GAMMA-IMAGING SYSTEMS FOR ECOLOGICAL AND NUCLEAR ENVIRONMENT MEASUREMENTS

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At the moment a large number of nuclear reactors require decommission and subsequent disassembly. After long operation time the basic and accessory reactor equipment has a high contamination level. The individual character of this contamination requires the development of the specific optimal decontamination strategy in each case. For minimization of the staff radiation exposure it is desirable first of all to remove the most contaminated fragments of the equipment which determine dose conditions. Then the subsequent and as a rule the most long part of the work can be carried out under rather soft dose condition.

One of main problems in determination of the decontamination sequence is the search and identification of the most contaminated fragments of the equipment. One solution of this problem is the application of gamma-ray imagers. As a rule the inspected premises are characterized by lack of free space, have the high level radioactive contamination and are filled with the equipment. In a number of cases the access to these premises is complicated and hand-operated installation of the imaging device in the premise is necessary. Because of large dose rate levels the installation should be realized as quickly as possible. Then the device should be controlled remotely from a rather clean premise. All these restriction are the reason for development of special portable gamma-ray imagers with small weight and reasonable sensitivity.

Some systems developed for nuclear environment and ecological measurements are described in paper. Systems are based on scintillating and modern solid state position sensitive detectors; the gamma image is formed on detector plain by pinhole or multi-hole coded aperture.

Introduction

The last two decades was time of intense development in the field of systems for obtaining gamma-ray imaging (SGRI) for use in enterprises of nuclear industry and some of the results of their use in solving of different tasks for their serial production and large-scale introduction to industrial use. Some developed systems have finished design and they are already used in many operations carried out with nuclear and radioactive materials [1-7].

Trends in safety standards in nuclear industry and in developing SGRI in countries with a developed nuclear industry have shown that soon a system for gamma-ray images will be used at many stages of processing of nuclear materials at various nuclear facilities. A lack of SGRI in the country will lead to an inevitable decrease in safety and competitiveness of its enterprises.

Systems for gamma-ray images in an industrial environment are different from similar systems for medicine and space research compactness, protection from radiation detectors and other features. Now they are used for remote searching (and control of the movement), gamma-emitting radioactive objects through their visualization. The advantage of this approach is the simultaneous detection of all radioactive objects in the field of view of the device. This unit can be installed away from sources of radiation-safe place. Additional security personnel ensured the possibility of a significant removal (up to 200 m) of the control computer operator on the location of the device. May apply the system for sorting radioactive waste in their conditioning, to manage and control the operations of radioactive sources, spent fuel and radioactive waste.

Extensive research on the choice of schemes and the production of industrial prototypes are conducted in all developed countries. At the same time in the world, these studies were prompted by the need to improve the safety of the nuclear industry, rather than liquidation of emergency situations, as in the Soviet Union and Russia after the Chernobyl disaster.

In almost all countries work on SPGI (both R & D) are conducted in the framework of public finance, and only at the stage of commercialization of developed prototypes, the results are transferred to private firms.

Currently 4 countries have commercially available systems.

In France, it developed in the CEA - Saclay portable gamma camera and Aladin, Cartogam[5,7,12,13]. Cameras brought to industrial designs and sells by firms EuriSys and Canberra. Developed a new standard operating procedures of nuclear materials and radioactive substances using SGRI.

In the U.S., the company AIL produces camera GammaCam [2] commercially, it is sold not only governmental organizations (Armed Forces), but also the private nuclear power plants in different countries. Various research organizations are developing and have a prototype of the device - Michigan University, Naval Research Lab. Company RMD Inc., Developed SPGI with the coded aperture [3].

In the UK SPGI produces firm BNFL, and the developments involved university laboratories [6].

In Germany, the firm NUKEM has developed several SPGI for use in commercial projects for the rehabilitation of nuclear plants [16].

Exact prices of industrial SGRI unknown (they are specified in the manufacturer of each purchase, depending on the customer), but unofficial estimates are around some (2-3) hundred thousand dollars (company AIL), 200 thousand Euros (firm Canberra), and depend, of course, on many conditions – additional equipment, maintenance.

An important SPGI feature is that they are composed of subsystems (radiation detectors, readout and processing electronics), which continuously and rapidly improved, and the number of sold specimens is too small. Therefore, even in the commercially available systems are continuous improvements, which are held by researchers and developers and manufacturing companies. The experience obtained during their practical application, is used to upgrade systems and to develop additional software to increase the efficiency of their use [13, 14].

The development and application of SGRI is important for all countries with nuclear industry of long history because of their mandatory application in future work on processing of spent fuel, dismantling of nuclear installations of numerous submarines, dismantling of research and power reactors and other nuclear installations.

Principle of operation of portable SGRI

The high-energy gamma rays passing through an aperture collimator device creates the inverted image on the gamma-ray scintillation detector, the glow of the scintillator is transmitted by fiberoptics at the entrance window of the electron-optical image intensifier the image is recorded by digital video camera based on CCD.

Full field of view of the device is determined by the angle of the collimator and the angular resolution - a hole diameter of the collimator and the thickness of the crystal scintillation detector.

Identification of gamma-ray sources based on superimposing of gamma-ray images and the visible image of the investigated object and subsequent analysis of the images to determine the location of the most contaminated parts of the studied object. Figure 1 presents the view of first computer controlled gamma-ray imager and acquired gamma-mages [1,5].

Fig.1 Photo of first computer controlled gamma-ray imager and scan results of contaminated pipelines of research reactors

The best options are portable SGRI with a special collimator based coded apertures instead of pinhole collimator. Image in such a system is obtained after mathematical processing of the shadow pattern of the source created a mask on the detector.

For acquisition, processing, storage and presentation of optical and gamma-ray imaging and control of all elements of the system a special software package GV-soft was developed [14].

Gamma-ray imaging at Extraction of Radwaste from Temporal Storage

Remediation activities and the work on decommissioning of nuclear facilities call for mapping of contamination of equipment parts, room walls and floors with gamma radionuclides. This can be done using instruments and systems built around remote methods of obtaining information about radioactive sources. During the last decade, a number of laboratories and companies have developed a variety of instruments for obtaining radioactive contamination distribution patterns [8,9,10], including instruments for gamma imaging of objects being examined [1-7].

To support activities on remediation of the RRC KI radwaste disposal site, and, in particular, allow for monitoring of radwaste extraction from the repositories, there was developed a device for obtaining gamma images of radiation sources (gamma imager) that is described in detail in references [9]. This instrument was used for identification of the most active radwaste fragments when discharging temporary repositories containing high-level radwaste. Obtained gamma imagers of radiation sources were used for estimation of the exposition dose rate (EDR) produced by the sources at the instrument location, estimation of the source activity and separation of the sources.

Gamma imager for Rehabilitation Project

Figure 2 shows a photograph of the gamma imager. The instrument consists of the detecting block of gamma-radiation – compact position sensitive detector (PSD) placed in leaden protection, replaceable two-cone collimator for formation of the gamma-image on PSD and black-and-white video camera established on the case of the device. Thickness of leaden protection is 20 mm. The position sensitive detector consists from scintillating crystal CsI(Tl) (thickness 3 mm and diameter 38 mm), a scaling fibre optic taper (FOT), the image intensifier (ImIn) based on a micro channel plate (MCP) amplifier with 2 MCP and digital video camera with objective for reading the image from the ImIn's screen for input in the computer. The instrument is connected to the control computer with cables (the control cable and video camera cable) with length 50 m. As the control computer the special personal computer is applied.

A set of replaceable two-cone collimators fabricated for the gamma imager allows changing the total angle of view and the spatial resolution of the instrument. The collimators are made of a tungsten alloy with the tungsten content of 96% and the density of 17.2 g/cm3. The collimators have the following parameters: size ∅18 mm x 20 mm, angles of view - 30^o, 45^o and 60^o, collimator opening diameters - 1.8 mm, 5 mm and 2.2 mm, respectively.

The gamma imager operating principle is as follows: the two-cone collimator forms a gamma image of an object on the flat scintillation crystal. The light image produced in the crystal is transmitted via the FOT to the input window of image intensifier. The amplified light image is read from the intensifier output window by the digital video camera and transmitted to the computer.

GV-Soft software developed for the system control allows selecting exposure for a frame of the detector digital video camera, summing frames obtained, subtracting background frames from information frames, performing mathematical processing of images during the instrument operation.

Obtained and processed gamma imagers are presented in pseudo colors and superimposed onto black-and-white images of the object shown by the external video camera of the gamma imager to identify the highest-activity sources.

The software developed enables additional processing of obtained images, such as image compression; median filtering; antialiasing; object outlining; highlighting of a contour (border) of a source location in the object gamma image and calculation of the number of pixels contained in the image, integral signal amplitude, average signal amplitude per image pixel, and variance of the signal; producing sections throughout the image field; changing the upper and lower limits of the signal level for display; changing the color palette; pixel-by-pixel addition, subtraction and division of obtained images; division/multiplication of images by a constant; addition/subtraction of a constant to/from an image.

Fig. 2. Appearance of the gamma imager

Evaluation of the EDR produced by separate sources with the gamma imager

When extracting radwaste from repositories, the radwaste activity shall be estimated to allow the radwaste sorting and packing into containers of various types. Allowable values of EDR at specified distances from a container are established by regulations for each container type used for transportation of radwaste. Given container characteristics (sizes, material and thickness) and EDR values one can estimate activity of radwaste that can be loaded in a container of one or other type.

To enable evaluation of radwaste activity with the gamma imager, an additional module of the image processing program was developed, and the instrument was calibrated against point gamma sources of known activity.

The gamma imager angular (and spatial) resolution is determined by the collimator opening diameter and the scintillator thickness. Figure 3 shows an image of a point source located at 1.5 m from the instrument. The diameter of the collimator used is 2.2 mm. The size of the CCD matrix field of the detector video camera is 782x528 pixels. The diameter of the gamma image field projected from the image-converter tube screen to the matrix is 565 pixels which corresponds to the scintillator diameter of 38 mm. The gamma image of the point source is in the center. The diameter of the point source image is 30 pixels which corresponds to the size of the gamma image over the scintillator field of ~ 2.5 mm.

A signal rate in a pixel of the instrument detector CCD matrix is proportional to the amount of gamma quanta energy released in the scintillator per time unit and hence is proportional to the exposure dose rate at the instrument location during period of the measurement.

The gamma imager is not spectrum-sensitive. Major gamma-radiators were identified in the radwaste using spectrometers. According to the spectrum measurements, the main radioactive elements in the radwaste contained in the repositories being discharged are ^{60}Co and ^{137}Cs, with the mean ratio between ^{60}Co and ^{137}Cs activities being ~ 1/20. Therefore, ^{137}Cs may be considered as determining the major contribution to the EDR in a repository and hence the instrument was calibrated against ^{137}Cs radioisotope for evaluation of the radwaste activity.

A point radioactive source of ^{137}Cs with the activity of 0.07 mCi was used for calibration of the instrument. The radioactive source was placed at different distances from the instrument at its axis. For each position of the source, its image was obtained and the EDR at the instrument location was measured.

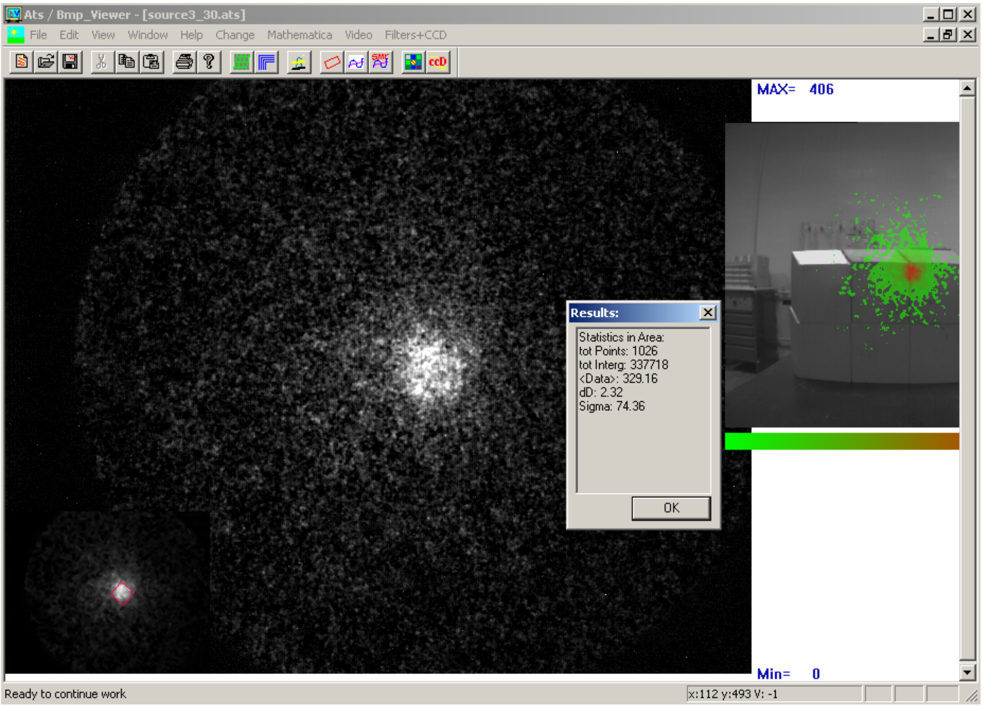


Fig. 3. The image of point source

The position of the point source in obtained gamma image was outlined manually in each image. Then the following values were calculated in the program: integral signal over the field of the selected image N_{tot}, area of the gamma image in pixels S, average number of counts per image pixel N_{av} and the signal variance. The data obtained are used to calculate the calibration factor of correspondence of the EDR detector signal from the gamma source:

$K=N_{tot}/StD$ (counts/s)/(μSv/hr),

where t is the image accumulation time. Table I presents results of the measurements.

Table I . Results of the instrument sensitivity measurements

Distance to the source, cm	Ntot, counts	S, pixels	t, s	D, μSv/hr	K, (counts/s)/(μSv/hr)
30	714825	1059	400	2.20	0.77
30	348695	1044	200	2.20	0.76
60	212280	915	400	0.80	0.72
60	128384	1088	200	0.80	0.74

K_{av} = 0.75(counts/s)/(μSv/hr)

The factor obtained was entered into the image processing program. Once a gamma image of a new radiation source has been produced, the source contour is found manually, and the EDR produced by the source at the instrument location is evaluated using the program. Upon finding the distance between the instrument and the source, the data obtained can be used for estimating the source activity and determining a container type for transportation the source.

Gamma-ray imaging at extraction of radwaste from repositories

A temporary radwaste repository represents a concrete and brick trench in the ground where radwaste (mainly various radioactively contaminated parts of reactor equipment, personal protective equipment, etc.) was placed and grouted in concrete. To reduce the EDR in the working area, an additional shielding structure of concrete blocks with a ceiling of concrete plates was constructed round the repository (Fig. 4). The repository was destroyed from the top using a hydraulic hammer, for which purpose one of the ceiling plates was moved aside.

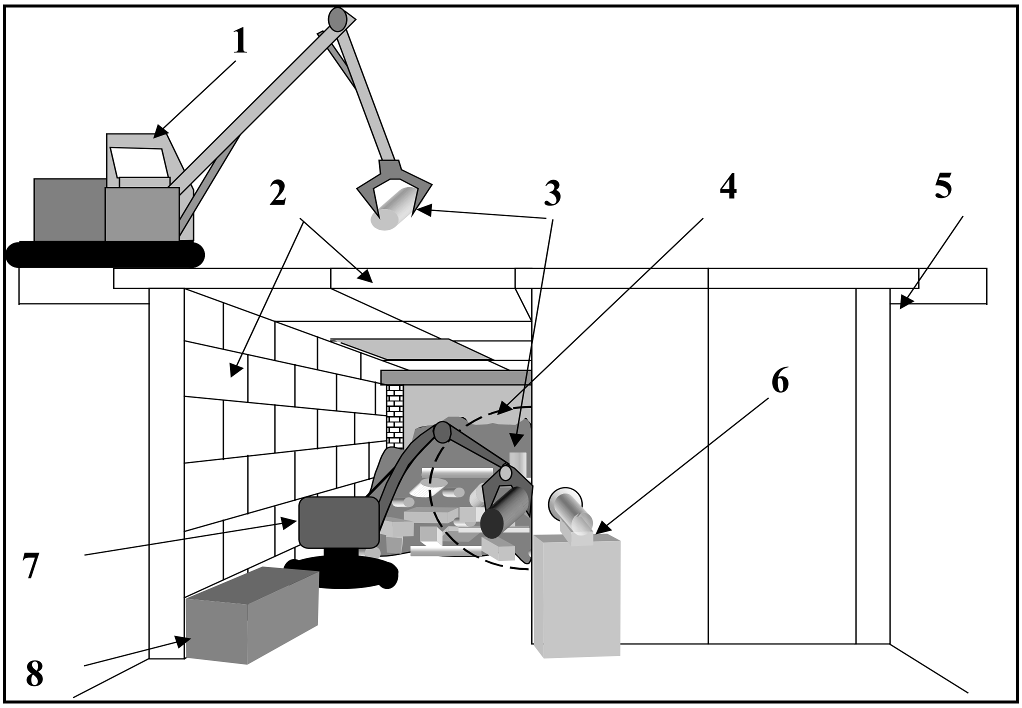


Fig. 4. Schematic of the radwaste repository. 1 – excavator used for radwaste extraction from the repository, 2 – additional shielding structure of concrete blocks with the ceiling of concrete plates, 3 – radwaste prepared for loading into containers, 4 – field of view of the gamma imager, 5 – ground level, 6 – gamma imager mounted on the stand at the repository entrance, 7 – radio-controlled BROKK robot, 8 – reinforced container for high-level radwaste.

To identify the most active radwaste components, the gamma imager was installed on a stand behind a concrete wall at the entrance of the repository shielding structure. To reduce background exposure of the detector, it was placed inside an additional 5-cm thick lead shielding (not shown in the figure).

Gamma images were recorded through an opening in the wall. The collimator with a 30o angle of view was used in the gamma imager, which allowed viewing almost the entire working area. The instrument operated in the continuous gamma imagery mode, with one gamma image produced usually in 160 seconds (80 frames of the detector camera with the 2-second exposure).

The radwaste was discharged from the repository using radio-controlled robots into either metal containers (low-level radwaste) or concrete containers (intermediate-level radwaste) or reinforced containers (for higher level radwaste).

At favorable radiation conditions (low EDR inside the shielding structure at the early stage of the repository dismantling), low-level radwaste was discharged with an excavator though an opening made in the shielding ceiling of the repository.

The work on extraction of the radwaste from the repository using the gamma imager was performed in the following way. First a gamma image of the repository was obtained, and radwaste components with the highest activity were identified from the combined gamma and video image on the PC monitor. Then a robot operator extracted the radwaste with the radio-controlled robot using the obtained image, and placed the radwaste at a certain distance from the gamma imager. A gamma image of the radwaste fragment was obtained, and the radwaste activity was evaluated. Depending on the activity, the operator placed the fragment into container of one or other type. Throughout these operations, the instrument operated in the continuous gamma imaging mode. If no pronounced radioactive sources were visible in the image, the radwaste was discharged by the excavator through the opening in the repository shielding ceiling and placed into metal containers. When a new strong radioactive source appeared, the operations were stopped. The radwaste fragment corresponding to the source was extracted from the repository remains, and its activity was measured.

Figure 5 shows successive gamma imagers obtained during operations on radwaste extraction and loading into containers. As is seen from Fig. 5a, the most active radwaste fragment is a highly contaminated pipe. Fig. 5b shows the pipe placed by the robot at a specified distance from the gamma imager for evaluation of its activity, and Fig. 5c shows transfer of the pipe to the container.

a b c

Fig. 5. Gamma images of the repository obtained during extraction of the high-level radwaste fragment. The images present superimposing of raw gamma-images presented in pseudo colours on black and white video images.

The gamma-images of long contaminated elements (tubes, confinement vessels, etc) were acquired for search the position of their most contaminated parts. Then these elements were cut into some parts and obtained parts were put into containers of different types according their relative activity. Other images of robot manipulations with high level radwaste, controlled by continues gamma-ray imaging are presented in Fig. 6.

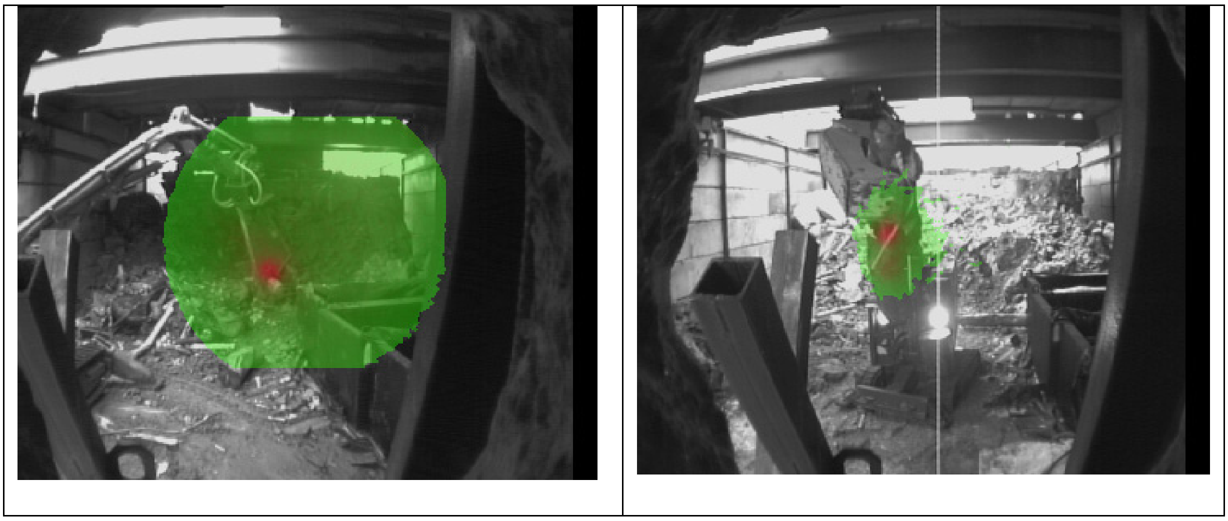


Fig. 6. Two frames of robot manipulation with high level radwaste controlled by continues gamma-ray imaging.

The monitoring the recovery of radwaste from the deep repository by gamma-ray imaging was very effective also. Some small active sources were found with SGRI (see Fig.7).

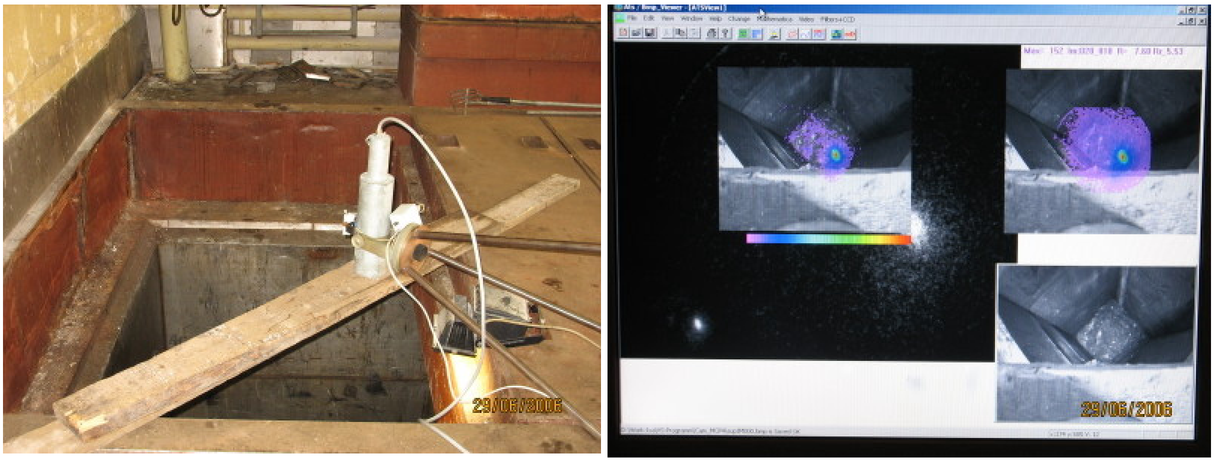
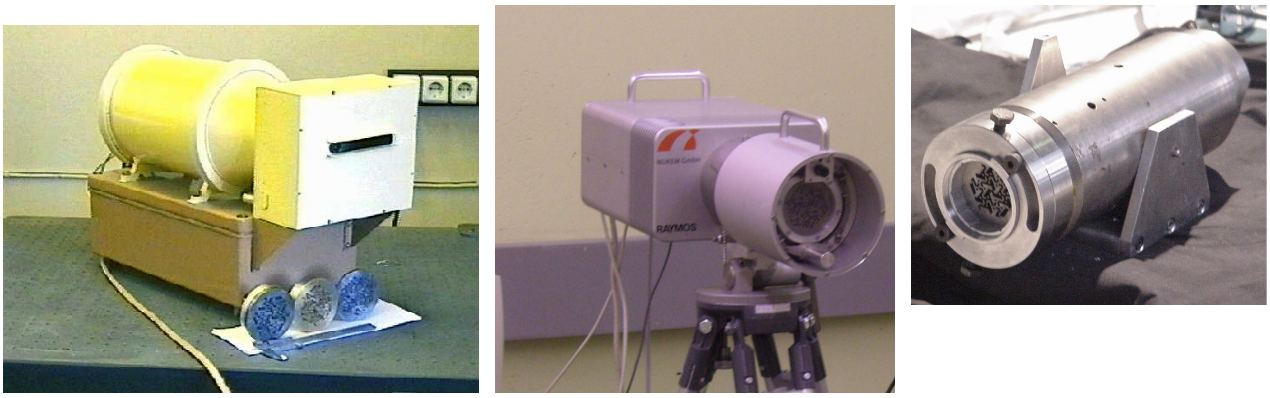


Fig. 7. Monitoring the recovery of radwaste from the deep repository (on the left - the system is installed above the repository, right - the image of a bright source at the bottom of the repository)

Gamma-ray imager with coded aperture

There were developed some prototypes of portable SGRIs with coded apertures, which are shown in Fig. 8 [11, 15, 16]. These systems have high sensitivity, appoximatly factor $\sqrt{N/2}$ higher than pinhole systems with the same angular resolution (N is number of holes in aperture). Apart this they have larger effective field of view (FoV) as they have appoximatly constant sensitivity versus angular position of a point source that is shown in Fig. 9 [15].



1 2 3

Fig. 8. Photos of developed systems with coded apertures 1- CMGVC (KI-SAIC); 2- RAYMOS (KI-NUKEM); 3- Cartogam (KI-CEA).

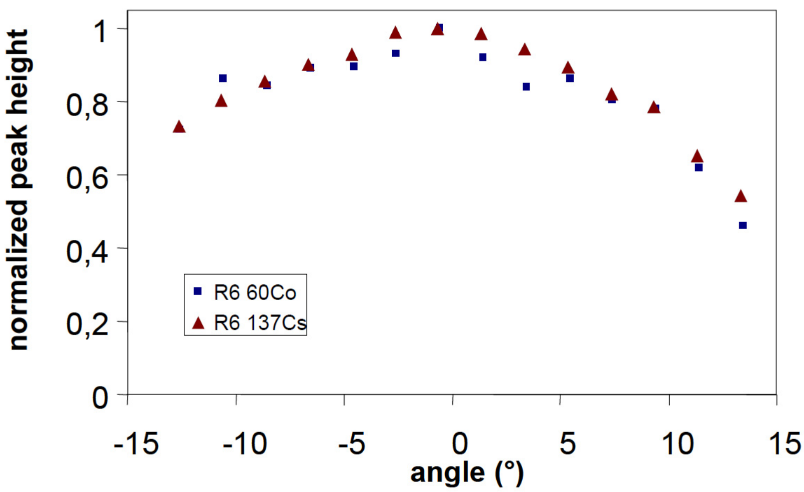


Fig. 9. Sensitivity of the camera versus angular position of a point source, for two gamma energies (mask of rank 6).

Tests of coded aperture cameras and software for image decoding have shown their reliable image acquisition not only for point sources, but for extended sources also. Exsample of extended source, obtained with RAYMOS camera is shoun in Fig. 10 [16].

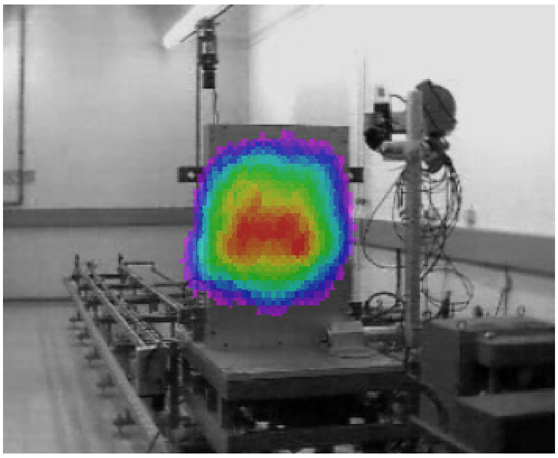


Fig. 10. The intensity distribution of gamma radiation from a collimated gamma point source scattered on a rectangular aluminum screen.

These properties of systems with coded apertures allow acquisition of gamma-images in difficult conditions, where conventional systems do not give the desired result.

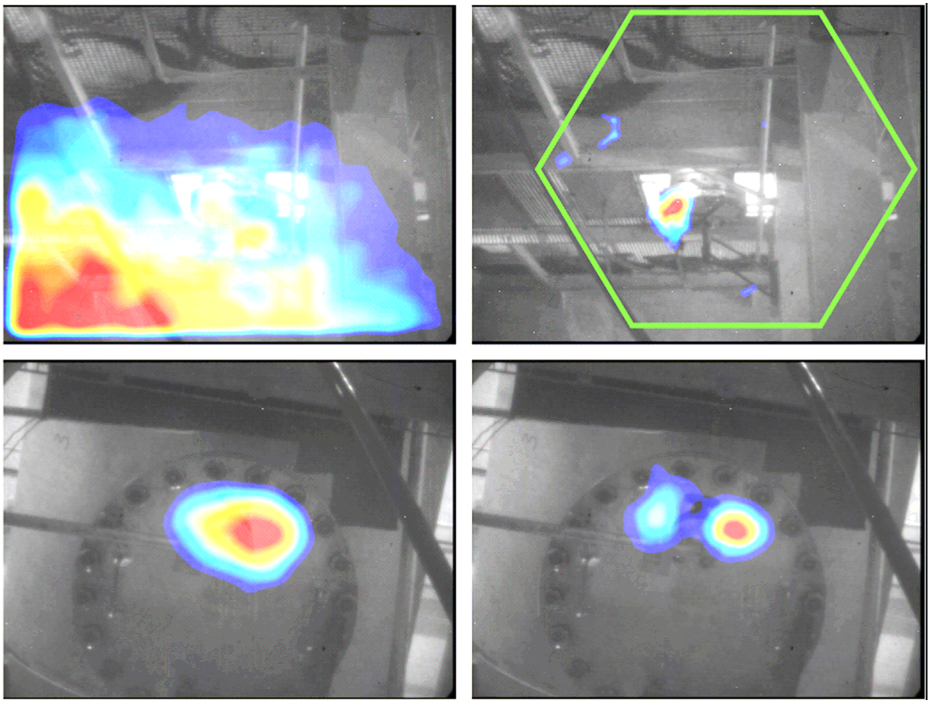


Fig. 11. Views of (top) a hot spot located on a plug under a heat exchanger in a very high-ambient dose rate and (bottom) a hot spot located just above the camera, with (left) the pinhole and (right) the coded-mask configurations.

Images obtained during on-site image measuremnts in the BR2 reactor in Mol (Belgium) in the framework of a collaboration with SCK-CEN and CEA are presented in Fig. The lower face of three heat exchangers was inspected, in particular hot spots due to contamination accumulation in plugs. For the first view (Fig. 11, top), the camera was located just under a hot spot and looked at a farther one. Thus the ambient dose rate was so high that in the pinhole configuration the camera was unable to detect the hot spot aimed at (top left). On the contrary, in the coded-mask configuration and using the mask-antimask procedure, the hot spot is clearly detected and located (top right). In the second view (Fig. 11, bottom), the camera looks at the nearest hot spot. The pinhole gives a good-quality image of the source (bottom left) but obviously the angular resolution is much better with the coded mask (bottom right).

Conclusions

Instruments for gamma-ray imaging are used for examination of radioactively contaminated components of equipment and rooms when preparing such equipment for dismantling. For the first time for instruments of such a class, the gamma imager was used for real-time imaging in the course of operations with radwaste, while being placed amidst a strong gamma field. Gamma images obtained were used for evaluation of activity of radwaste being extracted and for making decisions on methods to be used in operations with radwaste.

Since the basic contaminating element in the radwaste is one nuclide - ^{137}Cs, a possibility for using the gamma imager for evaluation of the EDR from individual radwaste fragments and sorting them by activity level was implemented.

When extracting radioactive fragments of reactor equipment highly contaminated with 60Co nuclide from the repository remains, the method used for evaluation of the dose rate and activity might be in error by a factor about 3.

Upon loading the radwaste into containers, there were measured EDR values for each container, activity of the radwaste loaded in the containers, and isotopic composition of the radwaste. If the measured EDR values exceeded the allowable levels, the corresponding container was reloaded.

The use of the gamma imager for preliminary sorting of radwaste allowed a significant reduction in the number of containers to be reloaded.

The visualization and removal of the highest-level radwaste in the first instance allowed a significant (2-5 times) reduction of the EDR inside the additional shielding structure, which made it possible to extract low-level radwaste with an excavator through the shielding structure ceiling.

Developed gamma-ray imaging systems are effective portable instruments for ecological and nuclear environment measurements of spreading of radioactive contamination.

Typical performances of developed systems are the following:

Gamma-channel FoV: 30^{o}

Angular resolution: 1^o

Sensitivity - registration of Cs-137 source for exposure dose:

0.05μSv (equivalent $3*10^8$Bq (10mCi) at 10 m in 10 min) with pinhole

5nSv (equivalent $3*10^7$Bq (1mCi) at 10 m in 10 min) with coded aperture

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