IOP Conference Series: Materials
Science and Engineering

PAPER • OPEN ACCESS

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IOP Conf. Series: Materials Science and Engineering **487** (2019) 012013 doi:10.1088/1757-899X/487/1/012013

About the development of a national system of response to the nuclear emergency for agriculture

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Abstract. The document discusses the development of a system for responding to a nuclear emergency that could affect the agricultural sector. The analysis of some decision support systems showed that while the development of such a system there should be taken into account the advantages of the existing software tools allowing to derive recommendations for countermeasures and remediation of agricultural territories affected by the radiation accident. The consequences of major nuclear disasters have shown that the new system should consider the international experience on mitigation of the impact to agriculture, as well as consider potential nuclear emergencies, which can affect the territories located in the vicinity of nuclear facilities.

1. Introduction

Current tendencies in the development of nuclear power engineering suggest the decrease of the probability of emergency situations at nuclear power plants (NPP) and other enterprises of the nuclear fuel cycle (NFC) to the level of “inherent safety” [1]. Nevertheless, the disasters at the Chernobyl NPP and Fukushima Daiichi have shown the significance of the problem of nuclear accidents, and, as follows, there arises the necessity of the development of the plans for protective measures in case of different radioecological situations associated with the design-basis and beyond-design-basis accidents, which can result in the radioactive contamination of the environment [2].

Specialists consider three stages of the radiation accident. They are early (acute) stage, intermediate stage and late (remedial) stage.

Early stage is the period from the beginning of the accident until the moment, when the release of the radionuclides into the atmosphere stops and when the formation of the radioactive trail ends. The duration of this stage depends on the characteristics, accident scale and meteorological conditions; it can last from several hours to several days. At the early stage, the external radiation dose is formed due to the gamma- and beta-radiation from radionuclides contained in the cloud. Inhalation of radioactive products from the cloud causes the internal exposure of humans and animals. From the point of the radiation effect, radioactive noble gases make the significant contribution to the exposure of biological components of agricultural and natural ecosystems. Critical objects during this stage are the population, residing in the vicinity of the source of radioactive release, and agricultural animals, grazing on the territories affected by accident [3-5].

An intermediate stage of the accident begins from the moment, when the formation of the radioactive trail ends, and lasts until the implementation of all the necessary protective measures form the population and fulfilling of the required range of sanitary and hygienic, as well as medical and preventive measures. Depending on the characteristics and scale of the accident, the intermediate stage can last from several days to several months. During the intermediate phase the main reasons of harmful effects are external exposure to radioactive substances deposited from the cloud on the soil surface, buildings, etc., and internal exposure to the radionuclides because of their ingestion with drinking water and food products. The significance of inhalation is determined by the opportunity of breathing in the contaminated fine particles of soil, plant pollen, etc., resuspended by the wind. During this period the radioactive contamination of agricultural and natural ecosystems has already been formed. The concentration of radionuclides in plants decreases due to the radioactive decay, biomass buildup and crop purification under the meteorological factors [3-5].

The late (remedial) stage can take from several weeks to decades because accidental radioactive release can contain long-lived radionuclides. This stage ends when all the restrictions to the population activities on contaminated territories are cancelled and sanitary, and dosimetric control is performed regarding the radiation situation under the conditions of the "controlled exposure". The sources of external and internal exposure for this stage are the same as for the intermediate stage. The main way of radionuclide transport to agricultural migration chains is root uptake [3-6].

2. Consequences of the accidents at the Chernobyl and Fukushima Daiichi nuclear power plants for agriculture

Major radiation accidents have shown that agriculture is the main activity, impact to which determines total consequences of radiation accidents for humans.

We should mention that the Chernobyl accident was acknowledged as an "agrarian accident" due to the following facts:

- the region affected after the accident belonged to the zone of intensive agricultural production, where the agricultural sector is one of the leading sectors of the economy;
- the majority of contaminated territories belongs to the agricultural lands;
- the consumption of agricultural products is one of the main sources of additional exposure of population;
- the main population cohort are the people living in rural areas and having "rural" diet;
- doses of external and internal exposure of rural residents in the region of the accident are 1.3-4.0 times higher than those for the urban residents [7].

On the territories with high contamination levels, there were prohibited or significantly restricted traditional economic activities. According to the regulatory and legal acts in 1986-1991, there were excluded from agricultural use 2 640 km^2 of lands in Belarus, 171 km^2 in Russia and 1 583 km^2 in Ukraine. There were excluded from agricultural use 1 762.5 km^2 outwards the state radioecological conservation area in Belarus and 1 013 km^2 outwards the exclusion zone (30-km zone) in Ukraine. In Belarus, these lands are related to the zones of evacuation (exclusion) and top-priority resettlement, in Ukraine - to the zone of a mandatory evacuation, in Russia - to the exclusion zone [8-10].

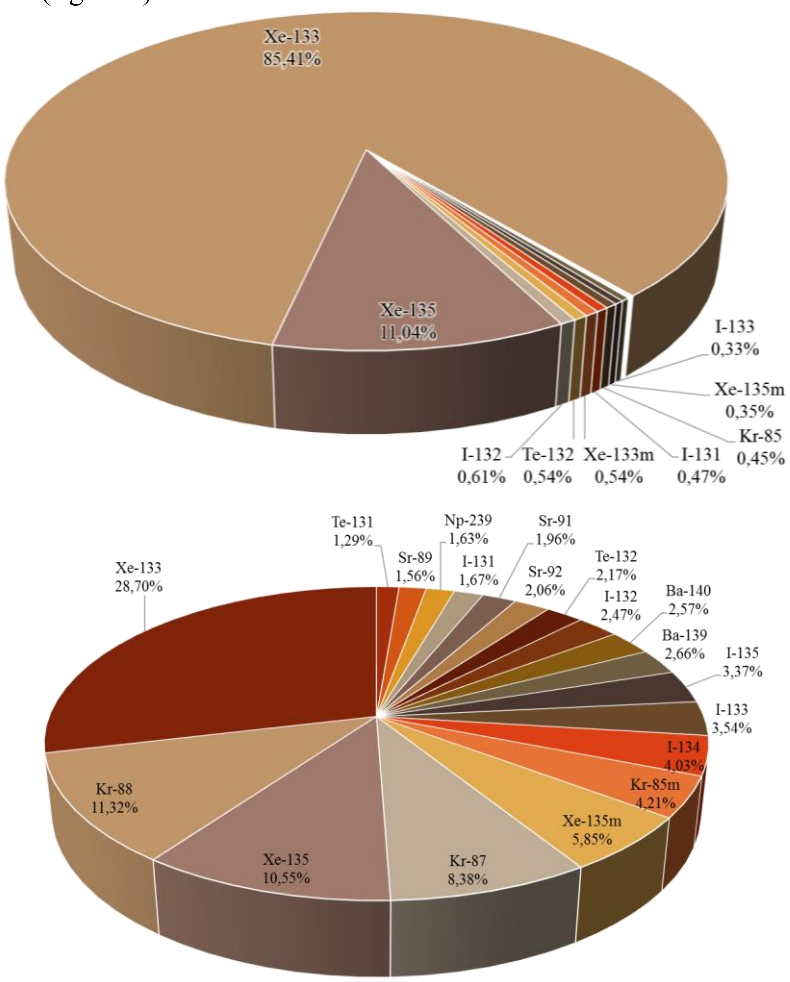
Emergency on the Fukushima Daiichi NPP led to the contamination of vast areas, a significant part of which belong to agricultural and forest lands. Territories, which had to be remediated, were up to 500 km^2 (external dose higher 20 mSv/a) and 1 300 km^2 (external doses from 5 to 20 mSv/a). The investigations of the regions with the highest impact showed that contamination of paddy fields ranges from 67 to 41 400 Bq/kg, and contamination of other types of lands (arable, meadows, permanent crops) ranges from 16 to 56 600 Bq/kg. The most contaminated agricultural areas are located in Fukushima prefecture, where the content of radionuclides in 3.6% of all the samples (including 4% of samples from paddy fields and 2.9% of samples from other types of lands) exceed 5 000 Bq/kg [11].

3. Consideration of scenarios of potential accidents

Improvement of reactor facilities and nuclear fuel cycle, in general, is aimed at the heightening of economic effectiveness and radiation safety. The necessary condition of justification of new nuclear technologies is the assessment of the consequences of radiation impact to the environment resulted from the emergency situations at NFC enterprises. The reasons for such situations can have different nature: natural disasters, “human factor”, terrorism and military actions, etc. Justification of the facilities of the nuclear industry, NPPs in particular, suggests not only the estimation of the radioactive effects on the environment during the normal operation but also in case of potential emergencies, including severe accidents [12].

The U.S. Nuclear Regulatory Commission initiated the State-of-the-Art Reactor Consequence Analyses (SOARCA) project to develop best estimates of the offsite radiological health consequences for potential severe reactor accidents for two pilot plants: the Peach Bottom Atomic Power Station in Pennsylvania and the Surry Power Station in Virginia. Peach Bottom is generally representative of U.S. operating reactors using the General Electric boiling-water reactor (BWR) with the gross capacity of 1412 MW_e and a Mark I containment. Surry is generally representative of U.S. operating reactors using the Westinghouse pressurised-water reactor (PWR) with the gross capacity of 890 MW_e and a large, dry (subatmospheric) containment [13, 14]. Accidental scenarios for Surry and Peach Bottom NPPs suggest the radioactive release of 60-70 different radionuclides with a total activity of up to 10^{19} Bq. Such situations can be rated 7th level according to the International Nuclear Event Scale.

For example, within the conservative approach, the scenarios of the severe accidents caused by any seismic or other catastrophic external events consider the loss of power, failure of safety systems and core damage, and, as follows, radioactive release into the environment, estimated $3.36 \cdot 10^{18}$ Bq at a height of 8.4 meters in case of the accident at PWR-890 and $2.38 \cdot 10^{19}$ Bq at a height of 39.6 meters for the BWR-1412 (figure 1).



a)

b)

Figure 1. Main radionuclides contained in the accidental radioactive release for NPPs with reactors PWR-890 (a) and BWR-1412 (b).

The analysis of scenarios [12] has shown that the accident at Surry NPP can result in the contamination (above 37 kBq/m^2) of ~90 km^2 of lands lying in the vicinity of the station, and in case of the accidental release from Peach Bottom NPP the contamination above 37 kBq/m^2 would cover ~150 km^2. These potential consequences might threaten the hypothetical agricultural activities performed on the territories located near such nuclear facilities. We should note that assessment of the radiation impact to the reference natural object (pine forest) showed that the affected area would be smaller: 4.5 km^2 for Surry and 100 km^2 for Peach Bottom. This confirms that fact that the territories with possible contamination of agricultural products would be larger than the areas with radiation damage of the natural ecosystems.

4. The idea of the national system responding to a nuclear emergency in the agricultural industry

In order to prevent and minimise the consequences of potential accidents at nuclear facilities for the agricultural sphere systems aimed at the response to the nuclear emergencies affecting food and agricultural production are necessary. Thus, the absence of the effective response system in agro-industry after the Chernobyl accident led to the unreasonably high content of ^{131}I in food products, consumed by the population and, as follows, to the increased entrance of ^{131}I into human organism and formation of high radiation doses for thyroid. This caused the significant number of thyroid cancers registered after the accident. In Japan, after the accident at Fukushima Daiichi NPP, they used the experience gained at the mitigation of the consequences after the Chernobyl accident. Actions taken during the emergency response in agriculture led to the reduction of radiation doses for the population during the first period after the accident to the relatively safe levels.

At the same time, not always reasonable actions during the emergency response in Japanese agriculture became the reason of formation of large volumes of radioactive wastes, i.e. to the generation of constant radioactive contamination sources. Moreover, this problem does not have any solution yet. Therefore, the timeliness and effectiveness of the measures to be taken during the emergency response in agro-industry directly influence the health of the population residing in the zone of the potential accident and possible damage to agricultural production due to radiation accidents. We should mention here, that nowadays the issues in the emergency response are of concern of international organisations, such as ICRP and IAEA. ICRP and IAEA issued new publications [15] and IAEA Safety Standards [16] containing requirements and recommendations, which are not considered now in terms of an existing emergency response system.

In the Russian Federation, there are response systems for the emergencies at facilities of the nuclear industry. For example, State Atomic Energy Corporation ROSATOM has the system of prevention and mitigation of emergencies [17]. Nevertheless, there is no national system of prompt intervention in the sphere of agricultural and food production in case of the radiation hazard, but at the same time there exist computer tools and decision-support systems, which could become the basis of such national response system. Current paper gives the example of some decision support systems (DSS) applied in the sphere of agriculture and food security:

PRANA. This system was developed in 1997 in Obninsk Institute for Nuclear Power Engineering. It is based on the principles and methods of radiological protection of the members of public and remediation of radioactively contaminated territories. It covers the basic countermeasures during the long-term period after the nuclear accident, their quantitative and qualitative characteristics including the rules and different restrictions of their application. This DSS uses GIS-technologies: vector maps of land use and associated databases, which are the system key components. During the assessment of the consequences of land contamination, recommendations on the application of protective measures and their efficiency, PRANA allows presenting the input/output information at different investigation levels (district, farms, fields, etc.) The particular attention is paid to agricultural measures: the assessment of their effectiveness is based on the use of economic and radiologic methods, including various kinds of cost-benefit analysis. Moreover, the program uses different methods for the analysis of uncertainties or inhomogeneous behaviour of population doses and contamination of agricultural products. Nowadays the system is developed for the contaminated territories of Bryansk region; maps and databases contain data on contamination levels of ^{137}Cs in soil and agricultural products [18].

ReSCA (Remediation Strategies after the Chernobyl Accident) was being developed within the IAEA TC projects in 2003-2008. It was aimed at the decision support in the sphere of population safety on contaminated territories in the Republic of Belarus, the Russian Federation and Ukraine to facilitate a selection of optimised remediation strategies in rural settlements. The DSS is based on data on contamination of agricultural products, settlements and pasture areas. Besides settlement-specific data, the system uses a set of generic country-dependent parameters, which are based on the expertise level knowledge gained during remediation activities in the affected countries. The principal output of ReSCA is an optimised strategy of remediation of contaminated areas at settlements, but there is a lack of recommendations on performing of activities on agricultural lands. As the input data, the program uses the values of concentrations of ^{137}Cs in soil and doesn't suppose any geoinformation units [19].

Also, we should mention here that decision support systems PRANA and ReSCA were developed before the Fukushima accident and, as follows, they do not consider the experience on mitigation of consequences and various parameters gained during the studies, which were conducted by the international community after 2011.

The RODOS system is the result of a close collaboration between almost 40 institutes from about 20 countries within the European Union, Eastern Europe and the former Soviet Union. The development of the system began at the end of 1980-s. Since 2010 RODOS system was followed by its newest JAVA based version named JRodos, which has been improved until the present time. JRodos is a decision support system for off-site emergency management and remediation issues after nuclear accidents, which has the primary aim to provide consistent and comprehensive information at local, regional and national levels, during all stages of a real event and while preparing for possible future events. The system has a module for deriving the recommendations on the application of agricultural countermeasures during the long-term period after the accident. The model estimates the effectiveness of the strategy according to the total contamination of food products, radiation doses, required sources, wastes and costs taking into consideration the time span during which pre-defined activity levels in food would be exceeded. The assessment is performed within the application of countermeasures in production and consumption of food products. The program considers the following countermeasures: food disposal and stopping of food production, food processing and storage, removal of animals from contaminated feed, use of sorbents in animal feed, change of crop species or variety, amelioration and changes in the types of land use [20, 21].

The development of Decision Support System for Nuclear Emergencies Affecting Food and Agriculture (DSS4NAFA) started in 2013 within the framework of the FAO/IAEA Coordinated Research Project D15015 "Response to Nuclear Emergencies Affecting Food and Agriculture". This decision support system has been developed and is being improved on the basis of contemporary information technologies for the management of data collection and visualisation and decision-making to ensure food safety and security using well-timed and complex planning on restrictions in food and agriculture production during a nuclear emergency. Beta version for extensive independent testing is expected to be available in July 2018. The DSS allows performing tasks on the response to nuclear emergencies considering the gained experience and situation studies. DSS4NAFA can be used during both emergency responses as well as for routine monitoring of nuclear and radiological incidents that could affect food and agriculture. Data here is managed in real-time and up-to-date information on the spatial and temporal distributions of radionuclides in the landscape for decision-makers and end-users [22, 23].

5. Conclusions

Development of the national nuclear emergency response system for agriculture should consider the international experience on mitigation of the consequences of nuclear accidents and use the advantages of the decision support systems mentioned above as its basis, taking into the consideration

IOP Conf. Series: Materials Science and Engineering **487** (2019) 012013 doi:10.1088/1757-899X/487/1/012013

the regulatory documents and standards of the Russian Federation. The analysis of these DSS has shown that to organise the efficient agricultural production regarding an emergency, the recommendations on countermeasure implementation should consider particular soil characteristics, peculiarities of separate farms and positive and negative experience of managing the effects resulted from major nuclear disasters. Moreover, such system should take into account the potential accident scenarios for the nuclear power plants located in the Russian Federation because the damage and consequences depend not only on the external environmental conditions but reactor types, main radionuclides and parameters of the radioactive release.

In summary, the national system of response to nuclear emergency in the sphere of agricultural production should include the advantages of contemporary decision support systems, which allow to derive recommendations on the performing of agricultural activities during the nuclear emergency for different investigation levels (region, farm, field, etc.) and monitoring of contaminated farmlands with the consideration of economic, agricultural and social aspects of the considered territories.

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