PROSPECTS OF XENON GAMMA SPECTROMETER APPLICATION AS A RECORDING DEVICE ON BOARD OF AN AUTOMATED AND ROBOTIC GAMMA-RAY SPECTROMETRIC COMPLEX FOR THE DECOMMISSIONING OF NUCLEAR PHYSICAL INSTALLATIONS

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The paper considers the structure of robotic gamma-spectrometric complexes for the decommissioning of nuclear facilities. It presents physical and technical characteristics of xenon gamma-ray spectrometer considered a key instrument for gamma-ray spectra measurements of analyzed objects and their activity. The study demonstrated the feasibility of xenon gamma spectrometers application in the decommissioning of nuclear facilities. Remotely received information from a gamma spectrometric complex is transmitted via Internet to a remote computer enabling real-time processing of the experimental data.

Keywords: *gamma radiation, energy spectrum, xenon, nuclide, nuclear facility, radioactive waste.*

Introduction

The use of effective, convenient and safe purpose-designed measuring tools in the decommissioning of nuclear installations is still considered relevant. This article discusses the development of an automated robotic gamma spectrometric complex (ARGSK) based on xenon gamma spectrometer (XGS) applied to investigate nuclear facilities undergoing decommissioning. Such spectrometers have already been successfully used for environmental gamma monitoring of various facilities, in customs inspection installations and to record cosmic gamma flares (with high energy resolution and large luminosity).

To provide personnel safety in the areas of extreme exposure and while handling contaminated materials, it is considered advisable to use automated and robotic systems that have already been developed and tested in practice.

Overview of available complexes

A few examples of robotic systems developed and used for control purposes, to mitigate the consequences of nuclear accidents, as well as those applied in nuclear decommissioning are discussed below.

In mid-1990s, personnel from the Nine Mile Point nuclear power plant tested and evaluated some mobile robotic devices, the use of which appeared to be optimal from the financial and safety

perspective under a promising project focused on radioactive waste characterization launched a few months earlier [1].

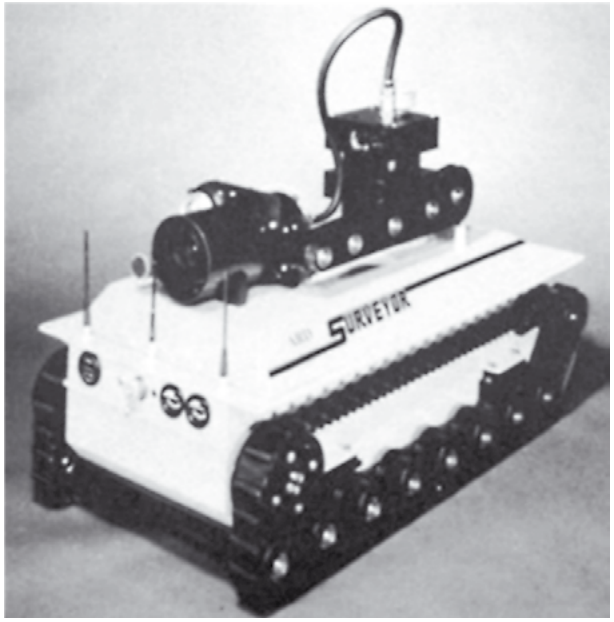

Figure 1. Robot SURVEYOR, 1985

The first robot in this series SURVEYOR (Figure 1) was a two-track tracked platform that could climb stairs at an angle of 45°, overcome water obstacles being up to 15 cm deep and other obstacles being up to 23 cm high [2].

When the damage caused to the fourth unit of the Chernobyl NPP was evaluated, a repair scenario was drawn up based on the state of the considered facilities and the needs for potentially applicable robotic systems were analyzed [3]. Relevant operations were most commonly referred to the characterization of materials with radioactive contamination, excavation, equipment dismantling using manipulators.

With regard to the characterization, the idea was to use systems the high performance of which has already been proven under previous operations involving hazardous environments with robot samples, in particular with the MACS (Mobile Automation Characterization System) and RCS (Remote Characterization System) developed by the US Ministry of Energy and NOMAD (developed by NASA). MACS was equipped with six NaI scintillation detectors, provided laser navigation and automatic exploration survey, while the RCS robot could perform subsurface mapping, but its GPS-based navigation system allowed external operations only. The NOMAD system could automatically avoid obstacles and provided high image quality.

The Pioneer 1 robot (Figure 2) was designed to assess the structural integrity of the sarcophagus at the Chernobyl NPP and to build a 3D map of the site. To withstand high radiation levels, some of its main elements were placed outside the operating area, while onboard components were usually protected with a thin lead layer (for example, 1.25 cm) [4]—[6].

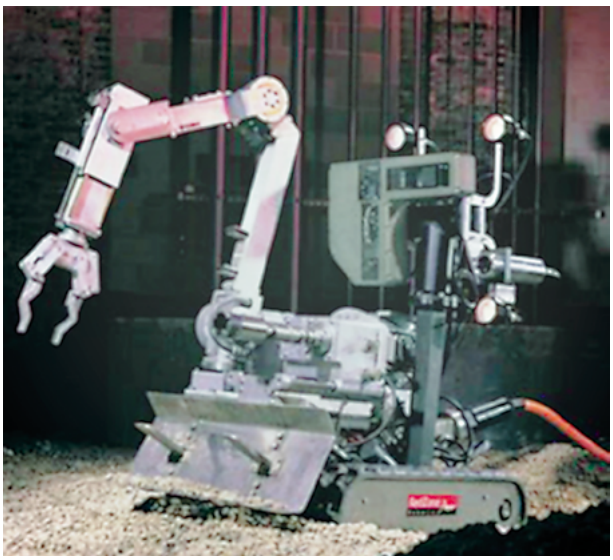

Figure 2. Pioneer 1 — robotic sounding system operated at the fourth unit of the Chernobyl NPP

On March 11, 2011, the Fukushima-1 NPP was damaged due to a major earthquake and tsunami in Eastern Japan. Three reactor buildings were severely damaged and radioactive material was released. It was not known whether it was safe to enter the buildings or not, so radiation studies involving robotic equipment were needed. Immediately after the disaster, a number of projects was launched to upgrade some existing robotic systems enabling their operation in the reactor buildings. The Tokyo Electric Power Company (TEPCO) took part in these projects.

The first Quince1 robot (Figure 3) was deployed at the site on July 20, 2011 and operated until October 20, 2011 [7]. During this period, six missions were completed allowing to determine the state of the NPP units and pipelines, which contributed to the planning and implementation of remedial efforts. However, on October 20, the Quince1 robot did not return from an observation mission in the building of the reactor's second power unit. On the way back, the communication cable was damaged and the robot was left on the 3rd floor.

The designs of a mobile robot equipped with a scintillation detector allowing to monitor the gamma radiation field were discussed in [8]. In addition, the system enables full 180° rotation providing the

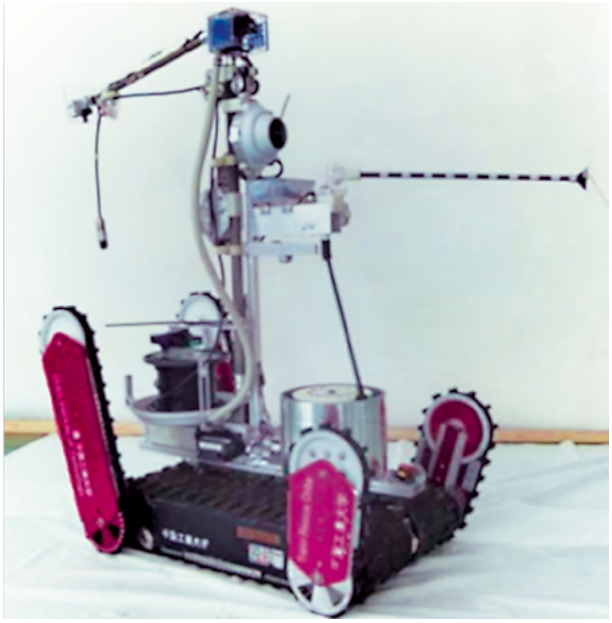

Figure 3. Robot Quince1

generation of radiation profiles. This installation is tasked to determine the location of nearby gamma radiation sources. The chassis is a Lynxmotion 4

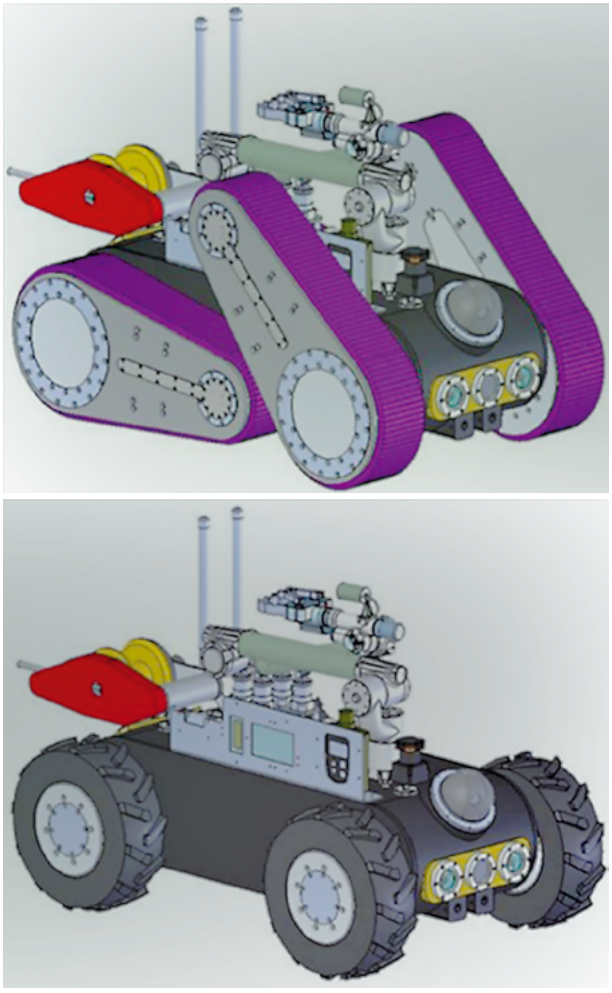

Figure 4. Robot RESCUER on caterpillar and wheel base

unit with a turntable installed on it. A lanthanum bromide ($LaBr_3$) based detector can be viewed by a Hamamatsu R6231 photomultiplier tube, while the Lynxmotion Bot II board with a BasicAtom Pro 28 processor is used as a controller.

Figure 4 presents the RESCUER robot designed to detect radioactive materials and take samples [9]. Application of robotic systems provide for the development of methods required to decontaminate the robot after its use in order to minimize any risk of radiation exposure to the operator and personnel which is seen as an important feature of this activity. Therefore, some additional coating is applied to the surface of the robot body to speed up and optimize the decontamination procedure. The robot is equipped with a multi-sensor system that provides area mapping. It is also fitted with an interface for semi-autonomous operation. The body structure is made of polycarbonate and AISI 304 BA (Fe/Cr18/Ni10) stainless steel.

This robot is navigated by a manual coding device and a differential global positioning system and is moving on wheels or tracks. For sampling purposes, special gripping devices and a container are provided.

A new RICA robot (570 × 430 × 330 mm) designed for RW characterization purposes was presented in [10]. Its weight is 80 kg. It is used to find the location of radioactive sources and to measure their activity. The robot moves using a platform with polymer tracks, which is equipped with two CCD front and rear-view cameras, as well as white LED-based headlights providing illumination. Depending on the task at hand, the robot can be equipped with various sets of tools, such as a mechanical arm for sampling purposes and a gamma spectrometer for characterization purposes (Figure 5).

The gamma spectrometer is based on a CdZnTe crystal and registers gamma quanta in the energy range of 50 keV—2 MeV. The robot is powered and controlled via a single 100m coaxial cable.

In 2012, the following JAEA robots were used at the Fukushima-1 NPP site: Brokk-40 (JAEA-1), two RESQ-A (JAEA-2/3), as well as an improved JAEA-3 (Figure 6) which was used to provide gamma-ray-imaging on different floors of the building constituting to the second power unit six months after the accident.

The PMORPH (reshapable) and SCORPION robots were designed to pass through a 100 mm diameter pipeline providing access to the interior of the nuclear reactor's primary containment at the first unit of the Fukushima-1 NPP. SCORPION was the last robot that attempted to explore the interior of the reactor unit 2.

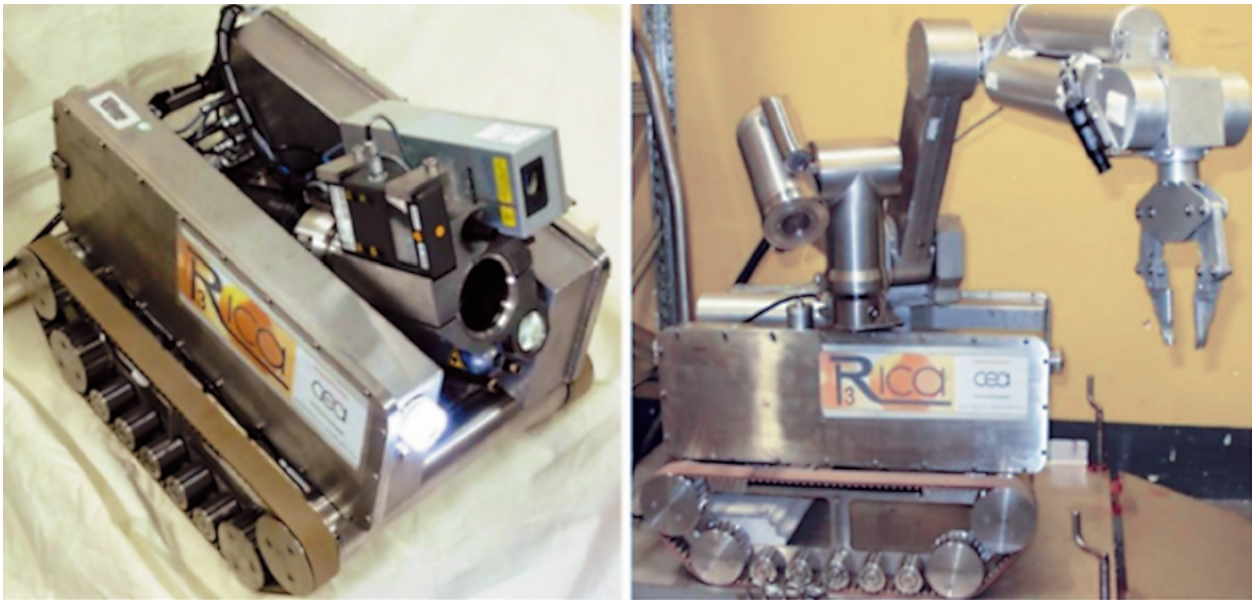

Figure 5. RICA robotic platform with gamma camera (left) and manipulator (right)

Figure 6. JAEA-3 robot with a gamma imaging system

Figure 7 presents robots PMORPH and SCORPION (taken from the TEPCO website) [12].

Thanks to the large number of developed robotic systems [13] one may opt for an optimal engineering solution that would provide success in the implementation of tasks associated with the characterization and monitoring of radioactive environmental contamination resulted from accidents at nuclear power plants, including the use of advanced detecting and spectrometric systems.

In the summer of 2018, the Gamma-Pioneer gamma-ray spectrometric system developed by the specialists of the National Research Center Kurchatov Institute and installed on the Brokk-90 robot was used to search for and characterize high-level waste (~ $3.17 \cdot 10^{12}$ Bq) held in storage facilities. A gamma-ray spectrometer based on CdZnTe [14]

Figure 7. PMORPH series robot operating inside the first unit of Fukushima-1 NPP (left) and a research mobile robot designed to monitor radioactive leaks (right)

was applied as a recording unit. This system can be effectively used to study items exposed to high levels of radioactive contamination, which is required during critical emergency operations in high-level waste and SNF storage facilities, as well as during the decommissioning of nuclear facilities.

This article describes a new automated and robotic complex based on a xenon gamma spectrometer developed at NRNU MEPhI, which can be used in the decommissioning of hazardous radiation facilities and RW management.

Xenon Gamma Spectrometer

For ground-based robotic complexes, it was proposed to use a xenon gamma spectrometer with a design capacity of 2,000 cm^3 as a detecting device.

XGS design is based on a pulsed ionization chamber with a screening grid filled with a mixture of ^{54}Xe xenon and 0.2% hydrogen at a pressure of 40 atm. Figure 8 shows the layout and a picture of a XGS with a sensitive volume of 2,000 cm^3. The table below presents its physical and technical characteristics.

Basic physical and technical XGS characteristics	
Power supply voltage, V	24
Power consumption, W	20
Dimensions, cm	Ø15 × 45
Weight, kg	5
Working capacity, cm^3	2,000
Registration efficiency for gamma quanta with an energy of 662 keV, %	6
Energy resolution for gamma quanta with an energy of 662 keV, %	1.7 ± 0.3
Measured energy range for gamma quanta, MeV	0.05 – 5
Density of the working substance (xenon), g/cm^3	0.3

The key advantages of the developed complex can be summarized as follows:

- vibroacoustic stability. The xenon gamma spectrometer is capable of operating under vibroacoustic effects up to 100 dB which does not cause any decrease in the energy resolution [15];
- temperature stability. XGS design is based on an ionization chamber, which is capable of operating at temperatures of up to 100 °C with no changes in the spectrometric characteristics of the device [16];
- radiation resistance. XGS spectrometric characteristics do not deteriorate when $1.5 \cdot 10^{10}$ particles pass through the neutron fluence detector [17].

The stability of XGS spectrometric characteristics has been confirmed by a decade of operating experience on the MIR orbital station [18]—[20].

Gamma spectrometers based on compressed xenon were used as part of a prototype complex applied to segregate and characterize radioactive waste [21], a portal complex used to monitor passenger traffic [22] and also in an automated system designed to monitor gaseous radioactive emissions from a nuclear reactor [23]. To process the analog XGS signals, a digital electronics unit based on programmable gate arrays [24] is used, which operate taking into account its features. The xenon gamma spectrometer is protected by a patent (RU109300 application of June 6, 2011 [25]) and the competence of the laboratory staff.

The main advantage of XGS is viewed in its good energy resolution (1.7 ± 0.3) % on the 662 keV line of the ^{137}Cs radionuclide [26], which is several times better than that of NaI and CsI scintillation detectors, whose energy resolution is 7—9% for 662 keV gamma rays.

In contrast to semiconductor spectrometers based on ultrapure germanium requiring liquid nitrogen for cooling purposes, XGS operation does not require any cooling.

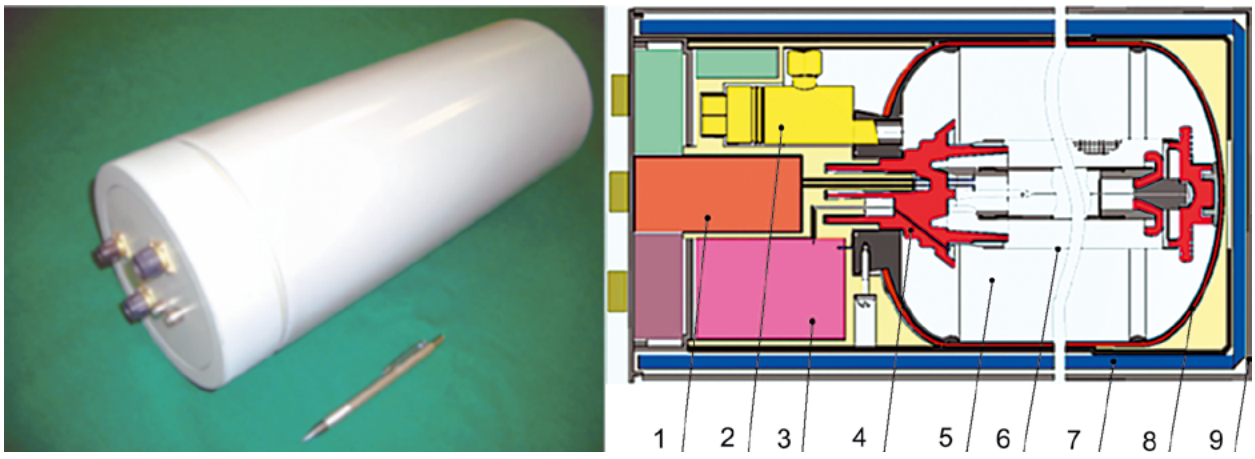

Figure 8. XGS appearance and layout: 1 – charge-sensitive amplifier, 2 – valve for the inflow of the working substance, 3 – power source, 4 – ceramic pressure seal, 5 – ionization chamber, 6 – screening grid, 7 – Teflon insulation, 8 – steel case with composite coating, 9 – outer protective housing

XGS designs, depending on the operating conditions, provide for different working capacities ranging from 20 to 6,000 cm^3 [27]—[29].

The presented developments of Russian and international companies demonstrate the general level of scientific and technical development in the field of mobile robotic systems designed for various purposes and should have the following characteristics:

- control range — not less than 100 m via cable line and not less than 500 m via radio channel;
- operating time — unlimited when power is supplied via cable and at least three hours from batteries;
- equipped with sampling devices with a loading capacity of at least 15 kg;
- high radiation resistance (assuming a total dose of gamma radiation amounting to 100 Gy);
- measured dose rate of gamma radiation in the range from 0.1 mSv/h to 100 Sv/h for energies of 0.05—3.0 MeV with an error of no more than 30 %;
- the measuring equipment of the complex should be able to determine the location of a radioactive source and to map the radiation contamination of objects and terrain;
- it should be fitted with gamma spectrometric equipment with an energy resolution of no more than 5 % for the gamma quanta energy of 662 keV.

The robotic platform shall perform the following functions:

- delivery of detection units installed on the platform to the objects considered under the study and their return to the control station;
- information transmission (video, spectrometric, on the platform state) to a remote operator's console.

The robotic platform shall meet the following requirements:

- mode of movement — wheeled (4 pcs.) or caterpillar (2 pcs.);
- engines — electric;
- weight of the payload moved by the robotic platform — not less than 20—40 kg;
- movement — in any direction on the plane (solid ground);
- operator uses remote control;
- operating conditions at temperatures ranging from + 5 to + 50 °C and humidity of up to 95 %;
- electromagnetic compatibility of the equipment applied;
- availability of GLONASS positioning system (GPS);
- low cost.

State-of-art in the development of a robotic complex (RC) by NRNU MEPhI

To date, a system providing remote communication, transmission and reception of signals from the gamma spectrometric system of the complex has been developed and tested. Control function, straight forward setting, temporary storage and transfer of gamma spectra measured by the XGS, which is part of the gamma spectrometric complex, is implemented using a software that should ensure reliable operation of the RC under severe experimental conditions.

For this purpose, PO-2 software was developed to provide remote control of the XGS, which was designed compatible with different operating systems (Windows, Linux).

For this purposes Python was used, which is a high-level general-purpose programming language: it seeks to improve the efficiency of the operator by simplifying the readability of the code. Figure 9 shows a screenshot of the PO-2 NABOR working window designed to work with the XGS and performs the following operations:

- reading data from XGS;

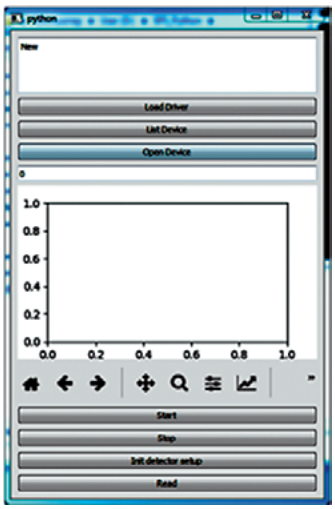

Figure 9. Screenshot of the PO-2 NABOR working window

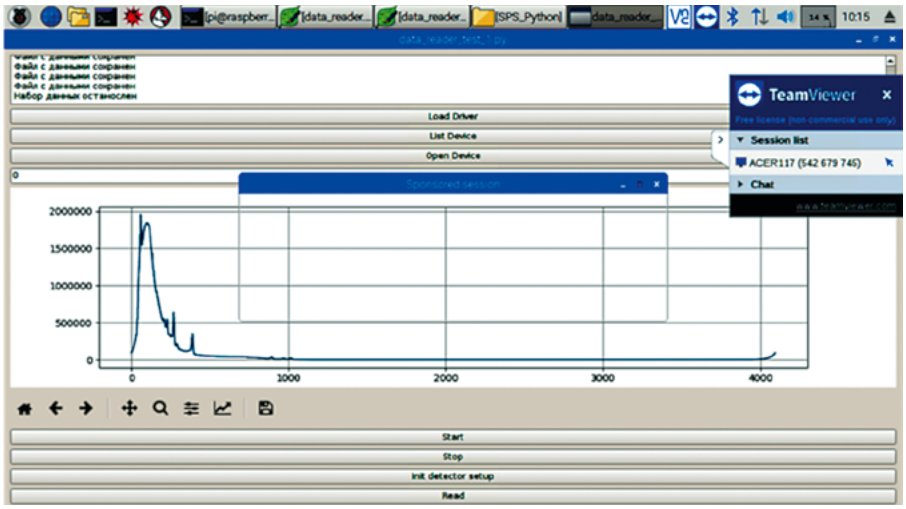

Figure 10. Gamma spectrum measured with Raspberry Pi

- writing the spectrum to a file;
- simple visualization of the energy spectrum giving an idea whether the XGS operation is correct.

The following packages and modules were integrated into PO-2:

- **PyQt5** — a package allowing to build graphical user interface;
- **Matplotli** is a plotting library required for spectrum visualization;
- **FTDID2xx** — library enabling operations with the FTDI driver through which data is transferred between the computer and the detector;
- **Save to SPS** — the function that allows to record SPS spectrum into files.

PO-2 NABOR operates according to the following algorithm:

- when the program is started, the FTDID2xx driver is initialized: it reads data from the XGS;
- connection is further established with the microcontroller FTDID2xx providing data exchange;
- the program adjusts the response threshold, the rejection threshold and the integration time of the signal coming from the XGS;
- spectrum acquisition starts by pressing the corresponding button;
- every two seconds the spectrum is updated in the program window;
- every minute the spectrum is saved to a temporary file on the PC's hard drive;
- spectrum acquisition can be stopped by clicking on the "Stop" button. In this case, the spectrum acquired over the entire measurement time is stored on the hard disk.

The Raspberry Pi 3 Model B+ 1GBRAM platform connected to the Linux Raspbian operating system (compact single-board microcomputer) was used to test PO-2 NABOR of the XGS remote control.

Using the XGS and a Raspberry Pi single-board computer, gamma spectra from ^{133}Ba, ^{60}Co and ^{22}Na gamma sources were measured. In this case, the energy spectrum was saved every minute in a temporary SPS file.

The Team Viewer program server providing remote access was launched on the Raspberry Pi platform, which allowed to control the acquisition of the spectrum and copy the experimental data to a remote PC. Figure 10 shows the PO-2 interface.

PO-2 NABOR was launched on the Raspberry Pi platform connected to the XGS via TeamViewer.

Further on, the histogram corresponding to the energy spectrum can be studied in more detail.

Zooming can be performed to view individual gamma lines in the measured gamma energy spectrum.

Gamma spectra from standard ^{133}Ba, ^{60}Co and ^{22}Na gamma sources were measured using PO-2 NABOR: ^{60}Co emitted gamma rays with energy levels of 1332.5 and 1174 keV, ^{22}Na — 1280 and 511 keV and ^{133}Ba — 383, 356, 302, 276 and 80 keV.

Figures 11 and 12 show energy spectra measured by PO-2 Python NABOR run on the Raspberry Pi platform.

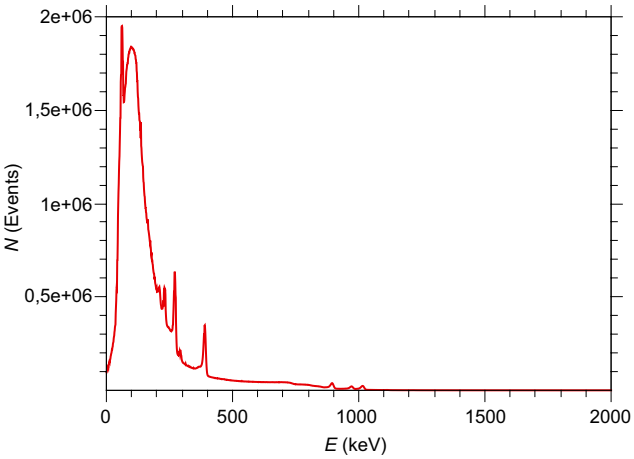

Figure 11. Gamma spectrum measured using PO-2 NABOR, on a linear scale

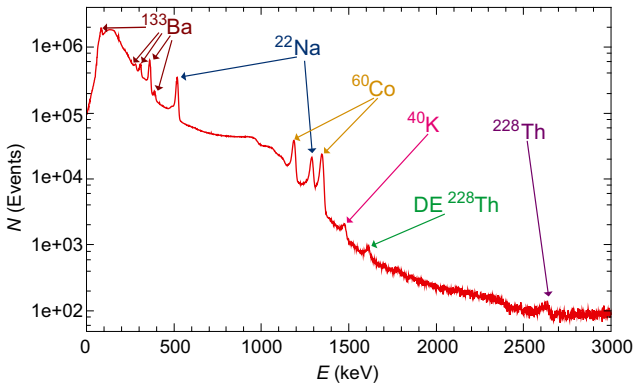

Figure 12. Gamma spectrum measured using PO-2 NABOR, in a semi-logarithmic scale

In the high-energy region (more than one MeV), these figures clearly show gamma lines characteristic of natural radionuclides ^{40}K and ^{228}Th providing the background gamma-ray flux.

The measurements performed have demonstrated high reliability of PO-2 NABOR.

Conclusion

The characteristics of the developed XGS and the additional systems designed as part of the gamma spectrometric complex provide the opportunities for their application in the detection and measurements of radioactive and fissile materials. They can be also used to monitor the radiation situation during RW management and nuclear decommissioning.

Next stages in the ARGSKA development provide for the development of a prototype gamma spectrometric complex involving a mobile platform, a navigation system and a XGS equipped with a digital electronics unit enabling wireless data transmission, which is used to manipulate and control the entire robotic installation.

It is also proposed to fit the platform with an additional mechanism providing horizontal XGS rotation along with the collimator by 360 degrees to scan the surrounding space. This would provide more efficient positioning of the detected gamma sources.

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