Public safety conditions under radiological emergencies monitoring comprehensive system mobile facilities application

S I Voronov¹, E V Popov², V A Sednev² and O S Voronov³

¹ Federal Research Center Nemchinovka, 6 Agrochemists Street, village Novoivanovskoe, Odintsovo district, Moscow region, 143026, Russia
² Academy of the State Fire Service of the EMERCOM of Russia, 4/2 Boris Galushkin Street, Moscow, 129626, Russia
³ Main Department of the Ministry of Emergency Situations of Russia in the Lipetsk region, 2 a Papin Street, Lipetsk, 398024, Russia

E-mail: vsi08@mail.ru

Abstract. The article presents examples of radiological emergencies with ionizing radiation sources used in radioisotope devices. A number of measures aimed at emergency response in relation to such emergencies, including in relation to the control of the radiation situation (CRS) and its assessment, are considered. A variant of building a complex of mobile CRS tools for a comprehensive monitoring system for the state of the population protection is presented. Special attention is paid to the justification and optimization of the CRS use in situations of control loss over IRS, including technical, organizational and scientific approaches to the use of these mobile tools. In order to optimize the group integrated use of mobile CRS tools, typical radiological situations are studied in advance and rational options for the mobile CRS tools using are selected, taking into account different environmental conditions, including natural-geographical, climatic and man-made factors. The considered approaches to optimization in the use of mobile means of comprehensive systems of the public protection conditions monitoring in radiological emergencies allow, first of all, to increase the efficiency of their use and ensure the successful implementation of tasks for the prevention and elimination of such emergencies consequences.

1. Introduction
Radioisotope devices (RID) with ionizing radiation sources (IRS) are used in various areas of human activity, including medicine, geological exploration, pipeline transport, metallurgy, food and light industry. RID with gamma-ray sources using the radioisotopes caesium-137 and cobalt-60 are the most widespread. In Russia, such IRS are used, for example, in the UR-8 level meters and the GR-7 relays. The radioisotope is usually protected inside of them by one or two stainless steel shells of 0.5-1 mm thick. The exposure dose rate of gamma radiation can be in the range of 3-10 Sv/h directly beside the UR-8 unit. Within IRS of beta radiation such radioisotopes as yttrium-90, strontium-90, promethium-147 and krypton-85 are primarily used. These types of IRS are usually protected by a 0.12–0.3 mm thick aluminum foil shell. Alpha radiation sources are used in RID to measure the content of radon, dust and various aerosols in the air in the metallurgical and mining industries. IRS are widely used for medical diagnosis and treatment of various diseases purposes [1, 2].
If the RID are destroyed, the sources contained inside of them can cause a serious danger to people and the environment. Such devices are subject to mandatory recording and strict rules of handling, but due to various reasons, there are cases of control loss over such devices, including loss of the device, theft, ingress of IRS into scrap metal and furnaces for metal remelting, construction materials [3, 4].

There is a high probability that if RID enter the melting furnace, depending on the nature of the IRS, radioisotope contamination may occur not only within the industrial zone of a factory, but also within a large adjacent area of the processing factory. For example, on 11th of June, 1998, elevated levels of caesium-137 were detected in the air in southern France and Northern Italy. The reason was the melting of a source with caesium-137 in the electric furnace at the Los Barrios steel plant, which caused economic, political and social consequences.

There were many cases of control loss over IRS that are used in medicine. For example, in Brazil in 1987, a source with a 50.9 TBq activity of caesium-137 was dismantled and stolen, and the landfill and surrounding area were polluted. As the result, 4 people were killed, 79 people needed treatment and 110,000 people were examined, 7 houses were demolished and 85 houses were deactivated. A similar accident occurred in Samut Prakarn (Thailand) in 2000, where the installation containing 15.7 TBq of cobalt-60 was dumped and 10 people received high doses of radiation, three of them died two months after the accident.

There were cases of IRS penetration into building materials and structures. For instance, in Ukraine, during several months in 1988-1991, residents of the apartment building were irradiated with caesium-137 source with an activity of 2.6 TBq walled up in an apartment wall, as the result, 2 people were killed [5].

The control loss over RID leads to the environment contamination with radioisotopes that get into the soil, water, and air masses and can later migrate using various ways of transmission such as transfer of sources by people, contaminated air masses and water flows or movement through food chains [6].

Cases of the control loss over IRS are carefully monitored in Russia. Over the past five years, radiation incidents and sanitary-epidemiological nature situations associated with the control loss over such sources have occurred steadily and regularly in the country. More than 200 incidents occur annually. For example, 222 cases of such incidents were registered in Russia in 2018 (2017 – 235 cases). It was 13 incidents less than in 2017. The most part of them happened in Moscow city (31 cases) and Moscow region area (30 cases), Saint Petersburg (30 cases), Orenburg (24 cases), Sverdlovsk (20 cases) regions. 32.0 % (71 cases) out of all the registered cases of IRS’s detecting was in scrap metal in 16 regions of the Russian Federation. The most common reason for such incidents registration was the detection of uncontrolled IRS, and the cases of calibration sources detection among them should be particularly noted. 192 accidents and radiation nature issues related to the control loss over IRS were registered in 32 regions of the Russian Federation in 2019. 20.3 % (39 incidents) of all the recorded cases are related to IRS’s detection in scrap metal in 12 regions of the Russian Federation. The most part of scrap metal lots containing sources was found in the Vologda (9 incidents) and Sverdlovsk (6 incidents) regions [7].

Such situations are related to the radiological emergencies category. Radiological emergencies are the control loss over the IRS, leading to an emergency (ES) of the following types: uncontrolled dangerous sources (untended, lost, stolen or found sources); misuse of dangerous medical and industrial IRS, malicious acts and threats; transport radiation emergencies [8].

The given examples and radiological emergencies data of the recent years allow to admit the relevance of high-quality IRS monitoring and the conducting of a rapid and effective search of lost radiation sources.

In case of such emergencies, the assessment and prediction of the emergency development at an early stage are of high importance. The assessment and forecasting of the radiation situation conditions will ensure an adequate response to threats and making of right decisions to carry out measures to protect the public as well as to eliminate the consequences of the accident with the least damage. The IRS detection and the conditions assessment is impossible if special technical facilities to
perform radiation investigation and monitoring are not used. Such facilities are the part of specialized radiation monitoring systems in Russia.

2. Results and discussion
Automated radiation monitoring systems (ARMS) and territorial radiation monitoring and emergency response systems (TRME RS) were created and are actively developed in some Russian regions in the last decade. These systems are integrated into the Unified state automated radiation monitoring system (USARMS), where state authorities and radiation control and monitoring networks are currently connected on the basis of automation of the processes of collecting, transmitting and analyzing information about the radiation conditions in the country [9, 10].

Such systems integrated in USARMS include comprehensive systems of the public protection conditions monitoring (CSPPCM), which were created in radioactively contaminated territories as well. CSPPCM consists of 4 subsystems. They are presented in Figure 1.

![Figure 1. Overall composition of CSPPCM.](image)

One of the main elements of the CSPPCM is a radiation conditions monitoring (RCM) subsystem. This subsystem is responsible for early detection of the radiation conditions changes within the locations of the measuring equipment installed on the territory of the Russian Federation region. The data obtained by the system for the radiation conditions monitoring is used by the regional territorial body of the EMERCOM of Russia for decision making purposes with regard to maintenance of radiation security of the public living in contaminated territories. A number of specific tasks relevant to the main tasks are executed by RCM CSPPCM subsystem:

- the implementation of constant automated monitoring of the radiation conditions within the territory of the Russian Federation region, including measurement of meteorological parameters;
- the processing and storage of prompt data on the radiation conditions within radioactively contaminated territories and its presentation to relevant authorities using GIS technologies;
- the automatic alarm generation in case of expansion of any parameter under control (warning, emergency) beyond the established standards levels;
- the data exchange throughout existing and enacting regional, departmental and state USARMS subsystems and other data-measuring radiation monitoring systems in accordance with established procedure.

Static facilities include: the center of collection, processing, transmitting and storing of data on radiation conditions (DCPC), communication channels, static radiation monitoring posts (Figure 2).

Mobile RCM facilities include: mobile radiometric laboratories (MRL); mobile complexes for aerogamma investigation via unmanned aerial vehicles (UMAV); fast-deployable radiation monitoring modules (FDRMM) [11].

Mobile facilities of RCM are a necessary complement to static radiation monitoring facilities. They help to ensure complete execution of the tasks in a better way during the process of collecting data on the radiation conditions. This is applicable, first of all, to the performance of specific tasks, such as: search for IRS and delineation of radioactively contaminated areas; conducting gamma-ray surveys of the area; exploration of traffic routes in radioactively contaminated areas; sampling and conducting prompt samplings analysis.
A number of general requirements were considered [12] during the creation of RCM mobile facilities:
- creation of facilities by using a modern high-tech base;
- high mobility and adaptability of facilities to physical, geographical and climatic conditions;
- integration of mobile facilities into the radiation monitoring subsystem of CSPPCM;
- comprehensive application approach according to the list of tasks of radiation monitoring execution within emergency situation conditions.

The development and formation of mobile radiation monitoring systems is currently being carried out as a part of the future development of CSPPCM.

The typical composition of such a complex is shown in Figure 3.

It is the integrated use of mobile RCM tools that allows rapid and most complete data collection on radiation conditions in case of the control loss over the IRS under a radiological emergency.

The largest part of the mobile facilities of RCM is made up of MRL, which are designed for operational radiation investigations, both under a radiation emergency case and for regular surveys.

MRL is able to perform the following main tasks:
- ground gamma-ray survey with simultaneous reference to the measurement coordinates and transmission of measurement results in real time;
- personnel, measuring and auxiliary equipment delivery to the work sites;
- determination of IRS location and assessment of the radionuclide composition of the source;
- selection and prompt analysis of soil, water and air samples;
- data collection, processing and transmission of the received data on possible radioactive contamination of territory to the early warning subsystem [13].

**Figure 2.** Static and mobile facilities of CSPPCM. *TCC - Technical Crisis Center.
As the rule, MRL in emergency response areas assigns the routes which in their turn should be determined in advance in accordance with the likely scenarios of a radiation emergency. Depending on the nature of the radiological emergency, MRL usually conducts radiation investigations of the designated route, designated area, IRS search, area and objects examination, sampling selection, prompt radiation conditions assessment. Routes of MRL and its usage options may be specified and changed due to the current situation specifics. With high mobility and modern high-tech automated abilities, the MRL is able to perform massive works on collection, processing and transmitting of the data on the radiation conditions in real time regime, if they are used in an efficient way which are based on optimizing methods of its usage, depending on a particular emergency nature and characteristics. The rout of movement MRL can be created by software and hardware systems designed for predictive assessment of evolving of a radiological emergency. Preliminary boundaries of the contaminated areas of the territory, spots set for measurements and possible calculated values on radiation conditions background and spectrometry can be defined within this kind of automated process of development of routs. Systems of forecasting and analyzing of radiation conditions are used to perform this task. Besides, other parameters can be defined for efficient usage of MRL in the specific situation, such as the frequency of radiation measurements for automated facilities, locations for additional control spectrometric measurements, locations for sampling on a MRL route of movement within a radiological emergency zone [14].

Alongside the MRL, other mobile facilities are used as the CSPPCM part to expand the range of methods to obtain high-quality and timely radiation monitoring data and, as the result, increase the emergency response effectiveness.

QDRMM is used as a quick-deployable facility for data radiation monitoring purposes within a local area of the territory. The area covered by the posts may reach several square kilometers. The module itself is an all-terrain passenger car. There are autonomous fast-installed radiation monitoring posts of the mobile complex that determine radiation monitoring data at the installation site and transmit it via radio channel to the data collection center of QDRMM, these data is transmitted to the
CSPPCM data collection and processing center of the region of Russia. Autonomous QDRMM posts installation can be executed in different versions both throughout the area or in a row. Options of the complex usage should be based on the results of research on optimization of QDRMM handling under typical radiological emergencies. Options for the effective use of QDRMM under specific emergencies, as well as for MRL, can be determined based on the results of a predictive assessment of the information modelling systems of decision-making support. Such systems of decision-making support for various radiation emergencies were created and are used for a long time [15].

Russia has a wide range of such systems used for different types of radiation incidents, different environments of radionuclide distribution, which consider various conditions and factors as well. Meanwhile based on the forecast of the evolving of an emergency, the locations of installation of autonomous compact radiation monitoring posts of the QDRMM in the local zone of a radiological emergency can be determined.

An option of optimal application of QDRMM under a radiological emergency on the territory of the industrial site is shown in Figure 4

![Figure 4](image-url)

**Figure 4.** An option of optimal application of QDRMM under a radiological emergency on the territory of the industrial site.

Mobile complex of aero gamma survey is one more facility used for radiological emergency response which has (Figure 4):
- ARM on unmanned aerial vehicles basis with suspended equipment for aero gamma investigation, video and thermal monitoring purposes;
- delivery of means of aerial investigation module to the area of its application on all-terrain "Jeep"-type vehicle basis.

ARM is designed to solve a number of tasks: evaluation of gamma radiation characteristics over a given area in real time regime within a wide range of gamma radiation dose rates and coordinate reference of measurement points; spectral characteristics of gamma radiation obtaining; prompt detection of radiation anomalies and their interpretation as spot or area sources of gamma radiation with a known radionuclide composition; photographs obtaining under the operator’s order or according to the flight program which are linked to coordinates of the underlying surface area of interest.

Being used in a proper way, this facility is quite effective for the IRS operational search and aero gamma investigation of a local area under a radiological emergency with delineation of radioactive spots. With a mobile transport base, this module can be quickly moved to the place where tasks are
performed, even in off-road conditions. This allows to determine a convenient site for ARM launching, even if there is no available road to this place. With a rational use of the AG IMC, its efficiency can be increased by 4 times. An example of optimization due to the rational use of the AG IMC is: the ARM launching site is determined in the center of the radiological emergency surveyed area. The ARM flight is carried out with a "snake" trajectory with the distance between tacks of 200 m in accordance with the recommended method of surveying the area and its returning is carried out with a straight trajectory to the take-off site. In these circumstances, on a single battery charge, the ARM is able to survey about 6 km$^2$. The battery is replaced on return. Further examination of three rectangular sections of the area is conducted from the same take-off platform according to the same option. Herewith one of the corners of each rectangular section is located at the take-off and landing point of the ARM. Using this option and if launch site of the ARM and its battery charging time aren’t changed a prompt and sufficient detail examination of a section of the area up to 24 km$^2$ in less than 4 hours is feasible. A kit of AG IMC with 3 additional charged batteries is needed in this case. If this option is applicable under a radiological emergency conditions AG IMC ensures the high performance in terms of time, surveyed area and quality of IRS searching indicators while searching for IRS with the surrounding area examination.

The optimized use of mobile facilities of RCM should also be considered from the perspective of processing of the received data on the radiological emergency situation and radiation conditions assessment. This ensures a high level of the assessment plausibility with regard to the radiation situation. When several means are used to collect data, reports on the parameters of the radiation situation may differ and be contradictory. Mathematical modeling methods based on a probabilistic assessment of the state of the radiation situation with the prognostic assessment and the data obtained from the RCM facilities can be used in operations study to optimize the use of RCM tools in this case. A scientific approach based on the application of the hypothesis theorem (Bayes formula) is reasonable to be applied [16]. During the simulation of an emergency radiological situation a priori probability of the radiation situation state $P_3(X_e), P_3(X_n)$ can be determined preliminarily by systems that provide a predictive assessment of the emergency situation [14], and the posterior probability of radiation conditions of $P_{RS}$ is determined based on a priori probabilities $P_3(X_e), P_3(X_n)$ and reports on the radiation conditions received from mobile facilities of RCM. The derived dependencies based on the hypothesis theorem for the conditions and situations under consideration are presented below.

$$P_{RS} = \frac{P_5(x_e) \cdot P(S_d / x_e)}{P_5(x_e) \cdot P(S_d / x_e) + P_5(x_n) \cdot P(S_d / x_n)},$$

(1)

For the considered complex of mobile facilities of RCM, the probabilities of a set of reports are determined by using the following formulas. $P(S_d/X_e)$ is the probability of a set of correct $Ce$ reports, if the radiation conditions were in the $X_e$ state, is defined for the considered complex of mobile devices as:

$$P(S_d/X_e) = 1P(Ce_{-X_e}) \cdot 2P(Ce_{-X_e}) \cdot 3P(Ce_{-X_e}),$$

(2)

where $1P(Ce_{-X_e}), 2P(Ce_{-X_e}), 3P(Ce_{-X_e})$ are the probability of correct reports about the state of the radiation situation within the allowable error given in considered 1, 2, 3 mobile RCM.

Analogically $P(S_d/X_n)$ is the probability of a set of erroneous $Cn$ reports if the radiation conditions were in the $X_e$ state is defined as:

$$P(S_d/X_n) = 1P(Cn_{-X_e}) \cdot 2P(Cn_{-X_e}) \cdot 3P(Ce_{-X_e}),$$

(3)

where $1P(Cn_{-X_e}), 2P(Cn_{-X_e}), 3P(Ce_{-X_e})$ are the probability of erroneous (incorrect) reports on radiation conditions within the given allowable error of the considered mobile RCM.

Only a part of the main dependencies used in this scientific approach is given.

For the purposes of optimization of the RCM mobile facilities group complex use, typical radiological cases are studied in advance and rational options of RCM mobile facilities use are selected within different conditions of a case, including natural-geographical, climatic and man-made factors.
3. Conclusion
The above scientific approach application to the data processing by RCM facilities and determination of a posteriori probability of the radiation conditions plays an important role, including the processes of informing of public and decision-making officials under radiological emergencies. Decisions and actions for emergency case response will significantly depend on the assessment of plausibility of the radiation conditions. Processes of informing are implemented through notification and informing systems. Within the CSPPCM construction a subsystem of informing functions, which, among other things, informs the public on the radiation conditions status, as well as on the procedures in case of its complication in order to protect the public from the negative consequences of an emergency.

The considered approaches of optimization of the CSPPCM mobile facilities use under radiological emergencies allow, first of all, to increase the efficiency of their use and ensure the successful implementation of tasks for the prevention and elimination of such emergencies consequences.

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