The use of specialized software for liquid radioactive material spills simulation to teach students and postgraduate students

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Abstract

The study proves relevance of specialized software use to solve problems of emergencies prevention of radioactive liquids spills to teach students and graduate students. Main assessment criteria of accidents at radiation-hazardous objects associated with radioactive liquids spillage is identified. A model of radioactive substances transport in emergency rooms is developed. It takes into account physical features of radioactive liquid spill from the source, air pollution during transition of radioactive liquid from the spill surface into the air and subsequent scattering in the emergency room under influence of local air flows. It is determined that the existing software tools for radiation exposure assessment do not comprehensively cover features of such events and possess number of shortcomings regarding accidents modeling with spillage of radioactive liquids indoors. Computer modeling and forecasting examples for hypothetical event related to liquid radioactive spill in the JRODOS system are presented. The training process of future specialists, specialties 183 "Environmental Protection Technologies", 143 "Nuclear Energy", 103 "Earth Sciences", and 122 "Computer Science" should be based on application of powerful scientific and methodological training base using modern achievements in the field of digital technologies. It is advisable to supplement curricula for students' and postgraduate students' preparation in the mentioned above specialties by studying issues related to: development of mathematical models and software for solving problems of emergencies prevention in case of radioactive liquids spills; usage of features of specialized decision software of emergencies prevention during spills of radioactive liquids.

Keywords

computer simulation, specialized information system, mathematical modelling, emergencies prediction, radioactive liquids, training of students, graduate students

1. Introduction

Nuclear energy has provided a significant share of Ukraine's total electricity production for many decades. So, stable operation of nuclear energy is a necessary condition for continued economic development of the country. Today in Ukraine there are main directions of theory and practice of safe operation ensuring of nuclear power plants (NPPs) that addresses complex issues of minimizing risk levels. There is a need for more realistic and accurate modeling of hazardous events at NPPs related to normal operation (events, frequency of implementation) which may exceed value of 0.01, 1/year) due to conduct of probabilistic safety analysis for Ukrainian NPP units and introducing of NRBU-97/D-2000 requirements for potential exposure of population in recent decades. Such events included accidents involving spillage of liquid radioactive material (LRM) after a probabilistic safety analysis. One of representative events related to radioactive heavy water spill took place at the Pakistani Karachi NPP (power unit No. 1) in 2017. Four people were irradiated as a result of the spill localization. The effective radiation dose of one of the liquidators reached a value of almost 40 mSv, which is 2 times higher than the set limit dose for personnel in Pakistan. This event was classified as the 2nd level according to the International Nuclear Event Scale (INES) according to the investigation results. Events of this type also took place in Ukraine. Insufficient level of staff skills and lack of readiness to eliminate emergencies of radioactive liquids spillage fast leads to emergencies and huge material costs for energy supply restoration [1].

Nuclear power workers should have skills to use digital technologies which help in modeling and prediction of systemic accidents conditions at radiation-hazardous facilities. Ability to apply these technologies is important for further professional activity. Given that digital technologies are constantly improving and new management systems are developing. It is important to familiarize training staff with the latest developments, systems, software and experience-exchange to apply these tools in further professional activities.

LRM spills are also possible at the Chornobyl Liquid Radioactive Waste Processing Plant, at

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oncology hospitals that use radioisotopes to treat patients, at uranium mining and uranium processing facilities, during transportation of liquid radioactive waste etc.

Thus, the urgent tasks are the following:

1) *for scientists and experts* – to improve the enterprises and organizations safety with risk of LRM spillage by developing mathematical and software solutions to prevent emergencies of this type;
2) *for scientific and pedagogical workers* – to update educational-professional and educational-scientific training programs for future specialists in Earth sciences, computer science, nuclear energy, and environmental protection technologies on development of mathematical and software tools ensuring solution of emergency prevention problems during LRM spills.

Various aspects of digital technologies use to prevent emergencies are discussed in publications [2, 3, 4, 5, 6]. Specialized software for computer modeling of various processes is described in works [7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18]. Analysis of foreign and domestic accidents and incidents with LRM spills [1, 19, 20, 21] shows that problem of radiation emissions impact estimation in such accidents remains relevant and needs further research. Existing mathematical and computer tools for radiation exposure assessment (MELCOR, CONTAIN, MAAP, etc.) do not comprehensively cover features of such dangerous events and possess number of shortcomings in modeling of accidents with LRM spills.

Peculiarities of future specialists training in Earth sciences, computer science, and environmental protection technologies were the subject of research in [22, 23, 24, 25, 26, 18, 27, 28, 29, 30, 31, 32]. However, the problem of specialized software usage for solving problems of emergency prevention (for example, the LRM spill) in training of students and graduate students is not sufficiently considered. Therefore it is relevant and needs further research.

The research aim – to investigate peculiarities of mathematical and software tools development for solving problems of emergency prevention in case of LRM spills and to describe 7 directions of this software application during preparation of students and graduate students majoring in environmental sciences, Earth sciences, computer science, nuclear energy, environmental protection technology.

The research tasks are:

1) analysis of incidents with LRM spills;
2) description of features of development of mathematical and software tools for solving problems of emergency prevention during LRM spills;
3) showing examples of computer modeling of atmospheric dispersion and effective dose by using system JRODOS.

2. Research results

In accordance with the probabilistic safety analysis for Ukrainian NPP units and the radiation safety standard NRBU-97/D-2000 requirements for potential public exposure, there is a need for more realistic and precise modeling of events at NPPs related to abnormal operation the frequency of which may exceed the value of 0.01 1/year). After conducting a probabilistic safety analysis, such events include accidents involving the spills of radioactive liquids at the area of facilities.

LRM are liquid solutions, which include impurities of radioactive elements (possible bounds in high-molecular complexes). The isotopic composition of LRM is determined primarily by the source of radioactive impurities. The main sources of LRM at nuclear power plants and nuclear complexes are as follows: primary coolant that is discharged for operational reasons; water that is used to backflush filters and ion exchangers; floor drains that collect water that has leaked from the active liquid systems and fluids from the decontamination of the plant and fuel flasks; leaks of secondary coolant; laundries and changing room showers; and chemistry laboratories.

According to INES [33], accidents involving spills of radioactive liquids, depending on the magnitude of the release and the corresponding radiation effects, can be assigned different levels of danger (from level 0 "Event with a deviation below the scale" to 7 "Major accident"). This approach reflects the design features of heat dissipation from the core of reactors operating on liquid coolant. During the severe accident with melting of the reactor core, the products of nuclear fuel fission come into direct contact with the liquid coolant and water of the emergency cooling systems, which will lead to further formation of radioactive liquids. Neutron activation of the coolant during the campaign at the reactor units also makes a significant contribution to the atmospheric release activity. In both, the first and the second case, the activity of the liquids represents a small part of the total release activity. Therefore, when assessing the consequences of severe accidents, the source term associated with evaporation of liquid spills is often neglected. However, if the accident involves the release solely from the evaporation from open surfaces, depending on the concentration of radionuclides in the liquid and the conditions of the accident, the release can pose a significant threat to personnel, public and environment.

2.1. Events related to spill of radioactive liquids

In previous publications, we analysed and systematized accidents with the spills of radioactive liquids. The place and year of the accident or incident, the level on the INES scale are indicated and a brief description of the event is given. It should be noted the low number of official reports on the radiation consequences of accidents and incidents related to the spillage of radioactive liquids.

As an example, in 2010 at the Ignalina NPP [34] there was a spill of about 300 tons of radioactive decontamination solution. Figure 1 shows the pictures of this incident. For this event, no official information on the results of dosimetric monitoring at the NPP site, as well as the classification according to the INES scale, was provided. Figure 2 presents the author's infographics of incidents with LRM spills at Ukrainian NPPs.

2.2. Mathematical model of radioactive substances transfer in emergency rooms

Figure 3 schematically shows processes that occur after incident with spill of LRM in the rooms of radiation-hazardous object.

Modeling of the LRM Evaporation. To solve the problem of unsteady LRM evaporation, four balance differential equations (1) were written to relate the main parameters of LRM and air

Figure 1: Photos of the accident with the spill of radioactive decontamination solution at the Ignalina NPP (Lithuania, 2010): view of the broken pipeline (a), general view of the spill part (b) [34].

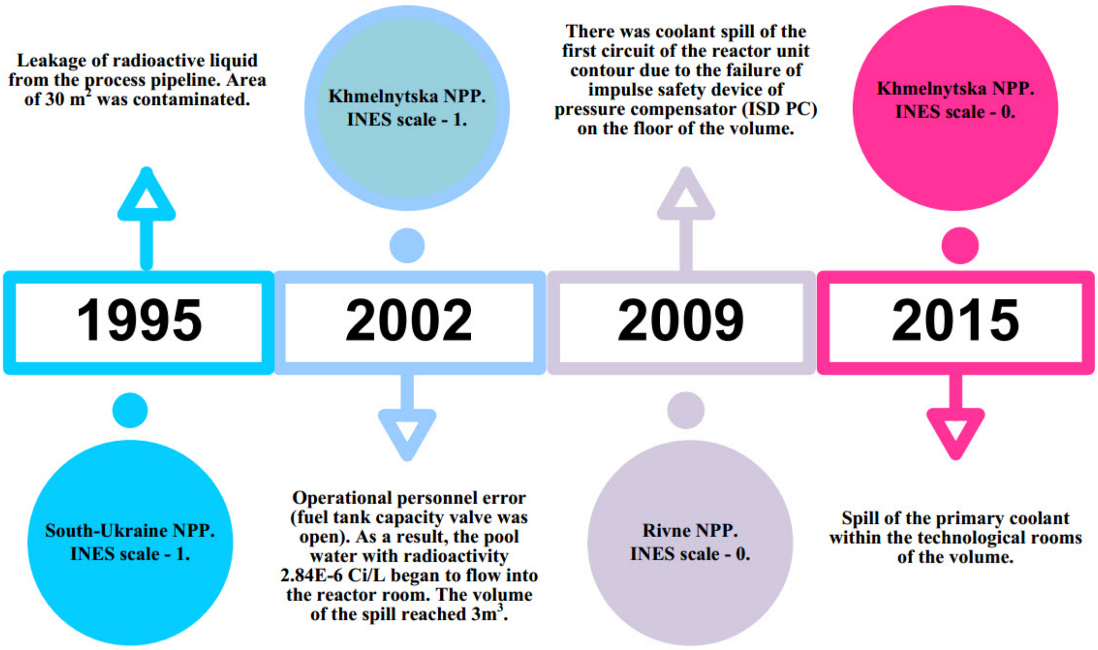

Figure 2: Infographics of LRM spill accidents at Ukrainian NPPs.

space of area over time:

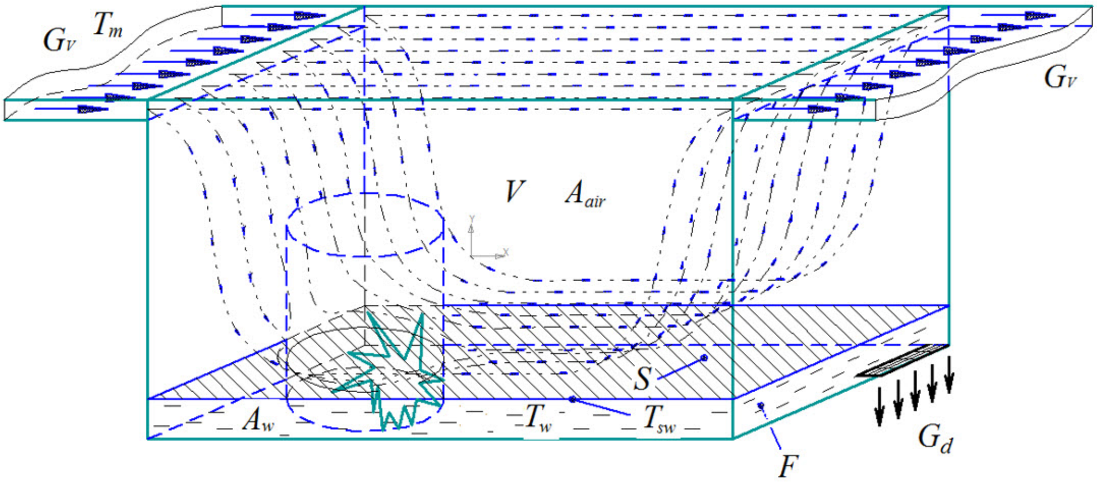

Figure 3: Conceptual scheme of air pollution after incident with spill of LRM in the rooms of radiation-hazardous object.

$$\begin{cases} \frac{dm_w}{dt} = -\beta_{sw}(p_{sw} - p_m)S - G_d \\ \frac{dm_a}{dt} = \beta_{sw}(p_{sw} - p_m)S - G_V \frac{m_a}{V} \\ \frac{dm_q}{dt} = G_V \frac{m_a}{V}(1 - \Psi) \\ \frac{dT_w}{dt} = \frac{r_w \beta_{sw}(p_{sw} - p_m)S + kF(T_W - T_f)}{c_p m_w}, \end{cases} \quad (1)$$

where m_a – current mass of SARM in air of the area, kg;

G_d – flowrate of LRM through the drainage channel (it also includes the volume of LRM leakage from the area), kg/s;

V – air volume in the area, m^3;

G_V – flowrate of involved air of forced ventilation (this parameter includes SARM leakage through the gaps or clearances in walls of the emergency area), m^3/s;

Ψ – coefficient of filtration (efficiency of filtration);

m_q – mass of released SARM into the atmosphere, kg.

This system of nonlinear differential equations includes polynomial functions. Using the Mathcad sphere for solving the system of equations (1) provides the desired functions in matrix form (the values of the functions at particular moments of accident).

Average activity concentration of the radionuclide in the area air A_{air} (Bq/m^3) is given by the formula

$$A_{air} = \frac{A_w}{V} H m_a, \quad (2)$$

where A_w – concentration of radionuclide in LRM, Bq/kg;

H – fraction of carried away solute with solvent vapors during evaporation.

The ultimate objective of the model is to determine the dynamics of LRM evaporation, SARM activity in the air space and the integral release of radioactive substances into the atmosphere.

Table 1
Modelling results and monitoring data.

Personnel member No	Effective dose received during response, mSv	Actual effective dose D_{eff}, mSv	Ratio k_{max}
1	6.9...43.0	20.8(+-30%)	2.07
2	9.3...57.6	24.2(+-30%)	2.38
3	11.4...71.0	30.9(+-30%)	2.30
4	12.6...78.7	36.2(+-30%)	2.17

The mass fraction of a radionuclide in the release relative to its original content in radioactive liquid is commonly used in practice:

$$q = \frac{A_w}{m_0} H m_q 100\%, \tag{3}$$

where m_0 – initial mass of LRM, kg.

This value is used as an input parameter for the assessment of doses to the public from atmospheric release.

2.3. Model testing

To confirm the effectiveness and accuracy of the modelling, a partial testing was performed at an example of real event that occurred at the Pakistani nuclear power plant in Karachi in 2017: overexposure of 4 staff members as a result of the accident. Reconstruction of irradiation doses was performed using the developed model and compared with the actual value of the dose accumulated by the liquidators during the works (table 1, figure 4).

According to the results of testing, the following is highlighted: the actual data are included in the calculated ranges of the effective dose, which is acceptable; the pessimistic estimate exceeded the actual measurement data by ~2.0-2.3 times (ratio k_{max} in table 1), which is acceptable; the development can be used as a tool for the reconstruction of exposure doses. However, further testing of the source term model are required.

2.4. Application of the model

Results of source term model can used as initial data to provide atmospheric dispersion modelling results and dose projection for the hypothetical event associated with the spill of liquid radioactive material. The example of such calculation in JRODOS system are shown in figures 5, 6.

Presented calculations were done using local scale model chain of JRODOS system. Total amount of activity released into the atmosphere (primarily ^{60}Co and ^{137}Cs) has been assumed about 2.5 GBq. Hourly resulted source term was used as input data to provide the results on near ground air concentration. Meteorological data in NetCDF format was provided as WRF results with 0.05° spatial resolution and selected from previous several years numerical weather

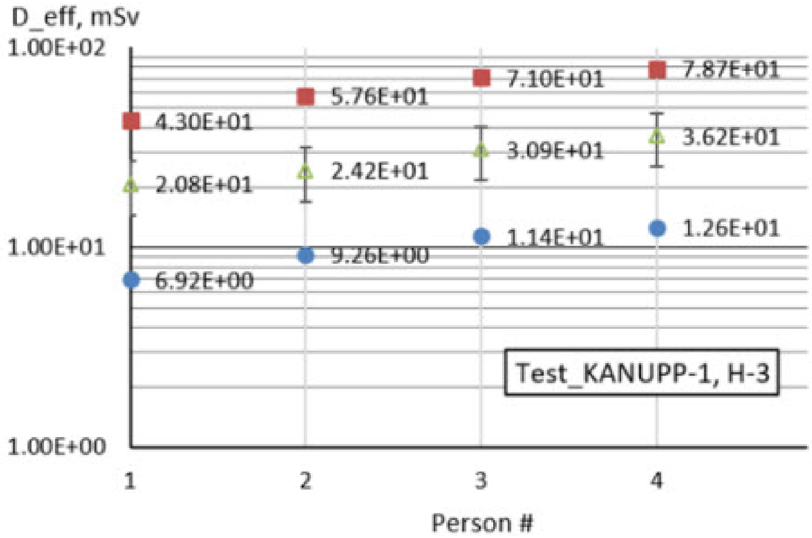

Figure 4: Modelling results and monitoring data.

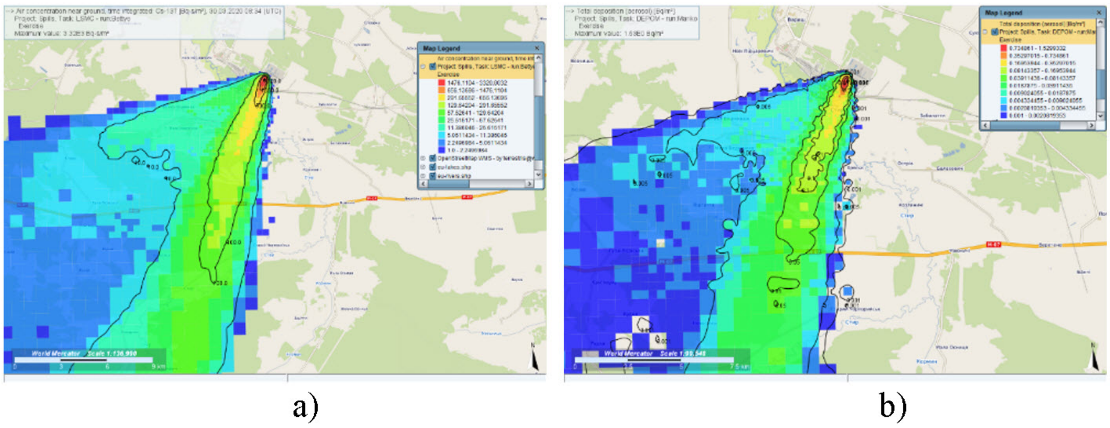

Figure 5: JRODOS atmospheric dispersion modelling results: air concentration near ground, time-integrated using LASAT model (a), total aerosol deposition using DEPOM model (b).

data. All results of radioactive material spreading as well as dose assessment were performed on the least calculation grid size 20 km.

For selected hypothetical scenario, 1-year effective doses at 2.5 km (size of sanitary protection zone around Ukrainian NPPs) do not exceed 3 μSv that is lower than established annual level for public 40 μSv. According to the results, on-site values for ^{137}Cs deposition can be around 1.5 Bq/m^2 (dry weather). Ground contamination is foremost limited by the NPP site and near range.

Practice of an application shows the source term model can serve as an useful tool to provide initial data for radiological consequence calculations. However, it depends on context of application and leave a place for further sensitivity analysis and model chains improvement.

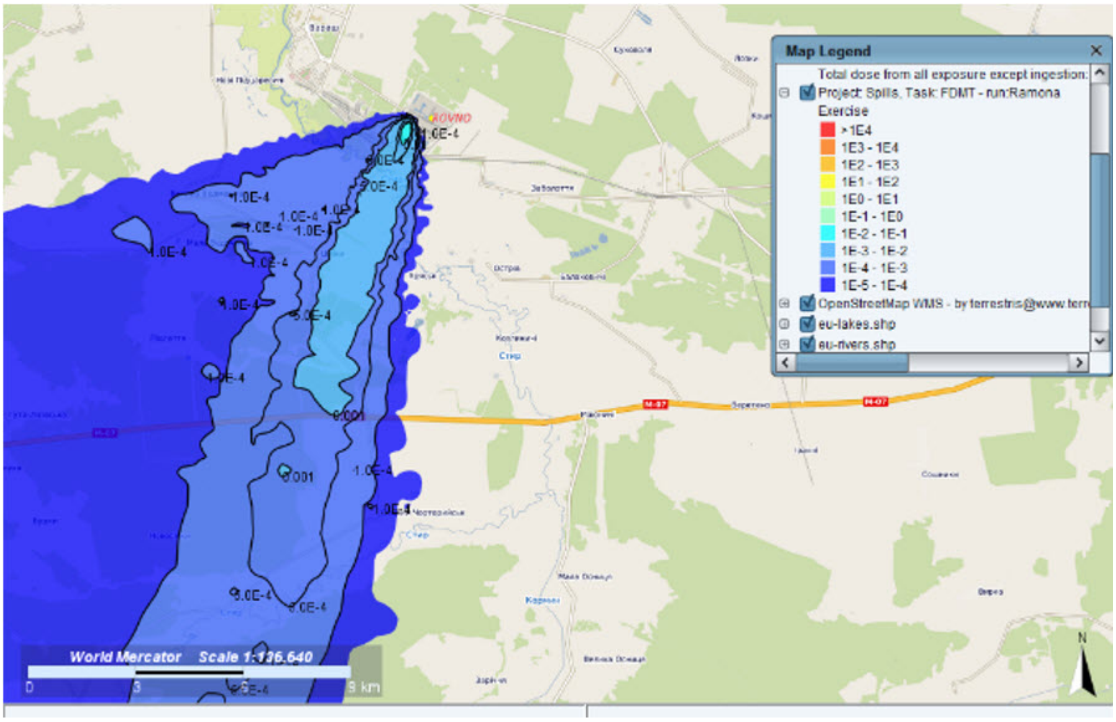

Figure 6: JRODOS dose projection results 1-year effective dose from all exposure pathways except ingestion (child).

2.5. Software for solving problems of emergency planning

In frame of FASTNET project experience of more than 20 countries was analyzed. The main output of the project is an investigation in the area of qualitative characteristic of source term – resolution in time. Taking into account spatial and temporal resolution of numerical weather predictions used in Europe countries, FASTNET group recommend the use of 15-min intervals in source term.

Practice of regular calculations demonstrates significant uncertainties in conjunction "source term – NWP-data". Under unstable meteorological condition with complex patterns of integrated concentrations, using of more than 15-min. source term intervals can lead to crusual impact on radiological consequences results.

Today JRODOS users can operate pre-estimated source terms data. Source term library filling can be specified by requirements to source term files taking into account meteorology data resolution.

Uncertainties of the source term on the prediction of atmospheric dispersion of released radioactivity involve both the amounts of radionuclides released and the temporal evolution of the release. Furthermore, the combined uncertainties of atmospheric dispersion model forecasting stemming from both the source term and the meteorological data are examined in [22].

In AVESOME project, a methodology is developed which can handle both a few-member source-term ensemble and a large ensemble spanning all possible releases. The AVESOME methodology will work well with the Rapid Source Term Prediction (RASTEP) system, which provides a set of possible source terms with associated probabilities based on pre-calculated source terms. The methods, which are being developed in AVESOME, allows for efficient real-time calculations by making use of scaling properties in the equations governing the release and the atmospheric dispersion of radionuclides. Accordingly, the computer-resource demanding calculations should be carried out at the high-performance computing (HPC) facilities available e.g. at national meteorological services, whereas less demanding post-processing should be carried out at the computer hosting the DSS.

A protocol is suggested for interactive communication between the DSS and the HPC facility enabling the requests from the DSS user for long-range atmospheric dispersion model calculations. It is based on an existing operational protocol extended with the capability of simultaneous handling of a number of source-term descriptions, including a full source-term ensemble.

Based on the results of the mathematical model with a view to further determination of radiological impact on the workers, public and the environment the environment can be used analytical methods and software tools:

- RODOS: ADM RIMPUFF with 10-min. time step + FDMT [12];
- RASCAL (INTERRAS) [11], HOTSPOT [7] ;
- ARGOS: complex terrain ADM, dose projection module (any other DSS);
- simplified gaussian models;
- sophisticated models for short range (CFD-, LES-modeling);
- NRC MACCS code (probabilistic tool) [15];
- GENII, RESRAD, PAVAN, ARCON 96, XOQDOQ (RAMP family) [13]; etc.

Worker's exposure (internal) can be assessed using analytical base and methods (NRC, ICRP, UNSCEAR [13]); dose conversion factors FGR-11/13, EPA [13]; analytic base of organization such as NRC, EPA, ICRP, and skin dose assessment in VARSKIN code; MICROSHIELD, ISOCSR to calculate dose from equipment and spill domain.

2.6. Features of future specialists training for nuclear energy industry

Experience of nuclear power units operating, the Chernobyl disaster, the tragic events at the Fukushima-1 nuclear power plant indicated the need to pay attention to safety issues and adhere to the principles of its culture at nuclear facilities. This can be achieved only with personnel qualitative training for nuclear energy industry. Currently in Ukraine there are 9 institutions of higher education that educate specialists for work in nuclear energy sector: National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Lviv Polytechnic National University, National Technical University "Kharkiv Polytechnic Institute", Odessa National Polytechnic University, Taras Shevchenko National University of Kyiv, Vinnytsia National Technical University, National University of Water and Environmental Engineering, Ukrainian State University of Chemical Technology, Kyiv Energy College. RNPP Vocational School also prepares specialists for work at nuclear power plants [35].

The Standard of Higher Education of Ukraine in the specialty 143 “Nuclear energy” [36] of bachelor’s level was developed taking into account the needs of vocational education (approved and put into effect by the Order of the Ministry of Education and Science of Ukraine No. 964 of July 10, 2019). Also the National Technical University of Ukraine “Igor Sikorsky Kyiv Polytechnic Institute” for the first time recruited for the master’s program “Physical Protection, Accounting and Control of Nuclear Materials” in the specialty 143 “Nuclear energy” in 2019. Term of study for Master degree is 1 year 6 months. Educational and professional training program meets requirements of current national legislation and recommendations of the International Atomic Energy Agency.

Students of specialty 143 “Nuclear Energy” have an opportunity to learn not only basics of nuclear and information safety and design of physical protection systems. They are also able to assess vulnerabilities and identify threats, develop regulations, prevent measures, manage emergencies and crisis situations. Training is conducted by highly professional teaching staff, including practitioners, specialists who completed internships at the University of Texas at Austin, Sandia National Laboratories and participated in training courses at the International Atomic Energy Agency. Also, students learn to operate nuclear power plants. They are engaged in of neutron-physical modeling and thermohydraulic processes in NPP equipment. The students solve problems of reliability and safety of NPPs. The graduates have exclusive right to obtain a license to operate nuclear power plants. They can hold positions from NPP engineer to CEO or work in other industry enterprises [35]. In February 2021, the first graduation of masters in the specialty 143 “Nuclear Energy” took place. Of course, specialists at various specialties and fields of knowledge (technical, chemical, ecological, biological, engineering) are required for work at NPPs.

The Standard of higher education for the master’s level of knowledge 18 “Production and technology” in the specialty 183 “Environmental technologies” determined that the main purpose of training is: formation of professional competencies necessary for innovative research and production activities for development and implementation of modern technologies for environmental protection.

The publication authors analyzed the Standard of Higher Education for specialty 183 “Environmental Protection Technologies” [37] and identified number of competencies of future professionals to use specialized software for solution of emergency prevention problems during spills of radioactive liquids. Also, the Standard of Higher Education for the master’s level in the field of knowledge 12 “Information Technology”, specialty 122 “Computer science” [38] was analyzed. Number of future professionals competencies to develop, maintain and improve specialized software for solving problems of emergency prevention in case of spills of radioactive liquids, they include (special (professional) competencies) were defined:

- specialty 183 “Environmental protection technologies”
  - K04. Ability to use modern computer and communication technologies during collection, storage, processing, analysis and transmission of information about the state of environment and industrial sphere;
  - K08. Ability to ensure environmental safety and sustainable development of society;
  - K09. Ability to use scientifically grounded methods in processing of research results in the field of environmental protection technologies;

K11. Ability to create physical and mathematical models of processes occurring in man-made pollution;
K14. Ability to assess impact of industrial facilities, their emissions and discharges on the environment;
K16. Ability to monitor state of environmental safety and assess degree of air pollution and industrial emissions into the atmosphere, water and water bodies, soils and land resources;
K19. Ability to design systems and technologies for environmental protection and ensure their functioning.

- specialty 122 “Computer science”

CK5. Ability to use mathematical methods for analysis of formalized models of subject area of particular project of its implementation and maintenance process;
CK9. Ability to develop software: understand and apply logic basics to solve problems; be able to design, execute and debug programs using modern integrated software (visual) development environments; understand programming methodologies, including object-oriented, structured, procedural and functional programming; compare currently available programming languages, software development methodologies and development environments, as well as select and use those that correspond to particular project; be able to evaluate code for reuse or inclusion in an existing library; be able to assess the configuration and impact on settings in terms of working with third-party software packages;
CK11. Ability to develop and administer databases and knowledge, possess modern theories and models of data and knowledge, methods of their interactive and automated development, processing and visualization technologies;
CK12. Ability to assess quality of IT projects, computer and software systems for various purposes, to possess methodologies, methods and technologies to ensure and improve quality of IT projects, computer and software systems based on international standards for quality assessment of information systems software, maturity assessment models information and software systems development processes;
CK13. Ability to initiate and plan computer systems and software development processes, including its development, analysis, testing, system integration, implementation and maintenance;
CK14. Ability to identify problem situations during the software operation and formulate tasks for its modification or reengineering.

Quality improving of education is one of the most important issues in development of any society. The modern world is evolving and changing rapidly, information technologies are being updated and improved. Therefore the domestic higher education system does not have time to adapt curricula and plans to requirements of the market and society. This problem is relevant in the field of training specialists in the following specialties: 183 “Environmental protection technologies”, 103 “Earth sciences”, 122 “Computer science” [18] and in the new specialty 143 “Nuclear energy". Therefore, we believe that it is important to add topics for development of mathematical and a software solution for emergency prevention in case of LRM spills in training of future professionals in the outlined specialties.

The choice of used software in educational process should be based on the need to form professional skills in students and graduate students. Also it is necessary to develop systematic thinking, the ability to select optimal tool for solving particular application problem [18]. It will greatly enrich their experience and allow them to understand specifics of LRM spills events simulating. It is important in preventing emergencies.

The following measures should be taken to increase effectiveness of specialists training for nuclear energy sector on issues of risk reduction during LRM spill incidents elimination:

- supplementing curricula of training students and graduate students to ensure acquisition of competencies to reduce risks during elimination of incidents with LRM spills;
- to introduce study of issues: on development of mathematical models and software for solving problems of emergency prevention during LRM spills;
- use of specialized software for solving problems of emergency prevention during LRM spills;
- to expand topics of bachelor's, master's, dissertation works of students and scientific degrees with problems on various aspects of the development of mathematical models and software tools for solving problems of emergency prevention in case of LRM spills.

3. Conclusions

1. It is determined that the main criteria for the assessment of accidents at radiation-hazardous facilities associated with the spill of radioactive liquids are: possible sources of release, the range of chemical and isotopic composition of the radioactive liquid; temperatures of radioactive liquids involved in heat and mass transfer processes; features of drainage, filtering and localizing; potential scale and degree of radioactive contamination; critical pathway and critical exposure group; characteristic conditions of on-site as well as off-site spreading of radioactive substances.
2. Existing mathematical models of the distribution of radionuclides in the air as a result of emissions cannot be used to solve the problem of estimating the radiation impact in accidents with spills of radioactive liquids due to some set of disadvantages. The authors of the publication developed a model that takes into account the physical features of radioactive fluid leakage from the source, air pollution during the transition of radioactive liquid from the spill surface into the air and their subsequent dispersion in the emergency room under the influence of local air currents (caused by ventilation).
3. A mathematical model of radioactive substances transport in emergency areas has been developed, which, unlike other models, takes into account the parameters of radioactive liquids composition and design conditions of their storage.
4. Features of the software of the decision of problems of the prevention of emergencies at flood of radioactive liquids are analyzed. It is determined that the existing software tools for radiation exposure assessment do not comprehensively cover the features of such events and have a number of shortcomings (do not take into account the process

of radioactive decay; inadequacy of the results and high uncertainties; do not allow to obtain most of the dynamic parameters required for a comprehensive analysis of radiation exposure, lack of models describing the transport of multicomponent radioactive air mixtures) for modelling the course of accidents with spillage of radioactive liquids indoors.

5. The publication provides examples of computer simulation of atmospheric dispersion and dose projection for a hypothetical event involving the spillage of liquid radioactive material in the JRODOS system.
6. Process of future specialists training in the specialties: "Environmental protection technologies", "Nuclear energy", "Earth sciences", and "Computer science" should be based on the use of powerful scientific and methodological training base using modern advances in digital technology. Therefore, we consider it appropriate to supplement curricula for preparation of students and graduate students in the outlined specialties by studying issues of: development of mathematical models and software to solve problems of emergency prevention in case of LRM spills; features of specialized software use to solve problems of emergencies prevention during LRM spills. For this purpose, it is proposed to use mathematical model of radioactive substances transport in emergency rooms developed by the authors and the corresponding software tools for assessing radiation impact on population and environment.

References

[1] Y. Kyrylenko, I. Kameneva, O. Popov, A. Iatsyshyn, V. Artemchuk, V. Kovach, Source term modelling for event with liquid radioactive materials spill, in: V. Babak, V. Isaienko, A. Zaporozhets (Eds.), Systems, Decision and Control in Energy I, Springer International Publishing, Cham, 2020, pp. 261–279. doi:10.1007/978-3-030-48583-2_17.

[2] C. Chauliac, J.-M. Aragonés, D. Bestion, D. G. Cacuci, N. Crouzet, F.-P. Weiss, M. A. Zimmermann, NURESIM – A European simulation platform for nuclear reactor safety: Multi-scale and multi-physics calculations, sensitivity and uncertainty analysis, Nuclear Engineering and Design 241 (2011) 3416–3426. doi:10.1016/j.nucengdes.2010.09.040.

[3] M. Dowdall, J. E. Dyve, S. C. Hoe, A. M. B. Buhr, A. Hosseini, J. Brown, G. Jónsson, P. Lindahl, H. Guðmundsson, S. Barsotti, S.-B. S, Nordic Nuclear Accident Consequence. Analysis (NORCON): Final Report, Technical Report NKS-353, Nordic Nuclear Safety Research, Roskilde, Denmark, 2015. URL: http://ep3.nuwm.edu.ua/12869/1/05-04-84%20..pdf.

[4] O. Popov, A. Iatsyshyn, D. Sokolov, M. Dement, I. Neklonskyi, A. Yelizarov, Application of virtual and augmented reality at nuclear power plants, in: A. Zaporozhets, V. Artemchuk (Eds.), Systems, Decision and Control in Energy II, Springer International Publishing, Cham, 2021, pp. 243–260. doi:10.1007/978-3-030-69189-9_14.

[5] Y. Wu, Development and application of virtual nuclear power plant in digital society environment, International Journal of Energy Research 43 (2019) 1521–1533. doi:10.1002/er.4378.

[6] Y. Kyrylenko, I. Kameneva, O. Popov, A. Iatsyshyn, V. Artemchuk, V. Kovach, Actual issues on radiological assessment for events with liquid radioactive materials spills, in:

A. Zaporozhets (Ed.), Systems, Decision and Control in Energy III, Springer International Publishing, Cham, 2022, pp. 139–156. doi:10.1007/978-3-030-87675-3_8.
[7] S. G. Homann, F. Aluzzi, HotSpot Health Physics Codes Version 3.0 User's Guide, National Atmospheric Release Advisory Center, Lawrence Livermore National Laboratory, Livermore, CA 94550, 2014.
[8] A. E. Kiv, O. V. Merzlykin, Y. O. Modlo, P. P. Nechypurenko, I. Y. Topolova, The overview of software for computer simulations in profile physics learning, CEUR Workshop Proceedings 2433 (2019) 352–362.
[9] I. G. Kotsyuba, A. V. Ilchenko, Vikoristannia programnogo zabezpechennia z metoiu optimizatsii sistemi povodzhennia z tverdimi pobutovimi vidkhodami mista Zhitomira (Use of software to optimize the management of solid household waste in the city of Zhytomyr), Ekologichna bezpeka 1 (2011) 13–16. URL: http://www.kdu.edu.ua/EKB_jurnal/2011_1(11)/13.pdf.
[10] D. B. Lawson, IT/Science: Computer Modeling, Geographic Information Systems (GIS), Probes/Sensors, in: M. Duran, M. Höft, B. Medjahed, D. B. Lawson, E. A. Orady (Eds.), STEM Learning: IT Integration and Collaborative Strategies, Springer International Publishing, Cham, 2016, pp. 35–66. doi:10.1007/978-3-319-26179-9_3.
[11] U.S. Nuclear Regulatory Commission, RASCAL 4.3 User's Guide, 2013. URL: https://www.nrc.gov/docs/ML1328/ML13281A701.pdf.
[12] W. Raskob, C. Landman, D. Trybushnyi, Functions of decision support systems (JRodos as an example): overview and new features and products, Radioprotection 51 (2016) S9–S11. doi:10.1051/radiopro/2016015.
[13] Sandia National Laboratories, 2021. URL: https://www.sandia.gov.
[14] M. Stojanović, V. Marković, Z. Kričković, R. Banković, Potential usage of GIS in education, in: Sinteza 2018 - International Scientific Conference on Information Technology and Data Related Research, 2018, pp. 255–260. doi:10.15308/Sinteza-2018-255-260.
[15] K. McFadden, N. Bixle, L. Eubanks, R. Haaker, WinMACCS, a MACCS2 Interface for Calculating Health and Economic Consequences from Accidental Release of Radioactive Materials into the Atmosphere MACCS User's Guide, U.S. Nuclear Regulatory Commission, 2007. URL: https://www.nrc.gov/docs/ML0723/ML072350221.pdf.
[16] Y. Zabulonov, V. Burtnyak, L. Odukalets, E. Alekseeva, S. Petrov, Plasmachemical plant for NPP drain water treatment, Science and Innovation 14 (2018) 86–94. doi:10.15407/scine14.06.086.
[17] Y. Zabulonov, O. Popov, V. Burtniak, A. Iatsyshyn, V. Kovach, A. Iatsyshyn, Innovative developments to solve major aspects of environmental and radiation safety of ukraine, in: A. Zaporozhets, V. Artemchuk (Eds.), Systems, Decision and Control in Energy II, Springer International Publishing, Cham, 2021, pp. 273–292. doi:10.1007/978-3-030-69189-9_16.
[18] A. Iatsyshyn, A. Iatsyshyn, V. Kovach, I. Zinovieva, V. Artemchuk, O. Popov, O. Cholyshkina, O. Radchenko, O. Radchenko, A. Turevych, Application of open and specialized geoinformation systems for computer modelling studying by students and PhD students, CEUR Workshop Proceedings 2732 (2020) 893–908. URL: http://ceur-ws.org/Vol-2732/20200893.pdf.
[19] The State Scientific and Technical Center for Nuclear and Radiation Safety, Information reports on violations in the operation of npps during 2020, 2020. URL: https://sstc.ua/

informacijni-povidomlennya-pro-porushennya-v-roboti-aes-protyagom-2020-roku.
[20] Y. Kyrylenko, I. Kameneva, O. Popov, A. Iatsyshyn, I. Matvieieva, V. Bliznyuk, N. Molitor, Source term model of radioactive liquid spills for actual decision support systems, E3S Web of Conferences 280 (2021) 09001. doi:10.1051/e3sconf/202128009001.
[21] International Atomic Energy Agency, The information channel on nuclear and radiological events, 2021. URL: https://www-news.iaea.org/EventList.aspx.
[22] I. M. Bialik, A. E. Yanchuk, Metodychni vkazivky do laboratornykh robit z navchalnoyi dystsypliny "GIS i bazy danykh" (Methodical instructions for laboratory work on the discipline "GIS and databases"), volume 1, The National University of Water and Environmental Engineering, Rinve, 2018. URL: http://ep3.nuwm.edu.ua/12869/1/05-04-84%20..pdf.
[23] H. Chemerys, V. Osadchyi, K. Osadcha, V. Kruhlyk, Increase of the level of graphic competence future bachelor in computer sciences in the process of studying 3D modeling, CEUR Workshop Proceedings 2393 (2019) 17–28.
[24] L. Datsenko, Expansion of geographic information components in the educational programs of cartographers at Taras Shevchenko National University of Kyiv, Problems of Continuous Geographic Education and Cartography (1) 20–23. URL: https://periodicals.karazin.ua/pbgok/article/view/9080.
[25] D. V. Dyadin, O. V. Khandohina, Konspekt lektsiy z navchalnoyi dystsypliny "Geoprostorovyy analiz ekolohichnoyi bezpeky" (dlya studentiv dennoyi form navchannya spetsialnosti 183 – Tekhnolohiyi zakhystu navkolyshn'oho seredovyshcha) (Lecture notes on the subject "Geospatial analysis of ecological safety" (for students of full-time specialty education 183 - Environmental technologies)), O. M. Beketov National University of Urban Economy in Kharkiv, Kharkiv, 2017.
[26] O. M. Hlushak, V. V. Proshkin, O. S. Lytvyn, Using the e-learning course "Analytic Geometry" in the process of training students majoring in Computer Science and Information Technology, CEUR Workshop Proceedings 2433 (2019) 472–485.
[27] O. Klochko, V. Fedorets, An empirical comparison of machine learning clustering methods in the study of Internet addiction among students majoring in Computer Sciences, CEUR Workshop Proceedings 2546 (2019) 58–75.
[28] V. Morkun, S. Semerikov, S. Hryshchenko, K. Slovak, Environmental geo-information technologies as a tool of pre-service mining engineer's training for sustainable development of mining industry, CEUR Workshop Proceedings 1844 (2017) 303–310. URL: http://ceur-ws.org/Vol-1844/10000303.pdf.
[29] S. L. Proskura, S. H. Lytvynova, The approaches to web-based education of computer science bachelors in higher education institutions, CEUR Workshop Proceedings 2643 (2020) 609–625. URL: http://ceur-ws.org/Vol-2643/paper36.pdf.
[30] V. M. Storozhuk, O. B. Ferents, Z. P. Kopynets, Problemy systemy pidhotovky inzhenerno-tekhnichnykh pratsivnykiv z pytan bezpechnosti promyslovykh pidpryyemstv (Problems of the system of training of engineering and technical workers on safety of industrial enterprises, in: Kompleksne zabezpechennya yakosti tekhnolohichnykh protsesiv ta system (KZYATPS - 2018), 2018, pp. 113–115. URL: http://ir.stu.cn.ua/handle/123456789/21495.
[31] V. M. Storozhuk, O. V. Melnykov, V. M. Hvozdyk, Neobkhidnist pokrashchennya pidhotovky maybutnikh inzhenerno-tekhnichnykh pratsivnykiv z pytan bezpechnosti

promyslovykh pidpryyemstv (Need of improvement training future technical officers in questions of safety of industrial enterprises), Technology and Technique of Typography 3 (2015) 115–124. URL: http://ttdruk.vpi.kpi.ua/article/view/54892. doi:10.20535/2077-7264.3(49).2015.54892.

[32] S. V. Symonenko, N. V. Zaitseva, M. S. Vynogradova, V. V. Osadchyi, A. V. Sushchenko, Application of ICT tools in teaching american english for computer science students in the context of global challenges, Journal of Physics: Conference Series 1840 (2021) 012048. doi:10.1088/1742-6596/1840/1/012048.

[33] INES The International Nuclear and Radiological Event Scale. User's Manual 2008 Edition, International Atomic Energy Agency, Vienna, 2008.

[34] A. Ozharovsky, Accidents and incidents. Comment: A shut-down Ignalina NPP: No RIP for Lithuania's cranky nuclear corpse, 2010. URL: https://bellona.org/news/nuclear-issues/accidents-and-incidents/2010-11-comment-a-shut-down-ignalina-npp-no-rip-for-lithuanias-cranky-nuclear-corpse.

[35] The State Scientific and Technical Center for Nuclear and Radiation Safety, Personnel Training and Professional Development: Driving Force of Future Nuclear Power, 2020. URL: https://sstc.ua/news/pidgotovka-kadriv-ta-pidvishennya-kvalifikaciyi-rushijna-sila-majbutnogo-atomnoyi-energetiki.

[36] Ministry of Education and Science of Ukraine, Standart vyshchoyi osvity bakalavra za spetsial'nistyu 143 Atomna enerhetyka haluzi znan' 14 Elektrychna inzheneriya (Standard of higher education bachelor's degree in specialty 143 Atomic energy in the field of knowledge 14 Electrical engineering, 2019. URL: https://mon.gov.ua/storage/app/media/vishcha-osvita/zatverdzeni%20standarty/2019/07/12/143-atomna-energetika-bakalavr.pdf.

[37] Ministry of Education and Science of Ukraine, Standart vyshchoyi osvity Ukrayiny: pershyy (bakalavrs'kyy) riven', haluz' znan' 18 – Vyrobnytstvo ta tekhnolohiyi, spetsial'nist' 183 – Tekhnolohiyi zakhystu navkolyshn'oho seredovyshcha (Standard of higher education of Ukraine: first (bachelor's) level, field of knowledge 18 – Production and technologies, specialty 183 - Environmental technologies, 2018. URL: https://mon.gov.ua/storage/app/media/vishcha-osvita/zatverdzeni%20standarty/12/21/183-tekhnologiya-zakhistu-navkolishnogo-seredovishcha-bakalavr.pdf.

[38] Ministry of Education and Science of Ukraine, Standart vyshchoyi osvity Ukrayiny druhoho rivnya (stupin' mahistra) haluzi znan' 12 za spetsial'nistyu 122 – Kompyuterni nauky (Standard of higher education of Ukraine of the second level (master's degree) in the field of knowledge 12 in specialty 122 - Computer Science, 2020. URL: hhttps://mon.gov.ua/storage/app/media/vishcha-osvita/proekty%20standartiv%20vishcha%20osvita/2020/12/03/122-kompyuterni-nauky-mahistr.docx.