacitor in series connected to preamplifier output. Such connection is not optimal for pole-zero compensation and at high count rates it may be negatively affected on spectrometric characteristics.

External preamplifier PA101C allows operation at higher count rates. This preamplifier has two amplification stages – charge sensitive and voltage sensitive. These stages are connected through a differentiating RC-circuit. Output pulses have closely to ideal exponentially decaying shape with one time constant. Such pulses are well compensating under subsequent differentiation in shaping amplifier.

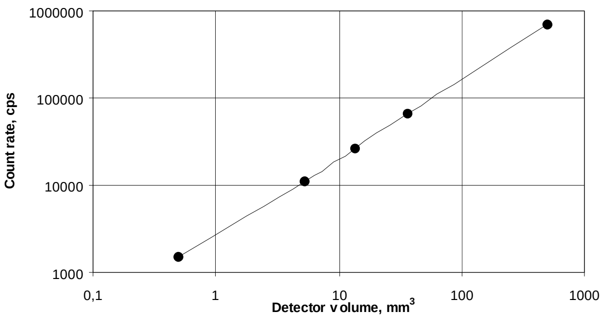

Fig. 4. Count rate vs. detectors volume in radiation field of 46 mGr/h

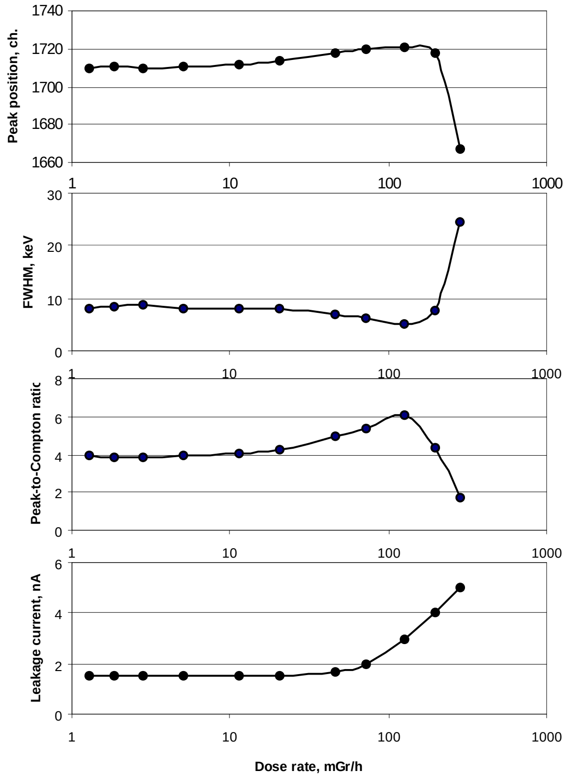

Fig. 5. Energy resolution (FWHM), peak-to-Compton ratio, peak position and leakage currant vs. dose rate for detector volume of 40 mm^3

For more successful application of the probes SDP310 for high count rates measurements more then 280 kcps it is necessary to modernize their preamplifier.

We have not found any limitation in the tested dose range for a probe with the smallest detector of volume 0.5 mm^3. Application of arithmetic extrapolation could assume that this probe will be able to work in radiation fields with dose rate up to 5÷7 Gr/h. However, this assumption requires an experimental testing.

Moreover, spectra degradations due to the influence of possible radiation defects may be observed under a long-term operation in a very intensity radiation fields. By the published results [15] spectra degradation connected with induced radiation defects may be visualized at absorbed dose (by Co-60) over of 25 kGr.

The dependence of energy resolution and peak-to-Compton ratio on dose rate had shown an interesting behavior. These parameters were slightly improved with increasing of dose rate up to certain value, fig. 5. This improvement was observed for all detectors in the similar radiation field. This may be connected with the changes of an electric field distribution inside of the hemi-spherical detectors, due to the volume charge created by the induced charge carriers. It is possible that a new electric field distribution results in better charge collection what is defined better energy resolution.

Fig. 5 demonstrates the dependence of detectors leakage current vs. dose rate. It could be seen that leakage current in strong radiation fields is noticeable increasing.

These changes are reversible. Detectors energy resolution and other parameters are returned to an initial state with dose rate reduction.

Shift peak position in the dose range of a normal detectors operation is not more then 0.6 %.

IV. High-Level Irradiated Items Measurement

The probes SDP310 with small size CZT detectors of volumes 0.5÷5 mm^3 were used for verification of high-level irradiated items stored in a NPP cooling pond. First of all it were irradiated fuel assemblies stored in different storage types and other non-fuel irradiated items, such as process and instrument channels, absorbers, control and safety rods and etc.

The measurements were done with the object of finding an optimal method for verification of all irradiated object stored in the cooling pond with minimum volume of transportation.

Irradiated fuel assemblies and other items are mainly stored in a suspension position inside or without cases. Suspended fuel assemblies are arranged in slots closely to each other. There are few types of spent fuel arrangement differing by surface density, fig. 6.

At inspection and verification of items stored in the storage ponds, it is necessary to obtain its specific features. The irradiated items stored in the ponds have its specific gamma spectra with typical lines. In case of irradiated fuel it is the line of the Cs -137 with energy of 661.6 keV, the most typical line of irradiated nuclear fuel. In a case of non-fuel irradiated items of stainless steel the most typical lines are lines of Co-60 with energies of 1173.2 keV and 1332.3 keV. For more exact identification of irradiated fuel, the lines of other isotopes such as Cs- 134 (604.6 keV and 795.8 keV) and Zr-95 (724.2 keV and 756.7 keV) can be used. The presence in the recorded spectra lines of a short-lived isotope Zr-95 may be used for the identification of items with short cooling time when identification of lines of other isotopes is hampered due to a very strong radiation field connected with high level of the short-lived activity. The line of U-235 of 185.7 keV and/or groups of Uranium X-ray lines with average energy of 100.8 keV may be used for identification of fuel assemblies with zero or very low burn-up.

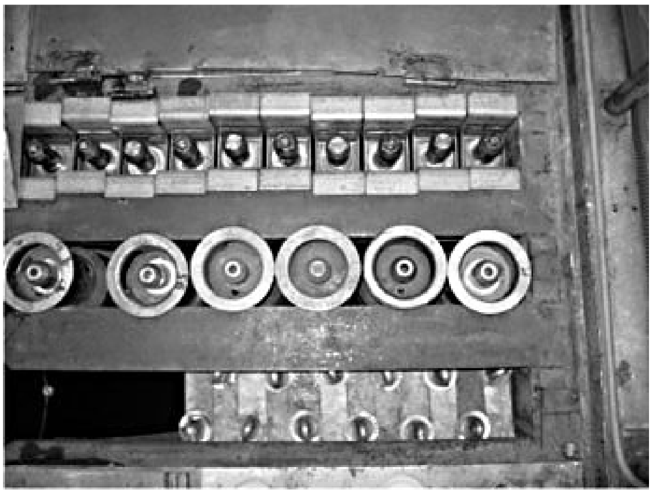

Fig. 6. Three storage types of irradiated fuel assemblies in a one storage bay.

The comparative data on a total counting rate, on count rate in peaks and about a ratio of intensities of peaks of Cs-137 and Cs-134, could also be applied for more reliable identification of irradiated fuel assemblies.

Energy resolution of used SDP310 probes in the most cases allows these measurements.

As usual there are irradiated fuel assemblies with different cooling times from a very short to 15 and more years and with different burn-up from 0 to 2200 MWd/FA in the storage ponds.

Closely located fuel assemblies with the high and low burn-up or/and fuel assemblies with long and short cooling times are the most complicated ones for measurements arrangement of irradiated assemblies.

Usual measuring procedure is carried out in an "ideal" arrangement of measurable items. Fuel assembly or other object is removed from the normal positions in a slot and positioned on the greatest possible distance from the others objects. In this case the most favorable conditions of the measurements are realized, but this may request a great volume of transportations.

We have used method without or with minimal volume of irradiated object transportation. The measurements were done with the probe SDP310 with detector of volume 0.5 mm^3. The probe was placed for measurements inside the special measuring underwater chamber, fig. 7.

This chamber has a waterproof case and a low weight tungsten radiation shielding with side thickness about 0.8 cm. Application of tungsten shielding additionally reduces the spectrometer input load, mainly because of absorption of a scattered low-energy radiation which do not have useful information. For some measurements a slot-like and hole collimators can be placed.

For spectra measurements fuel assembly on suspension is slightly lifted up by the lifting crane at the height of 1÷3 m. The created hole between the suspension and the slots beam is enough for insertion of the underwater measuring chamber.

The measuring chamber with the probe was submerged in water at a depth of 6÷12 m closely to measured assembly up to beginning of its fuel rods, fig. 8.

Lifting up the fuel assembly reduce influence of the neighbors assemblies. Small detectors dimensions and application of the additional tungsten shielding allow making

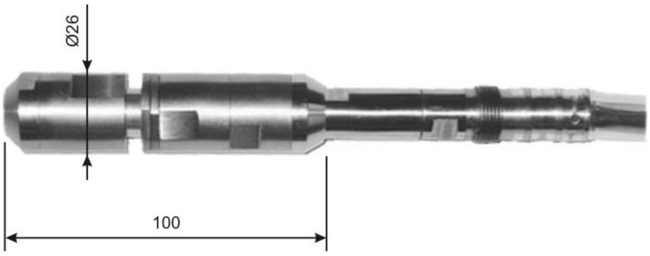

Fig. 7. Chamber for underwater measurement.

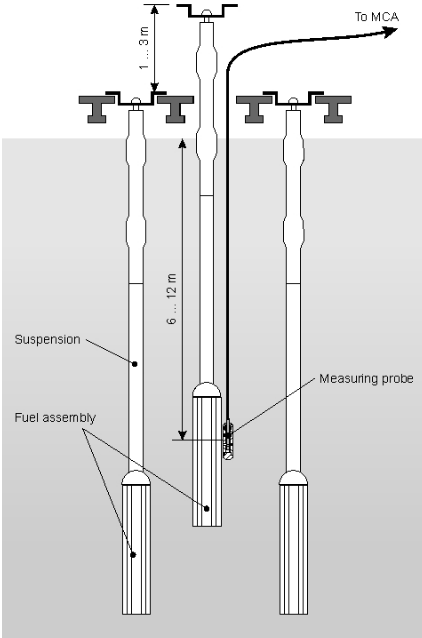

Fig. 8. Scheme of measurement of suspended spent fuel assemblies

measurements of the irradiated fuel with high burn up and with a short cooling time.

Fig. 9 shows one of recorded spent fuel spectra.

In the spectrum there are well-visible lines of Cs-137 and Cs-134 which can be used for the verification.

Other measurements methods with small size probes are available too. For example, they are the measurements with a small detection probe placed inside of a dry pipe at some distance from underwater end of the pipe. For the measurements of underwater objects the pipe end must be placed closely to measured object. In this case the dry pipe is served as a collimator, which is reduced the neighbors objects influence. This method can be applied when any transportations of the object is not available.

V. Conclusion

The presented results show the possibilities of small size CZT detectors and probes on their base for operation in strong radiation fields. It was shown that the probes of SDP310 types with CZT quasi hemispherical detectors of volume 40÷60 mm^3 can operated in radiation fields of dose rate up to 200 mGr/h, detectors of volume 10÷15 mm^3 can operated in radiation fields of dose rate up to 480 mGr/h. The detectors of volume 0.5 mm^3 basically could operate in very strong radiation fields of dose rate up to 5÷7 Gr/h. But this assumption requires additional experimental verification.

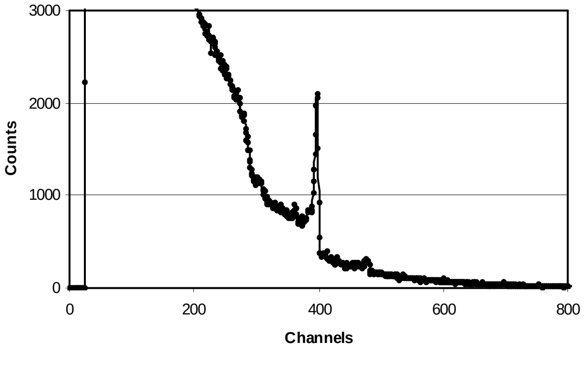

Fig. 11. Spectra of irradiated fuel assembly. Burn-up 1800 MWd/FA. Cooling time about 21 months

Limitation of probes SDP310 in more intensity radiation fields first of all is connected with the limitations of the used preamplifier. The preamplifier modernization will be done for more wide range of radiation fields operation.

The miniature probes with the small size detectors can be used for the high-level irradiated objects verification. Application of CZT detectors for underwater measurements in NPP storage pond could reduce the volume of transportation of irradiated object and reduce NPP operator's radiation exposure.

VI. References

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