# RADIATION MONITORING UNDER EMERGENCY CONDITIONS

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Radiation measurements provide key data needed in the management of nuclear or radiological emergencies. In this paper, the strategic aspects of radiation monitoring under emergency conditions are highlighted. The most important requirements for defining a good emergency monitoring strategy are presented for a country threatened by severe nuclear accidents. The implications of the new ICRP publications 103, 109 and 111 on the emergency management and the radiation monitoring strategy are also presented.

*Key words*: nuclear and radiological emergency, emergency monitoring strategy.

## 1. INTRODUCTION

Despite of all the safety measures that are taken in the design and operation of nuclear facilities, a possibility remains that an accident may happen. One of the most important aspects of managing a nuclear or radiological emergency is the ability to promptly and adequately assess the need for protective actions making use of the key relevant information available. Emergency monitoring is one of the main sources for obtaining the needed information.

Environmental radioactivity monitoring in normal circumstances is performed to ensure compliance with the basic safety standards. The radiological monitoring of the territory comprises two complementary parts: (*i*) global monitoring of the territory outside the zones where significant nuclear activity is carried out and (*ii*) close monitoring around sites where an activity liable to have a radiological impact on the environment is carried out. In practice, the radiological monitoring of the territory, which deals with the level of both artificial and natural radioactivity, is conducted in a continuous way using automatic measuring networks and in an intermittent way, *via* periodic sample taking and analysis. The radiation monitoring systems operating in normal circumstances can also be used, at least partially, for the purposes of early warning and plume tracking [1].

Managing measurements under emergency conditions in a proper way requires the existence of pre-prepared emergency monitoring strategies. The design of a comprehensive yet realistic emergency monitoring strategy is far from being an easy task. This strategy must start from the advance identification and analysis of potential hazard situations and must also be based on addressing the needs of the decision-making process. In addition, this strategy is affected by many factors whose status or related contents are known or available before any nuclear or radiological emergency arises. Examples include population distribution, geography and topography, land use, legislation and official agreements, fixed potential sources (nuclear facilities, medical facilities using radioactive materials etc.), routine monitoring arrangements and resources allocated to emergency monitoring [2, 3].

In this paper, the strategic aspects of radiation monitoring under emergency conditions are presented and the most important requirements for defining a good emergency monitoring strategy are given for a country threatened by severe nuclear accidents. In addition, the implications of the new ICRP publications 103, 109 and 111 on the emergency management and the radiation monitoring strategy are also presented [4, 5, 6].

## 2. ENVIRONMENTAL RADIOACTIVITY MONITORING IN NORMAL CIRCUMSTANCES

Article 35 of the EURATOM Treaty requires that each Member State shall establish facilities necessary to carry out continuous monitoring of the levels of radioactivity in the environment to ensure compliance with the basic safety standards. Article 35 also gives the *European Commission* (EC) the right of access to such facilities in order that it may verify their operation and efficiency. The routine environmental monitoring data are transmitted by the EU Member State authorities to the *Radioactivity Environmental Monitoring* (REM) data base which is the basis for preparing the annual reports describing the radioactivity levels in the EU. Both REM database and the annual reports can be consulted by the public [11].

The radiological monitoring of the territory comprises two complementary parts:

- global monitoring of the territory outside the zones where significant nuclear activity is carried out;
- close monitoring around sites where an activity liable to have a radiological impact on the environment is carried out.

Verification of the releases from nuclear installations in normal operation is best done by equipment installed in the stack and in the liquid effluent discharge line of the plant. The main objectives of the programs for close monitoring around sites are:

- to provide information necessary for checking whether systems for effluent treatment and control are performing properly;
- to provide early warning of any deviations from normal authorized operation;
- to provide information to enable the assessment of actual or prospective doses to members of the critical group resulting from authorized practices or sources;
- to detect any unpredicted changes in activity concentrations and to evaluate long term trends in environmental radiation levels as a result of the discharge practice;
- to provide information for the public.

In practice, the radiological monitoring of the territory, which deals with the level of both artificial and natural radioactivity, is conducted in two ways:

- in a continuous way using automatic measuring networks;
- in an intermittent way, *via* periodic sample taking and analysis.

At the national level, the automatic measuring network is usually composed of gamma dose rate monitoring systems distributed throughout the entire territory and around the nuclear facilities. In some countries, the national network for environmental radioactivity monitoring may include measuring stations which constantly measure the radioactivity of the air and river waters and gamma spectrometric measuring stations. In the event of a nuclear accident, the automatic measuring networks can play an important role not only in early warning but also in decision making, optimizing interventions and countermeasures implemented by the relevant authorities as well as keeping the country's citizens informed on a continuous basis.

The intermittent radiological monitoring is performed using off-line monitoring systems and laboratory based monitoring networks coupled with sampling programs which give pertinent information on the average extent of environmental and dietary contamination. Many of the air monitoring systems consist of automatic samplers with off-line measurement of the samples. The laboratory based monitoring networks are operated to measure environmental samples, foodstuff, drinking water and animal feed. The sampling program should be in accordance with the EU Recommendation 2000/473/EURATOM and provide representative samples able to reveal the average situation both in time and space.

## 3. EMERGENCY RADIATION MONITORING SYSTEMS

In a nuclear or radiological emergency, radiation measurements provide essential data needed to evaluate the radiological emergency situation and carry out proper countermeasures on time for protecting members of the public, emergency workers and environment. Various radiation monitoring techniques are used for emergency monitoring.

Table 1 shows the most important radiation monitoring techniques used under emergency conditions [3].

*Table 1*

Radiation monitoring techniques used under emergency conditions

| Radiation monitoring techniques | |
|---|---|
| External dose rate or dose | – stationary automatic systems for dose-rate monitoring;<br>– portable or mobile systems for dose-rate monitoring;<br>– integrated dose (TLD). |
| Airborne radionuclide concentrations | – stationary filter stations equipped for on-line measurements;<br>– stationary filter stations requiring filter collection for laboratory measurements;<br>– stationary filter stations equipped with advanced sampling. devices (*e.g.* on-line iodine monitors);<br>– stationary filter stations requiring filter collection for measurement of iodine;<br>– mobile air-sampling stations (gross beta measurements or gamma spectroscopy, laboratory analysis);<br>– aerial sampling at high altitudes (gamma spectroscopy of the filter in laboratory). |
| Deposition measurements | – in-situ measurement of surface activity on the ground (gamma spectrometry with HPGe detectors);<br>– aerial measurements of surface activity (NaI(Tl), HPGe);<br>– environmental samples (HPGe spectroscopy in laboratory). |
| Foodstuff and environmental contamination measurements | – sampling and measurements in laboratory (gamma, beta, alpha). |
| Individual dose measurements | – external exposure (TLD, electronic dosimeters);<br>– external contamination (alpha, beta and gamma monitors);<br>– internal contamination screening ;<br>– internal contamination measurements (gamma spectroscopy with HPGe or NaI(Tl) detectors);<br>– excretion measurements (laboratory analysis);<br>– individual accumulated dose (biological dosimetry). |

There is no unique way to design an overall emergency monitoring system at national level. However, in the structure of the national state-of-the-art systems can be identified the following modules [7]:

1. Monitoring systems at fixed stations, which are either operated in a fully automatic mode (on-line) or in a semi-automatic mode (off-line). Typically, dose-rate measuring stations and air sampler stations represent this kind of systems. In most countries the national early–warning networks are based on automatic dose-rate monitoring networks. However, air samplers equipped with a system for real-time monitoring of the filter can be included in the early-warning network, too.

2. Mobile measuring systems. These are special units (ground-based vehicles, ships, helicopters, airplanes) capable of performing in-situ measurements as well as collecting various kinds of samples. Mobile units can also be used to take stand-alone measuring devices to the field.
3. High-standard special laboratories for the measurement of various types of environmental and food samples.

The basic modules can be combined and integrated in various ways. An example includes the "emergency laboratory" which is often capable of both carrying out in situ measurements and analyzing environmental samples.

The proper management of an emergency situation requires the use of a few additional modules:

- Technical systems for fast and reliable data transfer. Data transfer is a crucial element in the overall performance of any state-of-the-art radiation monitoring system.
- *Decision-Support Systems* (DSS) for the analysis and prediction of the current and future radiological situation, simulation of potential countermeasures (*e.g.*, sheltering, evacuation, issue of iodine tablets, relocation, decontamination and food-bans) and determination of their feasibility and quantification of their benefits and disadvantages. The interface between measurement results and computer-based forecast and decision support systems (DSS) is important (*e.g.* data assimilation, guidance of measurement activities on the basis of forecasts.
- Systems for creating and displaying the overview of the radiation situation. These systems can be integrated with DSS or they can be independent systems with appropriate interfaces with DSS.

## 4. STRATEGIC ASPECTS OF EMERGENCY RADIATION MONITORING

Managing measurements in different emergency exposure situations in a proper way requires the existence of pre-prepared emergency monitoring strategies. The main purpose of the emergency radiation monitoring is to provide decision makers with data and information that – combined with other relevant data (demographic, social, economic, etc.) – can be used to decide on countermeasures. It should be pointed out that emergency monitoring strategies include both measured data and model results because monitoring and modeling are supplementary and cannot fully replace each other.

The development of emergency monitoring strategies must start from the advance identification and analysis of potential hazard situations [3]. The range of accidents and events causing an emergency is large and covers accidents at nuclear sites, medical facilities using radioactive materials, industrial sites that use or make radioactive sources or process materials containing naturally occurring radioactive material, or during the transport of radioactive materials. For these situations, because the use of the radioactive material is regulated and therefore planned or known about in advance, it is possible to develop a detailed monitoring strategy tailored for the specific characteristics of the potential accidents. For exposures caused maliciously (*e.g.* through the dispersal of radioactive material in a public place), it is not possible to plan a radiation monitoring strategy in detail because the exact mechanism and location of exposure cannot be known in advance. However, this does not preclude the preparation of generic monitoring strategies which must be flexible to enable these generic plans to be adapted to the actual situation that arises.

An emergency monitoring strategy must be based on addressing the needs of assessors and decision makers over time and geographic location, and developed as a function of the type of decision being made [2]. Taking into account the time evolution of the needs of the decision-making process, a nuclear or radiological accident is often divided into three phases such as: early (might not be relevant for radiological events), intermediate and late phases. In the case of an accident at a nuclear facility, the early phase is subdivided into the pre-release phase (or threat phase) and the release phase. The duration of each phase can vary depending on the nature of the release but is often estimated for the pre-release and the release phases with a time scale of hours/days. The intermediate phase may last from days to weeks and the late phase may extend from weeks to several years. In the pre-release phase, many countries are now basing, at least partially, their decisions concerning urgent countermeasures on indicators of plant status. Before and during release phase various dispersion models with versatile weather data and best-estimate source terms can be used. When results of radiological measurements are available they can be used to improve model calculations by data assimilation. After the plume passage the main emphasis naturally lies on measurements for evaluating the contamination of the environment.

Three physical areas around a site can be defined corresponding approximately to the zones in which different types of decisions will be necessary in case of emergency, and different monitoring data will be necessary to support these decisions. These areas are [2]:

- Urgent protective action planning zone, which is an area immediately around a facility designated as being at elevated risk of significant stochastic effects in the event of a severe accident. For this area, urgent countermeasures are pre-planned.
- Food and agricultural restriction area is the area in which it is likely that land contamination will occur but the need for urgent protective actions is less likely.
- Area farther from release site where restrictions on the use of food or water and agricultural countermeasures are unlikely.

To develop a monitoring strategy as a function of the type of decision being made, it is necessary to know the reasons for performing emergency monitoring, the physical quantities being measured and the type of measurements being made.

The main reasons for performing emergency monitoring are [2]:

- detecting any release and early-warning;
- predicting and tracking plume trajectory;
- implementing of urgent population protection countermeasures;
- protecting emergency and recovery workers;
- implementing agricultural countermeasures and food restrictions;
- implementing intermediate- and late-phase countermeasures;
- contamination control;
- informing government and public.

The most important emergency monitoring data are [2]:

- ambient dose rate and dose;
- airborne radionuclide concentration;
- evironmental deposition;
- food, water and environmental contamination;
- individual dose;
- object surface contamination;
- meteorological data.

The most important measuring systems and methods used for emergency monitoring have been listed in Table 1. In general, several techniques can be used to measure a given physical quantity. Also, several different types of counting equipment can be used for the same measurement.

In general, the radiation monitoring strategy is affected by different factors whose status or related contents are known or available before any nuclear or radiological emergency arises. Examples include population distribution, geography and topography, land use, legislation and official agreements, fixed potential sources (nuclear facilities, etc.), routine monitoring arrangements and resources allocated to emergency monitoring (measuring equipment, laboratory measuring capacity, decision supporting systems, emergency communication equipment, etc.). These factors cannot normally be changed quickly, at least not during the early phases of an accident.

The role of these factors must be considered in the development of radiation monitoring strategies. For example, all fixed monitoring networks used under routine conditions can also be used in emergency situations for generating the first alarm and performing dose rate measurements. The advantages of using fixed monitoring networks can be summarized as follows:

- they operate continuously and need only a little extra manpower in an emergency;
- they can gather a lot of information about nation-wide radiation situation in a relatively short time;

- upkeep and further development of a wide monitoring network enables direct communication channels between the central authorities and local administration.

However, it should be noted that mobile equipment has important roles in the framework of emergency monitoring. Thus, mobile measurements are needed to provide monitoring data from places not covered by the fixed networks and in some cases the combination of ground-based and aerial measurements gives the best result. Also, in some occasions mobile measurements may be the principal means of obtaining adequate data about the current radiological situation. Ground-based vehicles and aircrafts can perform direct measurements, collect samples and transport various measurement devices to appropriate places. Members of mobile teams must be trained to function as a unified group of experts, which is able to work independently if needed and which can adapt to circumstances that may be stressful both physically and mentally. In the future the unmanned vehicles may offer an efficient platform for certain types of radiation measurements.

The laboratory infrastructure used under routine conditions is another factor which must be considered in the development of radiation monitoring strategies. This infrastructure can also be used for measuring environmental samples under emergency conditions. The need for environmental radioactivity measurements in case of radiation emergencies is not limited to the rapid and detailed assessments prior to the implementation of countermeasures but also a valuable tool for verifying the effectiveness of the actions taken. However, in any emergency it is important that the results can be obtained relatively quickly, which means that rapid measurement methods should be used such as gamma spectrometry and gross alpha and beta counting. Environmental radioactivity monitoring requires a sampling strategy to be defined and adopted. The use of valid statistical sampling techniques increases the chance that a set of sampling units is collected in a manner that is representative of the population. Representativeness of samples is difficult to demonstrate and usually, representativeness is considered justified by the procedure used to select samples [8].

Environmental factors are other type of factors which affect both the behavior of releases and performing of proper radiation measurements. It is clear that the influence of environmental factors must be included in radiation monitoring strategies and in the practical management of measurements during a radiation emergency. For example, weather conditions play an important part in the consequences of an accident with radioactive substances to the atmosphere and bad weather may disturb or completely prevent performing of certain measurements. In addition, meteorological data and real-time dispersion and dose forecasting models provide the authorities with tools that can be used to estimate the influence of atmospheric conditions on measurements and to coordinate and plan measurement activities. However, it must be noted that all dispersion models have generic limitations or flaws caused by the simplified basic assumptions and incomplete algorithms underlying them.

From the point of view of atmospheric dispersion, there is a distinction between urban and rural land surfaces. Thus, a release plume experiences enhanced mixing and dilution as it moves from rural environment to towns and cities. Furthermore, in the case of a release actually occurring in the middle of a population centre (*e.g.* explosion of a dirty bomb), the authorities must understand the nature of the influence of surrounding structures on short-distance dispersion: wake areas behind the buildings, channeling of air flows along the street tunnels, lots of surfaces exposed to deposition, and so on. General dispersion models are of limited use in urban areas. In urban surroundings the basic aim of countermeasures is to minimize all external doses as well as the dose due to inhalation of radioactive materials while in rural areas the countermeasures must also include those concerning the production of foodstuffs.

Fast and reliable data transfer is one of the key factors of a well-functioning emergency monitoring system. Data communication can be based on telephone lines, fax machines, wireless radio applications, internet connections or satellite phones. Data formats are very important and they should be standardized but yet be flexible enough to allow the transfer of various kinds of radiological information. A modern radiation monitoring information system consists of one large multi-task module or a group of distinct modules, each performing one or more specific tasks and having appropriate interfaces with the other modules. It must be able to carry out the following main tasks:

- gathering/receiving measurement results, forecasts and other relevant information;
- storing various kinds of data using sophisticated data bases;
- analyzing measurement data and forecasts to create an overview of the situation;
- communicating with decision support systems and other prediction models;
- displaying and disseminating different kinds of situational analyses and overviews.

Shortly after the Chernobyl nuclear power plant accident in 1986, the European Union set up the ECURIE (European Community Urgent Radiological Information Exchange) system to make early-notification and reliable radiological information available to EU member states in case of nuclear accidents. In addition, EURDEP was started in 1994 for the exchange of automatic monitoring data among EU member states. The EURDEP and ECURIE systems are complementary to the IAEA's EMRCON system information system for radiological or nuclear emergencies and its ENAC (*Early Notification and Assistance Conventions*) web page [12].

International cooperation, support and sharing of various resources must be included as a factor in a national emergency monitoring strategy. The new Basic Safety Standards (BSS) Directive emphasize the need for coordination of emergency preparedness and response in case of accidents with cross-border impact [9]. The international community has created, under auspices of the *International Atomic Energy Agency* (IAEA) a system of international assistance in case of nuclear or radiological accidents. Rules governing this system are fixed in the Convention on Assistance in Case of a Nuclear Accident or Radiological Emergency. This convention, which is primary legal instrument, established an international framework to facilitate the prompt provision of assistance in the event of a nuclear accident or radiological emergency. Within the framework of this convention and the Convention on Early Notification of a Nuclear Accident, the IAEA established an *Incident and Emergency Center* (IEC) which operates 24 hours a day, seven days a week. The IEC facilitates the transfer of information, assistance of any kind, as well as procurement and transfer of material means if a country needs them. The emergency management arrangements cover not only incidents at nuclear power plants but also those involving the transport and disposal of radioactive materials.

## 5. NEW ICRP RECOMMENDATIONS AND THEIR IMPLICATIONS

With the ICRP recommendations from Publications 103, 109 and 111 new concepts and quantities have been introduced into emergency management and rehabilitation [3, 4, 5]. These recommendations played an important role as they influenced national, European or even international standards. Thus, the European Commission has revised the *Basic Safety Standards* (BSS) based on the guidance of ICRP Publication 109. The old approach of an emergency plan with different intervention levels is replaced by a more comprehensive system [9]:

- threat or risk analysis;
- overall emergency management system;
- emergency response plans for identified threats;
- pre-planned strategies for the management of each postulated event;
- establishment of reference levels, optimized protection strategies for different postulated events and related scenarios;
- management of contaminated areas;
- compulsory cooperation between Member States and third countries in addressing possible emergencies on their own territory which may affect other Member States or third countries, in order to facilitate the organization of radiological protection in these Member States or third countries.

The main novelty of the new BSS is the introduction of exposure situations, as defined by the ICRP in Publication 103. As for existing exposure situations, indoor exposure to radon requires extensive surveys of indoor air or soil concentrations. Requirements are also made on the management of residues from industries processing naturally occurring radioactive materials (NORM) and the radiation monitoring of building materials. The new BSS also emphasize the need for coordination of emergency preparedness and response in case of a cross-border impact. Thus, the emergency response plans shall include arrangements for prompt coordination with the emergency response organization in a neighboring Member State or non-Member State, for facilities in the vicinity of a national border. Therefore, harmonization of emergency management actions and radiation monitoring strategies of neighboring countries in Europe is of great importance.

IAEA has also revised the Basic Safety Standards and an interim edition was published in November 2011 [10]. There are four requirements of this BSS dealing with emergency exposure situations, covering the following topics:

- establishment of an emergency management system;
- development and implementation of protection strategies;
- arrangements for controlling the exposure of emergency workers;
- arrangements for the transition from an emergency exposure situation to an existing exposure situation.

The new ICRP recommendations will influence both the emergency management and the radiation monitoring strategies. Thus, the countermeasure simulation approach used by decision support systems must be changed by taking into account all exposure pathways. Consequently, strategies of several countermeasures must be analyzed and simulated with the ultimate goal not to exceed the reference level over a given time period, typically one year. Furthermore, ICRP recommends preparing for all possible scenarios. To facilitate this preparedness aspect of ICRP recommendations, new modules for decision support systems must be developed to support the generation of scenarios and the selection of management strategies including emergency monitoring strategies.

Publication 111 of ICRP considers areas contaminated, due to past practices, as existing exposure situations and gives the principles for its management. According to this publication, it is essential to establish a radiation monitoring system allowing follow-up of the radiological situation in contaminated areas and a health surveillance program. The monitoring system should be designed to provide regularly updated information to authorities and other concerned parties. In situations where individual lifestyles are key drivers of the exposure, individual monitoring is an important requirement, coupled with an information program. The key objective of monitoring systems is to assess current levels of human exposure (both external and internal) and environmental levels of contamination, and to allow the prediction of their evolution in the future. In practice, this supposes a radiation monitoring system providing measurements of ambient dose rates, concentrations of radionuclides in foodstuffs and the environment, and whole-body contamination of individuals.

## 6. CONCLUSIONS

A national system for emergency radiation monitoring should be designed to deal with all threats due to possible radiological and nuclear accidents including terrorist events involving radioactive materials. The most serious nuclear threat with cross-border implications is due to severe accidents at nuclear power plants. A national monitoring strategy should be developed by taking into account all nuclear threats and the strategic aspects previously mentioned. For a country threatened by severe nuclear accidents, a good emergency monitoring strategy can be defined on the basis of the following most important requirements:

- likely threats have been identified and their consequences analyzed in advance;
- there exists an early-warning system for carrying out routine monitoring activities and communicating alerts to authorities and those potentially affected in case of accidents;
- there exist well-functioning networks composed of fixed monitoring stations for measuring gamma dose rates and the radioactivity in air;
- there exist well-functioning mobile monitoring systems;
- the relations between fixed and mobile monitoring systems are defined and their main uses understood;
- there exist a laboratory network and plans for sampling and measurements;
- there exist methods for monitoring data quality checks;
- there are methods to cope with several types of uncertainty inherent in different phases of a nuclear accident;
- there are fast and reliable means of data communication and presentation of the results in curves, tables or maps;
- general dependence of radiation measurements on the accident characteristics, source term, season, environmental conditions, measurement location and measurement method are recognized and taken into consideration;
- there are interfaces between measurement results and different forecasts or decision support systems that both enable the correction of predictions on the basis of monitoring data using data assimilation tools and support the management of measurement activities on the basis of predictions;
- there are tools for evaluating different alternatives for action in the recovery phase;
- the strategy has interfaces with various societal and economic factors and takes into account all stakeholders;
- there are proven back-up systems and procedures at all levels;
- possibilities offered by international assistance and co-operation are recognized.

The new ICRP recommendations from publications 103, 109 and 111 should be implemented in the near future in order to be operational for managing radiological and nuclear emergencies and for radiation monitoring under emergency conditions.

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