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Modeling the distribution of radionuclides in the environment as a result of radiation accidents

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***Abstract*—In the present work the creation of decision support system in a radiation accident for a local scale is considered. The main analytical pollutants transport model in the atmosphere is based on Gaussian Plume model. The choice of initial data for modeling (including meteorological data from weather prediction models like GFS and WRF) is considered. The following technical details of GIS creating for a polymodels complex are considered: the use of modular structure, taking into account a surface roughness data, and values interpolation for graphical representation (based on IDW interpolation method). The underlying surface iodine 131 pollution for the maximum design basis accident of a nuclear power plant unit with a VVER 1200 reactor is conducted by created DSS. The results show that radionuclides maximum levels are lower than the level activity in excess of which protective measures should be carried out.**

***Keywords*—radioactive contamination, GIS, DSS, meteorological data, modeling, Gaussian plume model**

I. INTRODUCTION

At present time, the number of facilities at which accidents or incidents with the potential danger of radioactive substances release into the environment is growing. Due to the fact that incidents at such facilities are always accompanied by a threat to human life and health, as well as great material damage, there is a need to create systems for simulating such incidents at various stages of an emergency.

Recent studies of a similar direction have been studied and reviewed. In [1] the distribution of radionuclides ^{131}I was simulated using the Gaussian model and verified on real data. The authors also proposed some improvements to the existing model. The work [2] presents the case study results of environmental pollution at the Khmelnitsky NPP in Ukraine. Concentrations of radionuclides during emissions into the atmosphere were measured. This indicates the research topic's relevance and the validity of the atmospheric diffusion Gaussian models use in modeling radioactive contamination.

The main goal is developing decision support systems for radioactive accidents which allows to work with situations where there is a shortage of initial data for modeling, which is typical for the initial stage of an emergency incident development. By the way, at this stage, management decisions are required to minimize the negative consequences. It is worth emphasizing that in this case the decision-making time is in particular importance, because the amount of damage will directly depend on it. Modeling the spread of pollutants in the environment is a laborious task, because it requires a large number of initial parameters and calculations, results interpretation, visualization, etc. Therefore, the corresponding software package implementation becomes the most attractive option, the usage of such software allows to minimize the time for making a management decision in the current situation.

II. PROPOSED METHODOLOGY

A. *Definition of input data for modeling*

The main problem in forecast calculations of the radionuclides accidental releases consequences into the atmosphere is the initial data choice for modeling, from which the following groups can be distinguished:

- meteorological parameters (temperature at the ejection height, atmospheric stability category, wind speed / direction at the ejection height, type and pollutant cloud characteristics;
- radionuclide release composition;
- activity distribution by particle size during radioactive release.

Emergency scenarios are reviewed for five types of accidents at nuclear power plants (design and severe beyond design basis accidents without core melting and reactor core melting). Accidents are selected from the emergency situations list presented in [3], in terms of the radionuclides largest releases into the environment.

Each scenario includes the ejection's isotopic and fractional composition, with specific activities and the ejection duration for each of the isotopes. It should be noted that the use of these scenarios in modeling is possible only with a conservative approach (due to the fact that the isotopic and fractional composition will depend on various factors: for example, the degree of "burnout" of nuclear fuel, load size, etc.).

For the transport model of radioactive substances in the atmosphere, the meteorological parameters in the modeling area are the most critical. The values of these parameters relate to the data being changed and require constant updating. Meteorological parameters are used to calculate key values in the atmospheric transport model of pollutants: meteorological dilution factor, atmospheric boundary layer height, thermal rise of pollutants, atmospheric stability category, etc.

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When determining the category of atmospheric stability (according to Pascville), it was decided to use statistical data for the last 20 years of meteorological observations at the base meteorological station in the potential radioactive release facility area. This made it possible to significantly reduce the number of initial parameters required for the calculation and the simulation time.

Therefore, it is advisable to use an external module in the framework of this work, which provides an interface for importing current weather data. Due to this, it is possible to get rid of the dependence on a meteorological data particular provider, which is an undoubted advantage.

For the meteorological module used, the initial data is the GFS (Global Forecast System) model, which was developed by the National Center for Environmental Prediction (NCEP) and provides forecasts for up to 16 days. Also, GFS data can be further processed using the Weather Research and Forecasting (WRF) model. This processing allows you to increase the spatial (up to 1 km) and temporal resolution of meteorological forecasts. Results can be saved in grib2 or netCDF format.

When calculating the dispersion of possible accidental emissions into the atmosphere in the area where the nuclear power plant is located, the interaction effects of the surface atmosphere and the underlying surface are always taken into account. A heterogeneity characteristic of the underlying surface, affecting the air movement in the atmosphere surface layer, is the roughness coefficient z0, which has a length dimension. The roughness coefficient z0 is greater, the greater the average height of the irregularities. When modeling the dynamic parameters of the atmospheric boundary layer, the heterogeneity of the underlying surface is taken into account using mesoscale roughness coefficients. The profile area data is used to calculate the roughness coefficient [4].

Shuttle Radar Topography Mission (SRTM) open data was chosen as the source elevation data. To store data about the terrain, the PostgreSql database with the PostGIS extension is used. Pre-prepared data is imported into the database.

Since the developed system has a modular structure, interactions with external modules are organized at the interface level. Implementation of work with the terrain module is organized through the web interface through a GET request. Data is transmitted in JSON format.

B. Model for calculating atmospheric transport of radionuclides

For a local scale at an emergency development's early stage, the most suitable is the use of Gaussian models of atmospheric transport [5]. Gaussian models are experimental results generalization on the aerosols dispersion in the atmosphere and suggest the standard weather conditions presence (obeying the standard classification) that are quasi-stable during the pollutants spread in the atmosphere.

This model allows to make a pollutants spread forecast at distances of not more than 10 km from the source and to make an transfer's indicative rapid assessment of the to distances of not more than 30 km.

Conceptually, in Gaussian models, it is assumed that the dispersion of non-settling pollutant in the atmosphere horizontally and vertically occurs according to the normal distribution law with constant direction and speed of the wind and provided that the atmosphere remains stable [6].

The model is applicable not only for an instantaneous and continuous source, but also for a source of action's finite time. The model takes into account the atmospheric boundary layer height's influence (depending on stratification), the dependence of the Gaussian cloud dispersion on the underlying surface roughness [7].

In a generalized form, the calculation of the surface concentration of a polluting substance in the atmosphere according to the Gaussian model is carried out according to the formula (1):

$$q_{\text{tc}}(x,y,t) = M \cdot F(x) \cdot G_{\text{con}} \cdot t_{\text{s}} \tag{1}$$

where M – is the power of the source, Bq/s; t_{s} – source action time, s; F(x) – is the source depletion function; G_{con} – is the dilution function.

Based on the polluting substance surface concentration value in the atmosphere, it is possible to calculate the contamination density on the underlying surface as depending on the dry and wet excretion factor.

The contamination density of substances on the underlying surface D(x, y, t) is calculated as a sum of the deposition's density due to wet D_{w} and dry D_{d} fallout, which can be written in the following form [8] (2):

$$D(x,y,t) = D_{\text{d}}(x,y,t) + D_{\text{w}}(x,y,t) \tag{2}$$

The calculated deposition density and surface concentration are used in dosimetric models to assess the radiation evaluation of the population.

C. Dosimetric model

The most important for the protective measures planning and implementation is the assessment of the radioactive substances impact on the population. The numerical characteristics by which this impact can be evaluated are the doses of external and internal exposure. There are models that allow to switch from surface concentration and surface contamination density by radioactive substances obtained using atmospheric disturbance models to doses of external and internal exposure [8]. The dose from the cloud in the approximation of semi-infinite space is calculated by the formula (3):

$$H^{\text{ext}}{}_{\text{CL},\infty} = q_{\text{tic}} \cdot B_{\text{v}} \tag{3}$$

where q_{tic}, Bq*s*m^{-3} – time-integrated concentration at the point (x,y); B_{v} – dose coefficient linking radiation dose rate with volumetric activity of the current radionuclide.

The dose of gamma radiation from an endless flat surface contaminated with radionuclides is calculated by the formula (4):

$$H^{\text{ext}}{}_{\text{s}} = B_{\text{s}} \cdot K_{\text{sh}} \cdot \int_{t_1}^{t_2} D_{\text{s}} dt \tag{4}$$

Fig. 1. The modeling contamination result on the underlying surface in the case of the maximum emergency release for aerosols ^{131}I in the north-east wind direction (Bq/m^2).

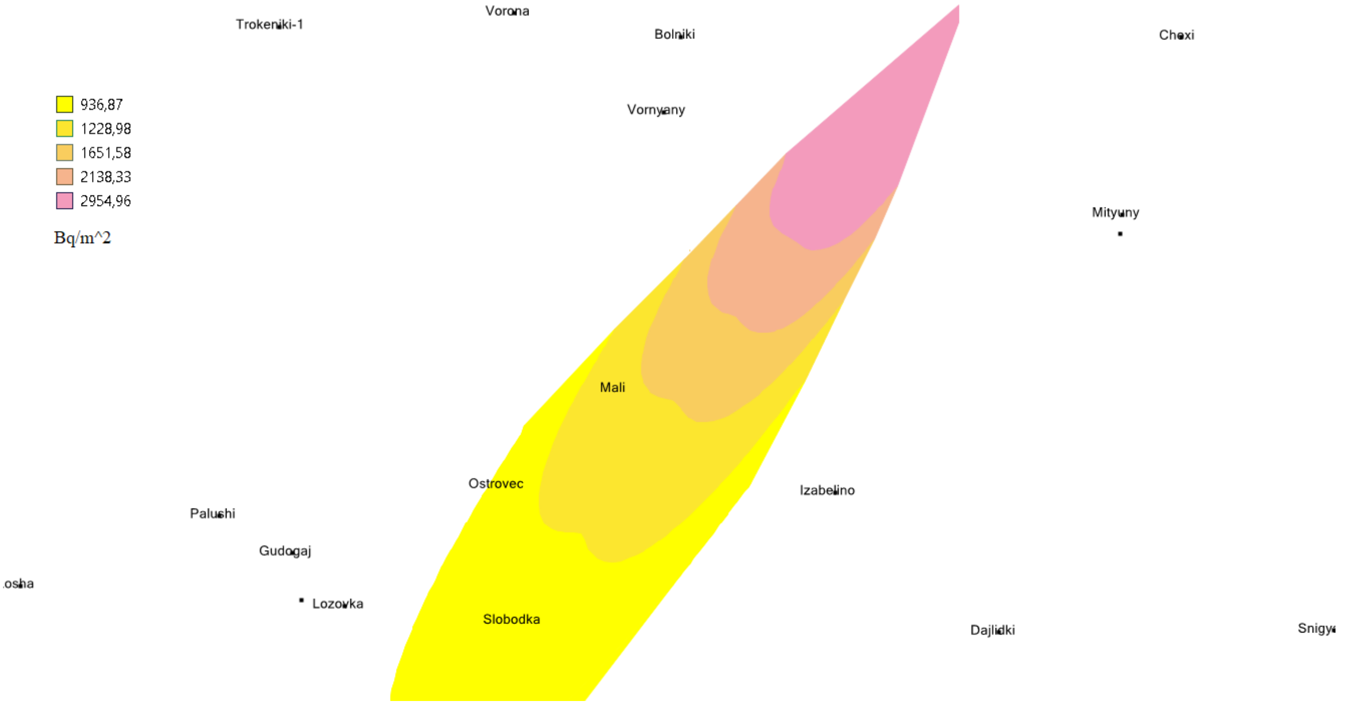

Fig. 2. The modeling contamination result on the underlying surface in the case of the maximum emergency release for aerosols ^{131}I in the south-west wind direction (Bq/m^2).

where D_s, Bq/m^2 – radionuclide contamination density on the ground; B_s – dose conversion factor; K_{sh} – the shielding coefficient, equal to default 1.0 based on the conservative forecast, but it is recommended to use 0.4 for long-term forecasts.

The internal exposure dose due to the radionuclides inhalation from a passing cloud is calculated as the multiplication of the time-integrated concentration q_{tc}, breathing rate V_1 and dose coefficient B_{inh} (5):

$$H^{\text{inh}}{}_{\text{CL}}(x,y) = q_{\text{tc}} \cdot V_1 \cdot B_{\text{inh}} \tag{5}$$

Dose coefficients are defined as maximum for various n groups of particle solubility in accordance with the IAEA recommendations on the coefficients choice for an unknown emission composition (for lung solubility).

III. RESULTS

A. Making recommendations on countermeasures

The results of modeling on the transfer of radioactive substances in the atmosphere and the calculations according to dosimetric models serve as initial data for the development of recommendations for a particular radiation incident.

Sanitary norms, rules and hygienic standards [9], approved by the Ministry of Health decree, are the regulatory document in the Republic of Belarus that describes the protective measures implementation in case of an accident at a nuclear power plant.

The provisions of this document (appendices 4 and 12) served as the basis for determining the criteria for developing recommendations to minimize the radiation accident consequences at an early stage.

To determine the criterion for making decisions on the dose of external exposure, hygiene standards Appendix 12 was used [9], which sets out the maximum dose rate levels for deciding on protective measures in radiation accidents.

The criteria for protective measures described above are used in this paper to support managerial decision making in a radiation accident.

B. Verification on model experiments

As the initial emergency scenario, the most negative scenario from the point of radioactive release into the environment view – the maximum design-basis accident – was selected. The scenario includes emergency emission level for iodine 131 = 3.9E+10. Fig. 1 shows the modeling contamination on the underlying surface result in the case of the specified scenario implementation for aerosols ^{131}I in the north-east wind direction, whereas Fig. 2 shows the result of a similar simulation in the south-west wind direction.

As a modeling result the radionuclides expected level is calculated for key points. For a graphical representation, the inverse distance weighting (IDW) algorithm was used; pixels with similar values were combined into ranges. A legend is available for each image received and includes physical measure unit, for each radionuclide level range the minimum value for entry and color are indicated.

The calculated data analysis of ^{131}I release due to dry fallout in the case of the chosen emergency scenario implementation shows that radionuclides maximum levels are observed at a 2-4 kilometers distance from the emission epicenter and are 10000-12000 Bq/m^2, which is lower than the level activity in excess of which protective measures are carried out.

IV. CONCLUSION

In the course of the work, the research issues were deeply studied: the regulatory framework in the population radiation safety field in the Republic of Belarus, nuclear power plants design bases, physical processes that occur in emergency situations, modeling the pollutants spread in the atmosphere, etc.

The results obtained during the study can be used for research in this area, and can also become the emergency response system part during the nuclear power plants operation. There is the prospect of integrating this modeling tool with surveillance systems (for example, automated radiation monitoring systems) to clarify the initial modeling parameters. In addition, it is possible to import the results of modeling the initial isotopic composition and specific activities of radionuclides from the corresponding systems.

This work has great potential for further research in the problem area and expanding the functionality of the created software. Improvements are possible in terms of the calculations speed, the other models use and the implemented models optimization.

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