Evaluation of doses in coupled rooms in case of beyond design accident basis

I O Zhuraukova, A G Lukashevich and A G Trifonov

Joint Institute for Power and Nuclear Research - Sosny, National Academy of Sciences of Belarus, Minsk, Belarus

E-mail: lonitkoira@gmail.com

Abstract. An object of research in this study are radioactive substances and its expansion in adjacent spaces. An objective of the study - to develop an assessment algorithm of the dose budget from the radioactive sources in adjacent spaces considering the convective transfer of radioactive substances. The universal scale of installation-420 (hereinafter-UGU-420) space is installed, the location is on the site of "JIPNR- Sosny" of NAS of Belarus (hereinafter – the Institute) in the software package simulations of COMSOL Multiphysics 3.5 a (hereinafter-COMSOL). According to the results of the test calculation of the relative concentration distribution radioactive substances in the volume of the space, taking into account barriers and ventilation pipeline, the dose budget on the employees of the Institute with possible release of radioactive $^{60}$Co was determined. The comparative analysis on the calculation results of radioactive substances and dose budget expansion was performed with the help of the developed software module for evaluation spread of radioactive emissions.

1. Introduction

The possibility of beyond design-basis accidents is highly improbable, the Chernobyl, the Three Mile Island nuclear power plant in the United States, the Fukushima nuclear power plant in Japan accidents showed that such accidents should be taken into account in nuclear power projects. Previously, such accidents were considered hypothetical and, in practice, were not considered in the projects. Now, the modern concept of safety requires taking into account such accidents in projects, limiting their consequences with the help of measures to manage beyond design basis accidents.

In the event of a radiation threat, practical measures should be taken to restore control of the radiation source and to minimize radiation doses, the number of irradiated persons, and radioactive contamination of the environment, economic and social losses caused by radioactive contamination.

The assessment of the possible scenarios of radiation accidents, the stages of development and the extent of their consequences are necessary to minimize the effects of radioactive contamination.

This study will allow to give scientific credence and to develop: measures to ensure radiation protection of personnel; procedure for radiation control in the event of a radiation accident; algorithm of personnel actions and interaction with emergency services for localization and elimination of radiation accident at the appropriate stages of its development; criteria for decision-making on carrying out protective measures in the event of an accident at facilities with increased nuclear and radiation hazard [1].

The object of research in this study are radioactive substances and their distribution in adjacent spaces.
The aim of the study is to develop an algorithm for assessing the dose budget from radioactive sources in adjacent spaces, taking into account the convective transfer of radioactive substances.

2. The process model transfer of radioactive substances
To identify the hazard and characteristics of the emission exposure, the physical and mathematical modelling of the emission transport based on the use of software modules have to be performed. The transfer of impurities and its deposition on the surface of the space is a complex and multifaceted task [2].

To assess the deposition of radioactive substances on the surfaces of the space in emergency situations and to simulate the flow and transported particulate matter, a system of conservation equations for individual phases was chosen, which are solved numerically together with equations describing the processes of interfacial transfer and the dynamics of interfacial surfaces. To describe the migration of radionuclides in the flow, the system of equations was supplemented by the equations of motion and conservation of aerosol particles. This system of conservation equations is supplemented by appropriate sets of initial and boundary conditions, as well as integral parameters of technogenic sources.

To simulate the flow dynamics the following system of conservation equations is accepted [4]:

\[
\frac{\partial \rho W_i}{\partial t} + \frac{\partial W_i}{\partial x_j} = 0
\]

\[
\frac{\partial W_i}{\partial t} + W_j \frac{\partial W_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial P}{\partial x_j} + \frac{\partial}{\partial x_j} \left( v_k \frac{\partial W_i}{\partial x_j} - W_i W_j \right) + g \delta_{ij}
\]

\[
\frac{\partial T}{\partial t} + W_j \frac{\partial T}{\partial x_j} = \frac{\partial}{\partial x_j} \left( a_k \frac{\partial T}{\partial x_j} \right)
\]

where \( W_i \) and \( W_j \) – components of the velocity of the transportation flow along the axes \( x_i \) and \( x_j \) (in this model - \( i, j = 1,2,3, i \neq j, x_1, x_2, x_3 \) – spatial coordinates); \( t \) - time; \( P, T \) - pressure, temperature; \( \rho \) - density; \( g \) - acceleration of gravity; \( v, a \) - coefficients of kinematic viscosity, thermal diffusivity; \( K \) - turbulent kinetic energy according to the «k–ε» turbulence model; index \( E \) effective value taking into account the model of turbulence.

To describe the migration of radionuclides in the flow, the initial system of the conservation equation is supplemented by the equations of motion and concentration of aerosol particles [6]:

\[
\frac{\partial C_k}{\partial t} + W_j \frac{\partial C_k}{\partial x_j} = \hat{\nabla} \left( D_k \hat{\nabla} (C_k) \right) - \lambda_k C_k,
\]

where \( C_k \) is the concentration of aerosol particles of fraction \( k \) in the carrier flow; \( D_k \) is the diffusion coefficient of aerosol particles of fraction \( k \) in the carrier flow; \( \nabla \) - the operator of differentiation by \( x_n, x_j \); \( \lambda_k \) is the decay constant of the radionuclide under consideration.

The equations above were implemented in the development environment of COMSOL 3.5 a computer programs. Simulation results are presented in figure 1.
Figure 1. Distribution of the field of concentration of radioactive aerosols range of changes in the relative concentration 0-1.

Despite the high activity of the installation, you can see in Figure 1 what happens in the proper construction of barriers and protections.

3. Method of calculation of dose budget

To determine the dose budget [7]:
1. To determine the ways of radioactive substances release into the environment.
2. To determine the composition and physico-chemical forms of radionuclides.
3. Subject to the release of radioactive substances into the atmosphere, to determine the wind speed and the direction.
4. To calculate the spatial distribution of radionuclides taking into account the deposition on different surfaces (on the model of convection-diffusion transport).
5. To make a map of the relative concentration of radionuclides distribution.
6. To determine the preferred pathways of radionuclides in the human body.
7. According to the composition of radionuclides, their concentration, taking into account the ways to calculate the possible doses of external and internal radiation.

In accordance with the principle of conservative approach to assessment and high uncertainty in the model, the following assumptions are made:
- short-term exposure when constant emission conditions and composition are expected;
- do not take into account the reduction of radiation due to partial stay in the shelter;
- irradiated personnel-adults (over 18 years of age), with a breathing volume of 1.4 m$^3$/h, performing light physical work, not consuming contaminated food.

For these conditions, the prognostic assessment of the total effective dose was carried out taking into account external and internal irradiation by inhalation [8]:
\[ E_T = (E_a + E_g) + E_{inh}, \]  

where \( E_T \) - total effective dose, mSv; \( E_a \) - effective dose of radionuclides in the air (in the cloud), mSv; \( E_g \) – effective dose of radionuclides in precipitation, mSv; \( E_{inh} \) – effective dose of inhalation, mSv.

The calculation of the effective dose from the radionuclides contained in the air and deposition \((E_a+E_g)\) was performed by the formula:

\[ (E_a + E_g) = K \sum_{i=1}^{n} C_i e_i T_e \]  

where \( T_e \) is the duration of irradiation, h; \( C_i \) is the concentration of the \( i \) radionuclide in the surface air layer, kBq/m³; \( e_i \) is the dose rate defined as the absorbed dose of gamma radiation of the \( i \) radionuclide at a height of 1 m above the underlying surface from the source in the form of a radioactive cloud \((\text{mGr/h})/(\text{kBq/m³})\), \( K \) is the transition rate from the dose in the air at a height of 1 m above the underlying surface to the effective dose for representatives of the \( i \)-th group of the population under irradiation from the Radioactive cloud, mSv / mGr.

The effective is calculated by the following formula:

\[ E_{inh} = 10^{-6} \sum_{i=1}^{n} (C_i e^i) T_e V, \]  

where \( e^i \) is the dose coefficient for personnel for the \( i \) radionuclide, S / Bq; \( C_i \) is the concentration of the \( i \) radionuclide in the cloud, kBq / m³; \( V \) is the respiration rate, m³ / h; \( T_e \) is the duration of irradiation, h.

According to the formulas above, the total inhalation dose, the effective dose of external irradiation was calculated.

4. Model of radioactive substances transfer for UGU-420

On the territory of the Institute, a powerful industrial isotope gamma-ray unit UGU-420 with 420 Ki activity was installed for experimental and industrial work related to the use of \(^{60}\text{Co}\) radiation sources.

This setting was taken as a subject of research. The building has 3 floors: the room where to be UGU-420, intermediate floor, and control room.

For the test calculation, a conditional scenario of radiation accident associated with the depressurization of the reaction zone of the installation with a source of ionizing radiation based on radionuclide \(^{60}\text{Co}\) with a total activity \((A_0) 1.6 \times 10^{16} \) Bq of without leaving the radionuclide outside the building was adopted.

The methods of calculation of dose budget were chosen, the assessment of radiation doses of employees in a radiation accident associated with the depressurization of closed sources of ionizing radiation with radionuclide \(^{60}\text{Co}\) with a total activity of \(1.5 \times 10^{16} \) Bq was performed, it should be noted that as a result of the accident the radionuclide remained in the volume of the building.

To the data assessment, a comparative analysis of the results obtained using the multiphysical package COMSOL 3.5 and the program code RESRAD-BUILD 3.5 was carried out. The results are presented in table 1.

| Zone number | RESRAD-BUILD 3.5 | COMSOL 3.5 |
|-------------|------------------|------------|
| Total effective dose, mSv | \(4.57 \times 10^3\) | \(1.04 \times 10^3\) |
| zone 1      | 1.52             | 1.5        |
| zone 6      |                  |            |
Using the values of relative concentrations, the volume activity of $^{60}\text{Co}$ was calculated for each of the zones (zone 1 of the room where the installation is located; zone 6 of the permanent residence of the personnel) with approximately the same concentration values.

5. Conclusion

Analyzing the values obtained, it can be concluded that the main way to form the dose of personnel – the dose from external irradiation. The data show a natural decrease in doses with increasing distance from the emission source. Under all the conditions considered at a distance from the source and barriers in the form of walls, the doses received during the passage of ionizing radiation do not exceed the dose limit for the personnel of 20 mSv, since the personnel is directly in zone 6 [5,10].

To evaluate the data, a comparative analysis of the results was performed, data using the multiphysical package COMSOL 3.5 and the software code RESRAD-BUILD 3.5. Calculation results using the COMSOL 3.5a software package, are in good agreement with the results obtained in the software code RESRAD-BUILD 3.5.

The main advantage of physical and mathematical modeling of emission transfer within the premises using the COMSOL 3.5a software package is the ability to take into account the characteristics of the premises, ventilation communications and, as a result, to obtain more accurate calculations for estimating the distribution of the relative concentration of radionuclides over the distance from the emission source.

The developed technique can be used to analyze the sequence of the accident development outside the body, but within the NPP containment. In addition, to assess the dozen budget experienced by the container during the development of an accident with damage to the reaction zone, followed by an analysis of damage to the containment. In this way, this technique can help you accomplish the objectives of a level 2 probabilistic safety analysis.

References

[1] Romanov G / Elimination of consequences of radiation accidents. Reference guide. M: Publ.-1993. - 336 p
[2] Methodical recommendations "Control of radiation doses of the population living in a zone of supervision of radioactive object in the conditions of its normal operation and radiation accident". Moscow, 2013.
[3] User’s Manual for RESRAD-BUILD Version 3, June 2003
[4] Pugliese, S / Finite element modelling of plume dispersion in the lower part of the atmosphere / S.Pugliese, M.Jaeger, R.Occelli // Air Pollution: Monitoring, Simulation and Control (ed. B. Caussade, H. Power, C.A. Brebbia) – Comp. Mech. Pub. Southampton-Boston. – 1996. – P. 99 – 108.
[5] Optimization of radiation protection in the control of personnel exposure: safety report Series № 21. – Vienna: IAEA, 2003. – P. 81
[6] Loitsyansky L / Mechanics fluid and gas. M.: Science, 1970. – P.904
[7] Bolshov L / Radioecology: Proceedings of IBRAE, - Moscow: Science, 2007. - 444 p.
[8] Steven G. Homann: Health Physics Codes ,Version 2.07.1, User’s Guide: -March 8, 2010.
[9] Gerhard Benz, Irmgard Hasemann: RODOS User Guide System Interface: - March 26, 2008
[10] Recommendations of the International Commission on Radiation protection. Publication № 60, part 1 of ICRP, Energoatomizdat, 1994