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QUANTIFICATION OF THE HAZARD DUE TO RELEASES OF RADIOACTIVE SUBSTANCES IN ACCIDENTS AND FIRES IN WORKPLACES WITH RADIOACTIVE SOURCES

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Research article

Abstract: In the Czech Republic, under normal conditions, the radioactive sources are used transported and stored in accordance with the relevant regulations and instructions of the State Office for Nuclear Safety (SONS), which is the regulatory authority of the state administration. Its main task is to ensure adequate safety and protection of persons in accordance with current international standards and guidelines. However, if there is an incidence, accident, or other emergency, these circumstances require taking some specific measures aimed at minimizing the impact of such situations on human health and the environment. During a fire in the workplace, the radioactive sources can get out of control or radioactive substances may begin to leak into the environment. In these cases, it is necessary to evaluate the radiation situation by means of measurement and monitoring both the external radiation and radioactive contamination of the air and the surrounding environment. For this purpose, a system of quantities and units has been developed for this purpose. If the system is not used correctly, this may cause serious confusion in some cases. Inappropriate use of quantities may also result in some misunderstanding regarding the evaluation of the severity of the radiation situation. The paper gives an overview of the relevant quantities and units in accordance with the latest recommendations of international organizations which are active in this area.

Keywords: Radioactive substance, fire, contamination, irradiation, radiation protection.

Introduction

Radioactive substance is defined as a substance that contains one or more radionuclides and whose activity (A) or specific activity (A_m) cannot be neglected from the point of view radiation protection aspects (Law, 1997; SONS, 2013). In terms of radiation protection it is therefore very important to follow certain procedures with respect to the transportation, use and storage of these substances, which are in compliance with IAEA (International Atomic Energy Agency), ICRP (International Commission on Radiological Protection), but also in accordance with the SONS regulations.

Nowadays, the radioactive substances are used in many medical, industrial and research facilities, where essentially a radioactive source (RS) can be sealed or unsealed emitter of ionizing radiation (IR). An unsealed source is defined as an emitter which does not meet the conditions for sealed source whose treatment or protective overlay provides verification test for leaks and excludes so for the foreseeable conditions of use, wear and leakage of radionuclides into the environment (Decree, 2002). The use of ionizing radiation has its advantages, which are normal (planned) situations always greater than the risk associated with the application of IR.

Among the high-intensity RS belong a nuclear reactor with nuclear fuel, and also radioactive generators as well as industrial and medical irradiators used in non-destructive testing and in radiotherapy, respectively. Some radionuclides may also be used for analyzing samples in terms of their composition. The specific activity of some frequently used radionuclides are summarized in Fig. 1.

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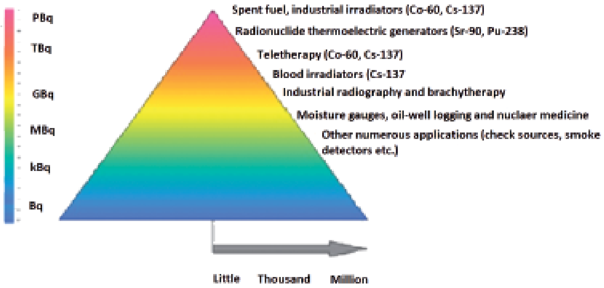

Fig. 1 Radionuclides used in some specific applications with their approximative activities (Hudzietzová et al., 2013)

In our everyday life, we are occasionally facing with the fires and, therefore, we cannot exclude their occurrences also at facilities with radioactive sources. The increased temperature may impair the shielding casing surrounding the source, thus a sealed source may not meet then the appropriate conditions imposed on its protective enclosure and will become in fact an open or unsealed source. During a fire, such a radioactive source can subsequently release some radioactive substances, and this may results in radioactive contamination of the air as well as the smoke that is formed during the fire and which can spread into the surrounding environment.

In any firefighting, the most important role is played by the Fire and Rescue Service (FRS) which are an inherent part of the national Integrated Rescue System (IRS). By intervening in an environment where there are radioactive substances or suspicion of possible radioactive contamination, these units are closely coordinating their actions with other specialized stakeholders, such as SONS, SÚRO (National Institute for Radiation Protection), IOO (Institute of Civil Protection) and SÚJCHBO (National Institute for Nuclear, Chemical and Biological Protection) (Sabol et al., 2013a).

The importance and the use of RS in recent years are growing, and so we cannot not entirely rule out the potential for unwanted exposure of persons above the relevant dose limits that have been set by SONS in accordance with relevant international recommendations. For this reason, one has to assume the occurrence of a radiological emergency or an accident. However, only in a few areas of human activities there has been paid such attention to the safety of people as it has been done in applications of radiation and nuclear based technologies (Klener, 2000). On the other hand, we must admit that unplanned situations associated with radiation overexposure of members of the public or environmental contamination can happen.

The radiation accident is an event that results in the leakage of radioactive substances or in excessive exposure of persons (Law, 1997). The consequences of radiation accidents are usually confined to the working area with RS (SÚRO, 2013). In the case of any radiation incident, the emergency plan serves to limit the consequences of exposure. The emergency plan includes the measures to minimize both internal and external exposures. The internal emergency plan is developed for the nuclear installation or workplaces engaged in operations with radioactive sources (Fig. 2). For transport of nuclear materials and RS relevant emergency plan has also to be available.

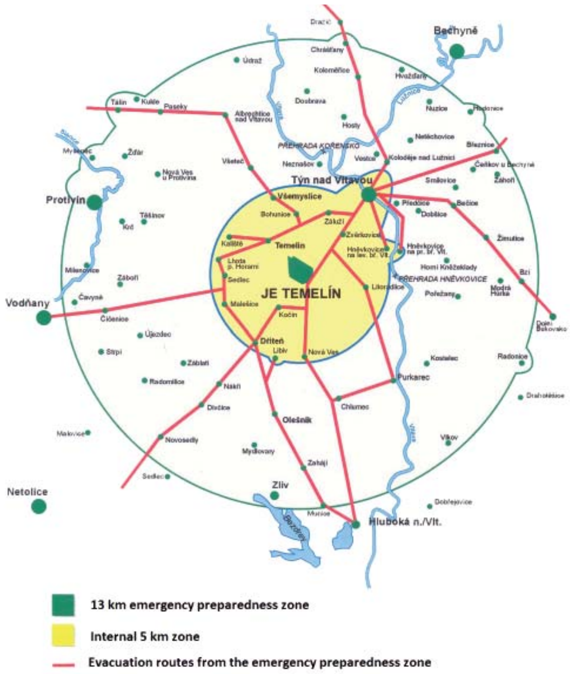

Fig. 2 External emergency plan of the nuclear power Plant Temelín (Pavlíček, 2006)

Radiation accident is defined as a radiation event, the consequences of which require urgent measures to protect the population and the environment (Law, 1997). Consequences of radiation ha-brews that reason affecting the workplace with RZ and its surroundings, especially the escape of radioactive substances into the environment (SÚRO, 2013).

Emergency is a situation which is important in terms of nuclear safety, radiation protection and that leads or may lead to unacceptable release of radioactive material or IR (Decree 1997). This situation, following radiation accidents, radiation accident or an elevated level of radioactivity or radiation, requires an urgent action to protect individuals (Law, 1997).

It must first be recognized by the very special situation and assess its severity. Subsequently, declaration of emergency activates affecting people who conduct intervention. In case of an emergency is to implement appropriate measures to reduce the causes of this situation and prevent further development of events and the release of radioactive substances. It is also important for full control over the RZ. On the basis of these procedures can be avoided or minimized exposure of the population.

Materials and methods

For the quantification of exposure, appropriate quantities and units have to be used. In 1977, key recommendations of the ICRP (ICRP, 1977) were published. They distinguished for the first time between stochastic (without a threshold) and deterministic (threshold) biological effects of IR. Other general recommendations of ICRP were published in 1991 (ICRP, 1991). The latest general recommendations issued by the ICRP in 2007 (ICRP, 2007). The ICRP recommendations are a basis for the IAEA standards and European Union directives, which for the Czech Republic as well as for other members of the EU obligatory are obligatory. Last IAEA safety standards were issued in 2011 (IAEA, 2011). Recommendations of ICRP and IAEA standards are reflected in the European Union directives (IAEA, 2011; Directive, 2012), which are also applied in the SONS regulations.

In the following section the selected quantities characterizing the source of ionizing radiation, dosimetric quantities, quantities of radiation protection and operational quantities are briefly discussed (e.g., Sabol et al., 2013).

The characteristics of the radioactive sources are used primarily reflected by the quantity of activity A [Bq] and specific mass activity A_m [Bq.kg^{-1}] as well as by the activity concentration A_v [Bq.m^{-3}] or surface activity of A_s [Bq.m^{-2}]. The activity is defined as the number of radioactive transformations per unit time (equation 1):

$$A = \frac{dN}{dt} \tag{1}$$

where dN is the mean number of spontaneous nuclear transformations occurred during the time interval dt.

The absorbed dose is the most important dosimetric quantity. The absorbed dose at a given point is defined as the radiant energy absorbed per unit mass of the material. The unit is the gray [Gy]. In terms of radiation protection, it is more appropriate to use the average in the organ or tissue, it is called the organ dose $D_{T,R}$. Organ dose is given by (2):

$$D_{T,R} = \frac{\overline{d\varepsilon}}{dm} \tag{2}$$

where $d\varepsilon$ is the mean energy imparted to the mass dm of the material.

The quantities of the equivalent dose and effective dose are used for setting dose limits or dose constraints. Both quantities are associated with only low levels of radiation and therefore serve for the assessment of stochastic biological effects. The unit of effective dose equivalent and the equivalent dose is sievert [Sv].

The equivalent dose H_T is related to specific tissues or organs and is defined by equation (3):

$$H_T = \sum_R w_R \cdot D_{T,R} \tag{3}$$

where w_R is the radiation weighting factor taking into account the type of radiation R and $D_{T,R}$ is the average absorbed dose in the tissue or organ. Quantity characterizing the exposure of the entire body is the effective dose defined by equation (4):

$$E = \sum_T w_T \cdot H_T = \sum_T w_T \cdot \sum_R w_R \cdot D_{T,R} \tag{4}$$

where w_T is the tissue weighting factor to allow for proper tissue radiosensitivity, w_R is the radiation weighting factor specific to each type of radiation and $D_{T,R}$ is the absorbed dose in the the organ or tissue T from radiation of the type R.

Since the main quantities of radiation protection (equivalent and effective dose) cannot be determined by direct measurement, the operational quantities have been introduced for the purpose of monitoring.

The total equivalent dose H_T is the sum of the total equivalent doses from external and internal exposure (equation 5):

$$H_T = H_{T,ext} + H_T(\tau) \tag{5}$$

The contribution from the internal exposure $H_T(\tau)$ is called the committed equivalent dose, where τ is the integration time following the intake of radionuclides in time t_0 and the equivalent dose rate $H_{T,p}$ at a time that is determined by the relationship (6):

$$H_T(\tau) = \int_{t_0}^{t_0+\tau} H_{T,p}(t)\,dt \tag{6}$$

In addition, the total effective dose is obtained by adding the contributions from external radiation E_{ext} and contributions from internal exposure $E(\tau)$, where $E(\tau)$ is referred to as the committed effective dose (7):

$$E(\tau) = \sum_T w_T \cdot H_T(\tau) \tag{7}$$

To determine the total committed effective dose from internal exposure after radionuclide intake of 50 years, one can use the relation (8):

$$E(50) = \sum_j e_{j,inh}(50) \cdot I_{j,inh} + \sum_j e_{j,ing}(50) \cdot I_{j,ing} \quad (8)$$

where $e_{j,inh}(50)$ is the coefficient for determining the committed effective dose based on the known intake of radioactive material inhaled of type j, $I_{j,inh}$ is intake of the activity of radionuclide j via the inhalation, $e_{j,ing}(50)$ is the coefficient for the assessment of the committed effective dose for intake of radioactive substances via ingestion of radionuclides of type I, $I_{j,ing}$ is the intake the activity of radionuclide j by means of ingestion.

Based on the knowledge of the relevant quantities and their units, we can correctly interpret the monitoring of external and internal contamination.

In monitoring of the external environment a very important role in early warning network (SVZ) locations of the installed monitors is important (Fig. 3, 4).

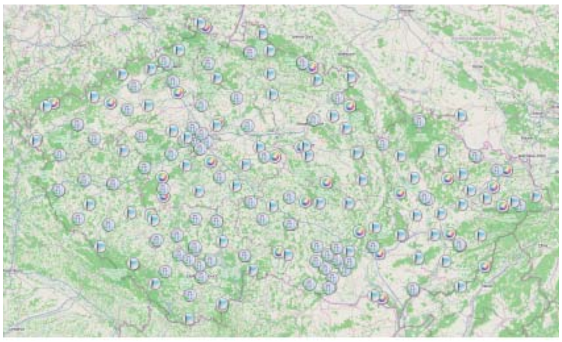

Fig. 3 Programme MonRaS - Location of measuring places for the early warning system (SÚJB, 2013b)

Fig. 4 One of the measuring sites of the network for the early warning (SÚJB, 2013b)

Storage, processing and publication of the results of radiation monitoring is implemented using software MonRaS (SONS, 2013b).

In the event of a radiological situation, such as during fire, the external radiation is usually determined using a personal dosimeter, which is worn on a standard location (left upper chest), based on which the quantity personal dose equivalent $H_p(10)$ is monitored. Because of the need to know the instantaneous value of the measured quantity $H_p(10)$, a personal electronic dosimeter is used. This dosimeter is equipped with an audio alarm signal that would be activated as soon as the radiation level is above a certain preselected level. For the workplace monitoring the quantity of the ambient dose equivalent $H^*(10)$ is used. The results obtained by personal dosimeters and radiation monitors provide the necessary information for determining the contribution of external radiation to the overall exposure in terms of the effective dose.

The monitoring of people for internal contamination is usually based on the use of continuous measurement of volumetric concentration of radionuclides in the air (Sabol et al., 2013b). For this measurement a special monitor using a suitable filter which separates the radioactive material from the remaining constituents of air is required. The radioactive substances collected on the filter are then measured using the appropriate detector. Monitoring of artificial radionuclides in the environment takes place through regular sampling of air and also of water or soil (Fig. 5). The results of the measurement of specific sampling sites are stored and processed using the MonRaS software (Fig. 6).

Fig. 5 Taking a sample from the soil (SÚJB, 2013b)

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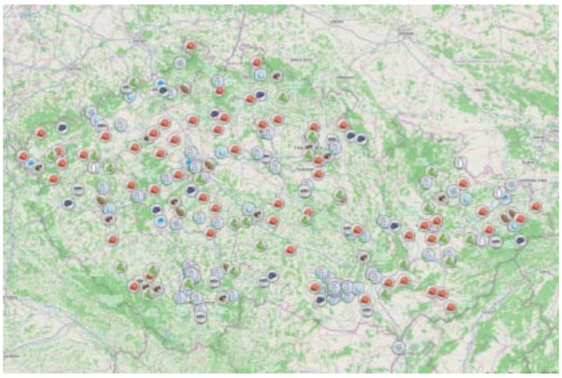

Fig. 6 Programme MonRaS - The locations for taking samples from aerosols, fall-out, surface and drinking water, milk, meat, fish, potatoes, forest fruit, mushrooms and fodder (SÚJB, 2013b)

At some industrial and medical facilities are often found radioactive sources, such as ^{60}Co, ^{137}Cs, ^{192}Ir and others. The intake of radionuclides leads to the exposure expressed in terms of committed effective dose. The internal contamination is caused by radionuclides which entered the body via inhalation, swallowing or drinking. It is assessed based on the measurement carried out with whole-body counters (Fig. 7) or collecting urine and excrement, the activity of which are then measured.

Fig. 7 Measurement of the whole-body internal contamination using a special whole-body counter (Wagner, 2011)

Results

Based on the above analysis of the system of quantities and units for the quantification of exposure, it is possible to evaluate the radiation situation with regard to the contributions from both external radiations as well as from internal contamination, which is caused by the entry of radioactive substances into the human body by inhalation or ingestion.

At the industrial and medical facilities one encounters often various sources of ionizing radiation, such as ^{60}Co or ^{137}Cs. The second mentioned radionuclide is usually in powder form, which can easily cause the contamination of the air that is then inhaled. The intake of this radionuclide may be determined based on the volume that has been inhaled, thus the body of an individual gets a certain amount of activity. Using the appropriate conversion factors, the amount of activity can be converted into the effective dose in accordance with equation (8). To some extent, the resulting irradiation depends also on the physical and chemical properties of a radionuclide in question. The relevant decree (Decree 2002) lists these factors for inhalation (h_{ing}) characterized for different types of absorption from the lungs into the bloodstream by the relevant class, i.e. F (fast), M (moderate) and S (slow). The conversion factors of some of the most common radionuclides are shown in Table 1 (the conversion factors of class S for an adult).

Tab. 1 Selected conversion factors for the calculation of ingestion committed dose equivalent from internal contamination (Decree, 2002)

Radionuclide	h_{ing} **[Sv/Bq]**	**Radionuclide**	h_{inh} **[Sv/Bq]**
^{56}Mn	$1{,}2.10^{-10}$	^{111}In	$1{,}2.10^{-10}$
^{55}Fe	$1{,}8.10^{-10}$	^{123}I	$1{,}2.10^{-10}$
^{58}Co	$2{,}1.10^{-9}$	^{125}I	$1{,}2.10^{-10}$
^{68}Ga	$2{,}6.10^{-11}$	^{131}I	$1{,}2.10^{-10}$
^{89}Sr	$7{,}9.10^{-9}$	^{137}Cs	$1{,}2.10^{-10}$
^{90}Y	$1{,}4.10^{-9}$	^{145}Sm	$1{,}2.10^{-10}$
^{99m}Tc	$2{,}0.10^{-11}$	^{166}Ho	$1{,}2.10^{-10}$

The elements that may be present in gaseous form, their date are given in relevant regulations (Decree 2002) showing the relevant conversion factors for inhalation (e.g. H_{inh} elemental ^{125}I this factor is 1.4 x 10^{-9} Sv/Bq for inhalation whereas this factor for elemental iodine ^{131}I is equal to 1.4 x 10^{-9} Sv/Bq). Using the above conversion factors one can approximately determine the effective dose due to the inhalation of radioactively contaminated air.

Conclusion

In fighting fires, the units of the Fire Brigade are mainly engaged where they cooperate with other special components of the Integrated Rescue System and other professional institutions. In case of fire on the site area with radioactive sources, it is essential that the intervening units are properly prepared including protective clothing and equipment, and possess adequate monitors to measure external radiation or estimate internal contamination. Of course, all personnel are supposed to be appropriately trained. These requirements are absolutely necessary wherever the workplace affected by a fire occur has any high-activity radioactive sources. Due to the high temperatures the containers that are used for storage or transport may be affected in such a way which may result in radioactive contamination of air, surface or ground at the site as well as in its surrounding. Therefore, the firemen have to be aware of the situation and have to be familiar how to monitor external and internal exposure including some knowledge in interpreting the results using relevant quantities and units.

Acknowledgments

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