THE DEVELOPMENT OF WASTE ASSAY MONITORS BASED ON THE HPGe DETECTORS

by

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The results from the development and the evaluation of radioactive waste monitors for small, medium, and large volumes of those wastes are presented. The efficiency calibration of monitors was made using the standard sources in point geometry as well as by using the complex calculation of the efficiency curves using the Monte Carlo simulation method. The volumetric activity sources were manufactured in the form of real 200, 400, and 700 litre barrels with matrix-fillers in order to calibrate the monitors using the direct verification method. The peculiarities of the software that controls the monitors are presented.

Key words: HPGe detector, waste assay monitor, radionuclide waste

INTRODUCTION

According to the IAEA data, by the end of year 2015 there were 441 operational nuclear reactors in the world and further 68 reactors were in the various stages of construction [1]. During the course of operations, the nuclear reactors produce wastes along with their main product. Due to the specifics of reactors activities the wastes could be radioactive and dangerous for human beings. Along with the commissioning new NPP, the nuclear industry must decommission a considerable number of NPP over the next twenty years: 157 nuclear reactors over the world were finally stopped or were at the decommissioning stage. Furthermore, more than 480 research reactors and several hundred units servicing different parts of the fuel cycle are in the process of finishing their operations [1]. The decommissioning and the disassembly of nuclear energy units will add to the quantity of radioactive wastes which should be recycled in accordance with the existing standards.

The procedure for handling radioactive wastes (RAW) in the nuclear industry is specified in the IAEA documents [2] and is described in detail in [3]. The RAW should be characterised according to its physical, chemical, and radiation properties so that the safest and the most economically effective variant for the waste treatment can be chosen.

The characterisation of wastes and safety requirements demand that the enterprises should have modern technical means that provide an effective solution of RAW management. At the present time, several companies already have arranged the development and the industrial production of the equipment for RAW characterization [4-8]. An analysis of the designs of various RAW monitors shows that they all share a similar structure and apply similar technical solutions. However, despite the evident similarity of applied base solutions, the actual RAW monitors produced by each company are rather unique and customized because their designs are aimed to satisfy multiple requirements specific to each customer.

Having the relevant technologies and the capacity to produce our own HPGe detectors [9], which provide a high efficiency of gamma-radiation registration and an excellent energy resolution, we demonstrate, in the present article, the results of the development of our own equipment for RAW characterization based on these detectors.

THE DEVELOPMENT OF RAW MEASUREMENT DEVICES

All waste assay monitors (WAM) developed are gamma-spectrometers based on the HPGe detectors with various additional devices that provide the optimal measurements conditions for RAW characterisation. The HPGe detectors with the required efficiency of gamma radiation registration can be cooled by the liquid nitrogen or the electromechanical cooler [9]. In order to block the radiation from the unrelated sources and to provide the required aspect angle, the monitors are equipped with the collimation system consisting of

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lead shields which could be replaced manually or fully automatically. To amplify and process the signals from the HPGe detectors, all monitors types are equipped with the same multichannel analyser (16k) and the software package that assures their unification.

MOBILE WASTE ASSAY MONITOR

A mobile waste assay monitor has been developed to characterise a single radioactive object of arbitrary shape. It could also be applied for the monitoring of the premises. The HPGe detector, usually with the registration efficiency (10-20)%, the liquid nitrogen cooling, fig. 1(a), good for 24, 48, or 72 hours, or the electromechanical cooler, fig. 1(b), could be rotated in any spatial direction in 15° steps. To shield the detector from the unrelated radiation, the spectrometer is equipped with a modular lead shield with a thickness of 25 mm or 50 mm, a back shield, and a set of removable collimators, which provide the required aspect angle. To define the distance to the object of the measurement and provide the visual indication of the centre of the radiant surface from which gamma quanta are registered by the detector, the monitor is equipped with the laser range finder. The device can be operated remotely by cable and/or wireless connection to the radiation exposure of the operator. Such monitor provides the detection limit $0.2 \cdot 10^3$ Bq   25 % for Cs-137 in 200 L barrel with the density of 1.7 kgL^{-1} at a distance of 0.3 m between the barrel with the detector (efficiency 20 %) and over the measurement time of one hour at the uniform distribution of activity and the density of the matrix material at the outer background   300 $nSvh^{-1}$.

To simplify its transportation throughout the territory of the enterprise and the various industrial premises, the monitor is assembled on a mobile trolley (fig.1). The trolleys are equipped with the hydraulic lift that can raise the detection unit up to 0.8 meters; the back wheels are equipped with brakes and the drop-out feet with the adjustable height to increase the stability. The monitor could also be placed on a mobile base (electric car) to investigate the extended NPP decommissioning territories [10].

STATIONARY WASTE ASSAY MONITOR

The stationary monitoring systems are required to characterise the average and the large volumes of radioactive waste. The barrels of various configurations are applied usually as the containers for RAW and other materials. The Hercules 200 radioactive waste monitor is designed for the analysis of solid, bulk, and liquid radioactive wastes placed in barrels, boxes, and other packages of arbitrary shape (fig. 2). The monitor measures the activity of the radionuclides with the gamma-radiation in the range of 100 to 2000 keV and is optimally suited for the measurements of objects with an average density of 2500 kgm^{-3} in barrels with a volume of 200 litres.

The monitor includes the HPGe gamma spectrometer with an automated collimator and the possibility for the vertical motion, the barrel rotation mechanism with a strain gauge balance and the drive for the horizontal motion, the dosimeters for the measurements of the dose rate, and the software. The HPGe detector, generally of (30-50) % registration efficiency, is protected against the scattering radiation from the

Figure1. The mobile monitor of radioactive wastes (a) with the liquid nitrogen and (b) the electromechanical cooling

Figure 2. The Hercules 200 stationary WAM for the characterization of 200 litre barrels

outside with the lead shield of 100 mm thickness. The radiation flux from the measuring object to the HPGe detector is defined by the collimator, whose operation is fully automated. The distance between the detector and the waste sample to be characterised can be adjusted to achieve the required activity range. The sample is rotated constantly around the vertical axis to partly compensate for the nonuniformity of the package filling. The rotation of the RAW packages improves the measurement accuracy for the non-uniform filler densities or irregular distribution of the activity through the package volume. The minimal detection activity is ~3 kBq for Cs-137 for the uniformly distributed density and the activity, specified above, in the 200 L barrel with the measurement time of 30 min at the background 300 nSvh^{-1}.

At the start of the measurement, the software evaluates the package dose rate and provides the recommendations for the appropriate positioning of the package relative to the detector or the adjustment of the collimator. At the second stage, the program defines the necessary exposure time and acquires and stores the spectrum. At the final stage, the software automatically processes the obtained spectrum, identifies the radionuclides, and calculates their activities. A protocol that provides the specific activities for each detected radionuclide for gamma emitters is generated, as well as the calculated values of the specific activity of alpha and beta radiation for each radionuclide, if they are available. To improve the accuracy of the definition of the radionuclides activities in the barrels with the irregular density, the monitor provides a measurement mode that performs multiple measurements at different vertical positions along the barrel (segments). The operator can select the mode and up to 16 vertical positions.

MONITOR WITH ROLLER CONVEYOR

When a very large quantity of RAW must be characterised, the high capacity monitors with the automatization of all operations are necessary. The Hercules 400/700/RC monitor with the roller conveyor belt and the rotary table (fig. 3) was developed to measure the radioactivity of wastes packaged in standard

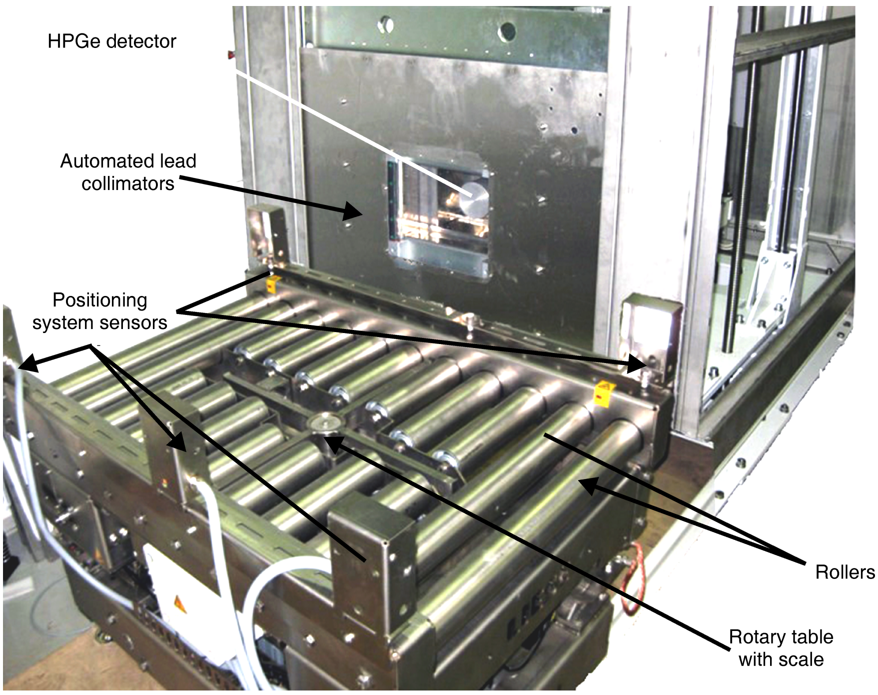

Figure 3. The RAW monitor with the rolling transporter

metal barrels with volumes of 400 and 700 litres of various sizes (the diameters of 540-840 mm and the heights of 825-1275 mm) and weights up to 2000 kg, measured by the scales with an accuracy of 2 kg.

The monitor measures the activity of radionuclides with gamma radiation in the range of 100-2000 keV with the HPGe gamma detector, whose registration efficiency in the present monitor is usually (30-50) %. The lower range of the activity measurement for the radionuclide Co-60, the material with the density of 1.7 kgL^{-1}and the measurement time of one hour is 3 kBq, with an accuracy 20 % (P = 0.95). The available variants of the monitor have from 2 to 8 sensors for the initial determination of dose rate.

The device is designed so that the barrel is transferred automatically from the loading place to the measurement place (rotary table), and after the completion of the measurement, it is transferred to the discharge place for the measured barrels. The automated loading-discharge for several barrels is meant.

After the barrel is placed on the rolling transporter by the loader, the monitor automatically determines the barrel size and the barrel is transferred to the measurement place by the roller transporter. When the barrel moves to the measurement place, the dose rate measurement sensors are automatically moved towards the barrel up to a specified distance. Based on the result of the dose rate and the input count rate measurements, the software selects the optimal distance and the configuration of the collimators for the activity measurement. Then the measurement of the activity of the barrel's content is carried out with the rotary table. The segmentation of the barrel measurement up to 16 segments is available. The information of the activity measurement together with the information from the bar code reader is saved in the data base. To comply with the relevant labour protection and safety rules, the data from the monitor additionally are sent by an RS-485 or WiFi interface to a remote PC.

DUST AND HUMIDITY PROTECTION

Real operation conditions of the WAM on nuclear sites sometimes require their protection against the dust and humidity. Figure 4 presents the measurement part of the WAM for the dust- and moisture-proof variant (IP 44). The front part of the monitor is protected with the roll-up shutters that provide a closed state for the inner part of the monitor during the detector motion. As it shifts up and down, the HPGe detector is protected against the environmental ambient by a special polymer glass with a small absorption coefficient, which attenuates the gamma radiation energy of 100 keV only by 7-8 %.

SOFTWARE

All monitors that we developed are equipped with the software suite that includes the software package WAM-soft for the system control and the automation, the software package SpectraLineHandy, and the software package EffMaker.

Figure 4. The measurement part of WAM in the dust- and moisture-proof case (IP 44)

The software package WAM-soft allows the operator to configure the measurement configuration of RAW radiation (place the objects to be measured into the desired position, adjust the shutter opening of the collimators, start the rotation, *etc*.), as well as to prepare for the measurement execution in various modes (routine analysis or detailed drafting).

The software package SpectraLineHandy [11] executes the control of the spectrometer, displays the measured spectra, identifies the radionuclides, and determines the RAW activity by applying the calculated efficiencies for gamma quanta registration obtained by any calibration method. When the calibration is carried out with the sources in point geometry, the software package SpectralineHandy is also able to carry out the following functions:

– account for the radiation absorption in the container walls,
– evaluate the activity in the case of the unknown thickness of the container wall,
– correct the thickness of the container walls in case when the outer layer material is not set up correctly, and
– correct the efficiency based on the distance between the source and the detector.

Also, it should be noted that the software package provides a data base of transport containers, which can be augmented by the user.

The software package EffMaker [11] is used for the calibration of the monitors with the Monte Carlo simulation method by the manufacturer before the product release and also by the user during the operation as required by the research or other measurement tasks (the non-standard geometries, the expanded energy range, *etc.*). The WAM that we developed can be equipped with other software in accordance with the specialists' request.

METROLOGICAL ASSURANCE

Like all measurement devices, the WAM based on the HPGe detectors require serious metrological assurance. On the basis of the existing metrological standards, the applicable regulations and measurement methods accepted in the nuclear industry [12], we have selected certain calibration and monitor validation methods as the metrological assurance, manufactured a set of the volumetric activity sources for the direct verification of calibration results, and provided a package of application programs to support the measurements and ensure the reliable results.

The calibration of the monitors' efficiency is made with the standard sources in point geometry as well as with the complex calculation of the effectiveness curves using the Monte Carlo simulation method (fig. 5a). To allow the direct verification of the monitors' calibration we have manufactured and certified the volumetric activity sources in form of real 200, 400, and 700 L barrels that contain matrix-fillers (fig. 5b).

The manufactured volumetric activity sources were certified by the D. I. Mendeleyev Institute for Metrology VNIIM [13]. The experience obtained during the monitor calibration shows that in case of a detailed account of the measurement configuration (the wall thickness and material, the density and properties of the filler-matrix, the correct distribution of the activity by the volume, *etc.*) the differences of the calculated registration efficiency values and the values obtained from the real measured barrels with calibrated activities do not exceed 20 % in the range of 100-2000 keV. Thus, the presence of the standard activity sources in the form of real barrels with fillers enable verifying and assuring the specified accuracy of the WAM calibrations. The details of the metrological assurance of the monitors we developed are presented in [14].

CONCLUSIONS

The waste assay monitors we have developed are intended for small, medium and large volumes of RAW. The calibration of the efficiencies of the WAM with standard sources in point geometry and with the complex calculation of efficiency curves by the Monte Carlo simulation method provide a reliable calibration for the monitors. The comparison of the calculated dependencies of the registration efficiency on energy and those ones obtained from the real measured barrels with the sources of calibrated activities demonstrate that the differences in the values do not exceed 20 %. Thus, the presence of the standard activity sources in the form of real barrels with fillers provides the verification and the specified accuracy for the calibration of the RAW monitors. The software provided with the system ensures the correct calculation of the radionuclide activity with our WAM.

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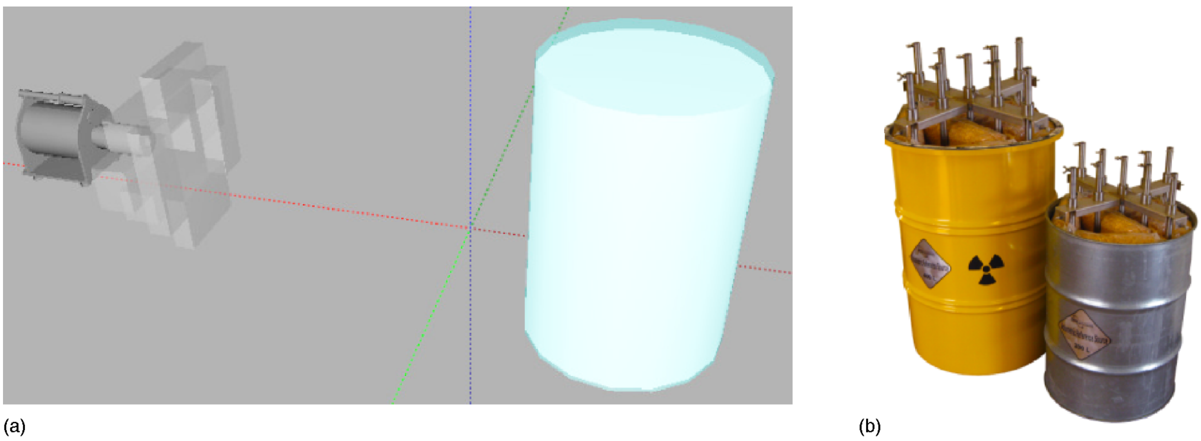

(a) (b)

Figure 5. The monitors' calibration with (a) the complex calculation of the efficiency curves by the Monte Carlo simulation method and (b) the volumetric activity sources – "Barrel 400 L" and "Barrel 200 L"

AUTHORS' CONTRIBUTIONS

The development of the conception and the design of WAM was made by A. Sokolov, the software development by A. Kail. F. Finkel has developed the metrological assurance. V. Gostilo has executed the development of automation conception and the automation programms.

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РАЗВОЈ МОНИТОРА ЗА ИСПИТИВАЊЕ РАДИОАКТИВНОГ ОТПАДА ЗАСНОВАНОГ НА HPGE ДЕТЕКТОРИМА

Приказани су резултати развоја и оцењивања монитора за испитивање радиоактивног отпада малих, средњих и великих запремина. Калибрација ефиканости монитора извршена је применом стандардних извора тачкасте геометрије као и комплексним прорачунима кривих ефиканости применом Монте Карло симулације. Запремински извори направљени су у облику буради запремина 200, 400 и 700 литара са матричном испуном како би се извршила калибрација монитора путем директног очитавања. Могућности програма који управља мониторима такође су приказане.

Кључне речи: HPGe *дешекшор, монишор за исйишивање радиоакшивноī ошйада, радиоакшивни ошйад*