ADAM SYLWESTER JAROSZEK

APPLICATION OF THE DECISION SUPPORT SYSTEM RODOS IN THE EVENT OF NUCLEAR REACTOR ACCIDENT WITH SCENARIO OF RELEASE OF RADIOACTIVE ISOTOPES TO THE ATMOSPHERE

ABSTRACT *Decision support systems are increasingly popular due to the fast delivery of information about development of the situation during the nuclear accidents. The information provided by decision support systems facilitate proper selection of necessary protective actions and correct allocation of services involved in the activities.*
The RODOS system is designed for forecasting the dispersion of radioactive isotopes in the atmosphere. It can be used in case of real radiological nuclear emergency as well as for emergency preparedness purpose.

Keywords: *nuclear safety, decision support systems, dispersion models, isotopes, emergency, radiological events, CBRN*

1. INTRODUCTION

A number of advanced security features and restrictive regulations for nuclear reactors effectively prevent severe accident resulting an contaminations and radiological effects in population. The probability of the severe accident is very small (1E-7 events per reactor year for the new III generation reactors), however Fukushima Daiichi nuclear disaster convinced the operators about need for Decision Support Systems (DSS) systems. Nowadays DSS are used as a basic tool to calculate potential radiological impact and help to decisions about appropriate measures. DSS are based on mathematical radionuclides dispersion model in the atmospheric air and modules for estimating doses resulting ionizing radiation. DSS can calculate real time can calculate real time diagnoses or prognosis of the radiological situation during or after

Adam Sylwester JAROSZEK, M. Sc.
jaroszek@poczta.paa.gov.pl

National Atomic Energy Agency (PAA), Bonifraterska 17, 00-203 Warsaw (Poland)

a release from Nuclear Power Plant (NPP). In cases of the real threat caused by a nuclear accident, fast estimation of the radioactive cloud trace and potential dose for the public is essential in the crisis management. In the engineering practice it is common to use DSS for calculations in design and operation phases of the facility, for example to determine radius of the limited use area or calculations of the environmental impact during normal operation (limited noble gases emissions from the containment stack).

2. DECISION SUPPORT SYSTEM RODOS

The RODOS (Real-time On-line DecisiOn Support) system has been developed within a number of EU projects coordinated by Karlsruhe Institute of Technology (KIT). System is designed to calculate transport of radionuclides in the atmospheric air and estimate potential contaminations and doses for humans in affected areas. System provides comprehensive support in decision process for operators of nuclear facilities and people responsible for emergency management. The system is “On-line” and “Real-time” because it can support decision making based on real time meteorological and radiological data. The article is focused on the application of the RODOS system to early stages of nuclear accident. The system, however, can be used for all the phases:

- very early stage: before the release (for example to plan evacuation before the release);
- early stage: during and shortly after release for early protective actions based on early countermeasure criteria;
- mid-term stage: mostly to decide whether to introduce food countermeasures;
- late and very stage: mostly to undertake decision concerning contamination areas and contaminated food.

In Poland the system is maintained and ready for use by PAA (National Atomic Energy Agency). Two fundamental elements in the system are: mathematical dispersion model based on three dimensional weather fields and dose calculations including also the ones based on the activity of foodstuff and feedstuff. There are four dispersion models implemented in the system intended for simulations in various conditions:

- RIMPUFF – local scale puff diffusion model– basic principle of the model is an assumption that the distribution of contamination concentration along the wind axis is normal distribution. Model release a series of the time-integrated “puffs” in the computational domain for simulation: advection, diffusion and deposition. Probability density of the normal distribution is represent by sigma parameter. This parameter depends on atmospheric stability and wind speed. The range of the model is 800 km (for 5 km resolution grid). Formula for the calculation of the concentration [Bq/m^3] in the computational domain point is given by:

$$C = \frac{M_z}{2\pi\sigma_y\sigma_z\vartheta}\exp\left(\frac{y^2}{2\sigma_z^2}\right)\left\{\exp-\left[\frac{(z-H)^2}{2\sigma_z^2}\right]+\exp-\left[\frac{(z+H)^2}{2\sigma_z^2}\right]\right\} \tag{1}$$

where: C – concentration $\left[\frac{Bq}{m^3}\right]$, z i H – release heigh parameters, σ – puff diffusion parameter in horizontal and vertical directions.

- DIPCOT – (DIsPersion Over Complex Terrain) – is Lagrangian puff particle model which is designed to simulate dispersion over complex terrain in homogenous and inhomogeneous conditions. Shape and concentration distribution of radioactive cloud is determined from certain number of fictious particles displaced in computational domain. For turbulent diffusion simulation model uses a random component added to account for turbulent diffusion. Trajectory of the single particle is given by the equation:

$$x_i^{n+1} = x_i^n + (\overline{u_i} + u_i')\Delta t \;) \quad (2)$$

where: x – location of the particle in domain, $\overline{u_i}$ – mean wind velocity, $u_i^{'}$ – turbulence coefficient.

- ATSTEP – Gaussian puff model for distances up to 50 km, and can calculate real-time radiological situation during release for 24 hours. In ATSTEP model puff transport is achieved by two trajectories. In inhomogeneous wind fields (over very complex terrain) two separate puffs trajectories perform shape and orientation of the plume.
- MATCH (Multi scale Atmospheric Transport and Chemistry model) – Eulerian long range model with the functionality of calculating transport above the troposphere. To reduce time of long range calculation only important nuclides are selected, namely ^{137}Cs, ^{131}I, ^{140}Ba, ^{133}Xe, ^{88}Kr.

a) b)

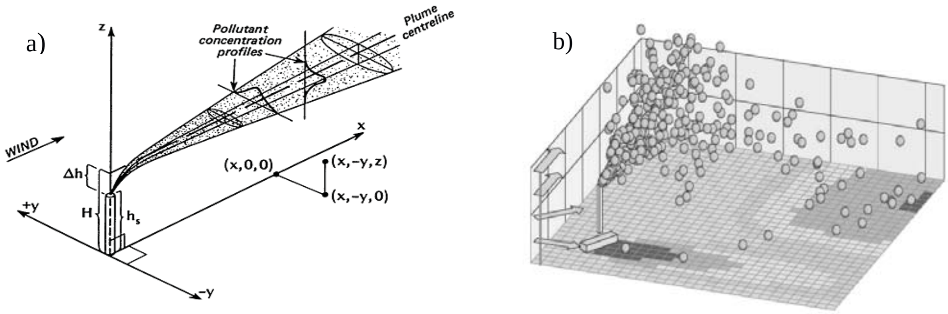

Fig. 1. Schematic representation of Gaussian plume and Lagranian particle models

- LASAT – (Lagrangian Simulation of Aerosol Transport) – three-dimensional Lagrangian particle model. The dispersion model LASAT computes the transport in the lower atmosphere (up to heights of about 2000 m) on a local and regional scale (up to distances of about 200 km). Emission sources can be defined in forms like: point, line, or area. Model simulates the dispersion and the transport of a representative certain number of particles utilizing a random component added to account for turbulent diffusion simulation (random walk process). LASAT can handle different particle sizes (to simulate transport of isotopes with different volatilities).

3. MODULES FOR CALCULATING CONTAMINATION, DOSES AND AREA OF POTECTIVE MEASURES

As a result of the release of isotopes to atmosphere the population is exposed to a certain dose of radiation. The dose can be expressed as absorbed dose [Gy] which is a measure of the energy deposited in a medium (like human body). The dose that we can use to assess the exposure and possible biological effect (e.g. cancer) is effective dose [Sv]. Effective dose is a measure designed to reflect the amount of radiation determines likely to result from the exposure .Effective dose takes into account a number of factors, such as: absorbed dose [Gy], exposure time [t], type of ionizing radiation (α, β, γ, n), exposure of individual organs and tissues, sex of the exposed organism. Dose as a result of the environmental contamination can be received from the following exposure:

- External radiation:
  - air (cloud shine)
  - ground (deposition)
  - water
- Inhalation:
  - gaseous airborne radionuclides
  - dust (also as a result of the resuspension process)
- Ingestion:
  - plant food
  - meat
  - milk
  - aquatic food
  - water (ground water, surface water)
  - soil.

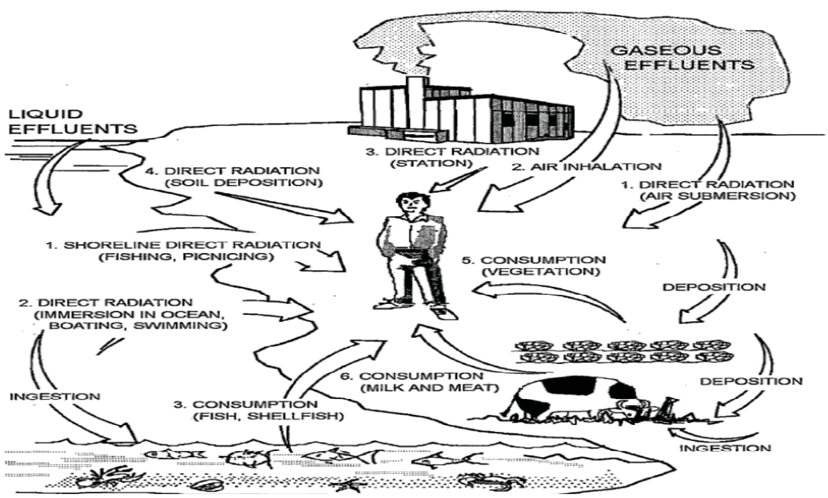

Fig. 2. Exposure pathways [2]

RODOS software for dose public assessment takes into account all of the pathways. Correctly estimated doses support decision making process in civil protection management. Early countermeasures proposed by the system are based on national levels stored in the system database.

TABLE 1
Early countermeasure levels in Poland

Actions	**Doses levels**
Evacuation	Effective dose 100 mSv/7 days
Sheltering	Effective dose 10 mSv/2 days
Distribution of stable iodine	Absorbed dose thyroid organ 100 mGy

There are several packages of modules implemented in the RODOS system (Fig. 4 presents overall structure of the RODOS system) for estimating doses for population and helping decision about taking appropriate actions in affected areas:

- **DepoM** – module for calculation deposition of the radionuclides. Module calculates wet deposition (resulting from precipitation) and dry deposition (resulting from sedimentation and turbulent diffusion). The results from DepoM module are used as input data for other modules,

TABLE 2
Dry deposition parameters

Isotope group	**Dry deposition parameter [m/s]**
Noble gases	0
Elementary Iodine	0.01
Organic Iodine	0.0005
Aerosols	0.001

- **FDMT** (**F**ood Chain and **D**ose **M**odule for **T**errestrial Pathways) – module for simulating the transport of the radionuclides in the food chain and for calculating doses from ingestion pathways. The model uses climatology and agrarian statistic data sets (land use, type of soil, local population diet). Statistic data base for the Polish area is implemented in the system these data is essential to get accurate results, especially for contaminations with isotopes such as Cesium and Strontium (low mobility in root systems) ,
- **EmerSim** – module for determination of potential areas affected by countermeasures (evacuation, sheltering or stable iodine distribution) and estimating potential doses for affected areas without protective actions,
- **ERMIN 2** (European Model for INhibited areas) – module for analysing strategies for remediating and returning to normal use inhabited zones that have been contaminated. Model takes into account results from deposition calculation and environmental description information. Module gives results, such as: collective doses [Sv/man], doses for workers participating in emergency actions, radioactive wastes amount, costs and efforts related to the chosen protective action.

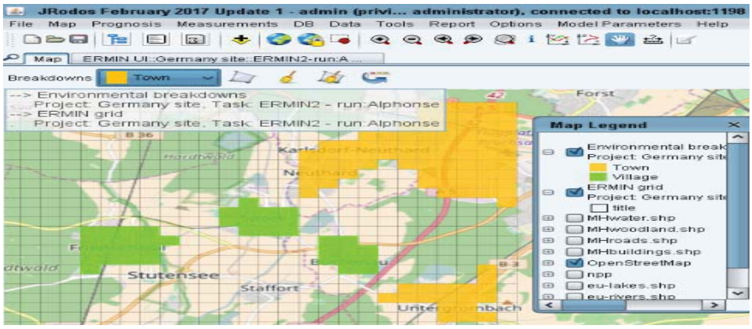

Fig. 3. Parametrisation of the area for the Ermin model
green – agricultural area, orange – urban area

- **AgriCP** (AGRIcultural Countermeasure Program) – module for the modelling the efficiency and cost of agricultural countermeasures. The model is based on data from FDMT module about radionuclide transfer in food chain, and from DepoM about ground contamination. AgriCP determines protective actions for agricultural areas.
- **Web-HIPRE** (LATE PHASE OF ACCIDENTS). Web-HIPRE is a module integrated into RODOS system for long-term strategy management in contaminated areas. Web-HIPRE is created for multi-criteria decision support and provides set of decision analytical methods to support cooperating group of decision makers. Web-HIPRE decision model takes into account result of other RODOS modules and builds decision model (attribute tree and corresponding decision table). Templates in decision model provide background information about countermeasure and remediation strategies. The module aims at increasing the confidence of decision makers in choosing the right long term strategy for contaminated areas.

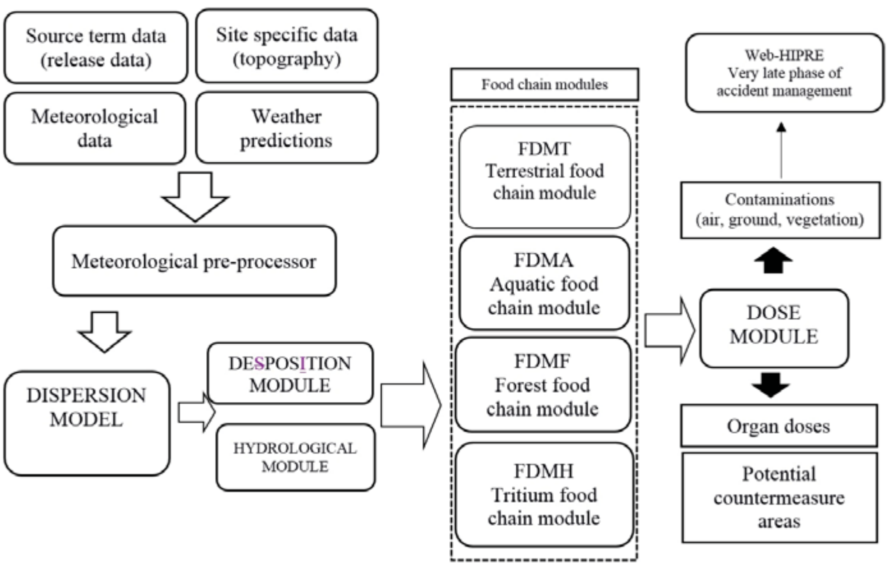

Fig. 4. Scheme of the calculation chain in RODOS system

4. THE PROCESS OF PREPARING A PROGNOSIS FOLLOWING A NUCLEAR ACCIDENT

The process of the transport of radionuclides in the atmosphere is complex. Isotopes can occur in three types of forms: gas, aerosol and particulate. All forms are characterized by different diffusion process in the atmosphere. In addition in case of severe nuclear accident with core melt, there is a release to atmosphere about 65 isotopes characterized by different chemical forms, radioactive decay and volatility. In the system user define a number of parameters that determine the process of radionuclides dispersion in the air [3]:

- Topography,
- Meteorological conditions,
- Properties of the radionuclides,

In the first step in creating prognosis the user is obligated to enter geographical coordinates of the release point or choose reactor from a database. The second step is to define the source term parameters:

- Time of release [h],
- Types of isotopes,
- Activity of the isotopes or various groups of isotopes [Bq],
- Heat flux of the release [kW].

The software has an expanded database with types of reactors and radioisotope inventories. Defining source term of the release is very sensitive step because it directly affects the accuracy of the final results. Therefore quality of the source term input data is particularly important. It is good practice to have support from nuclear operator on providing the most accurate data and use data from radiological monitoring – in this respect it should be mentioned that the RODOS system enables real-time data transfer in case of the emissions from the stack. In the next step user defines meteorological conditions. Meteorological data can be defined in two ways, data from Numerical Weather Predictions (NWP) and manual input from actually meteorological observations (e.g. from local meteorological station). RODOS system uses NWP data from HIRLAM (High Resolution Limited Area Model). These dates contains specific field information about: precipitation, planetary boundary layer, surface roughness, wind velocity and direction, temperature, geopotential height. NWP data is used by meteorological pre-processor (RMPP) which parametrizes the data in three and two dimensional fields for dispersion models. Pre-processor uses three dimensional field for: wind velocity, temperature and pressure and two dimensional fields for ground roughness, topography, planetary boundary layer, friction velocity, convective velocity, atmospheric stability, precipitation and Monin-Obukhov length (relation between parameters characterizing dynamic, thermal, and buoyant processes). In dispersion process the most important data is wind velocity and turbulence. The scale of turbulence is defined by stability class of atmosphere. Stability class parameter directly determines degree of the dilution of the radioactive cloud in atmosphere. The most pessimistic meteorological scenario is class stability F (strong stability) and wind velocity 1,5 m/s [4]. In this scenario dilution processes are very low therefore doses from inhalation are very high in affected areas. The final step is to choose appropriate dispersion model (Lagrangian puff or Lagrangian particulate) for a particular application depending on a number of factors, such as: weather data, how accurate the doses need to be, period the doses are to be calculated over, whether the model is to be applied to accidental or routine discharges [6].

It should be noted that uncertainty assessment in DSS is the most poorly understood part of the code. Uncertainty of the results is a sum of the errors in each modules as well as input data, in particular source term. In decision support systems, there is strong effect of the uncertainty propagation from all input data sources (Fig. 5). This phenomenon of course can significantly affect final results and decisions.

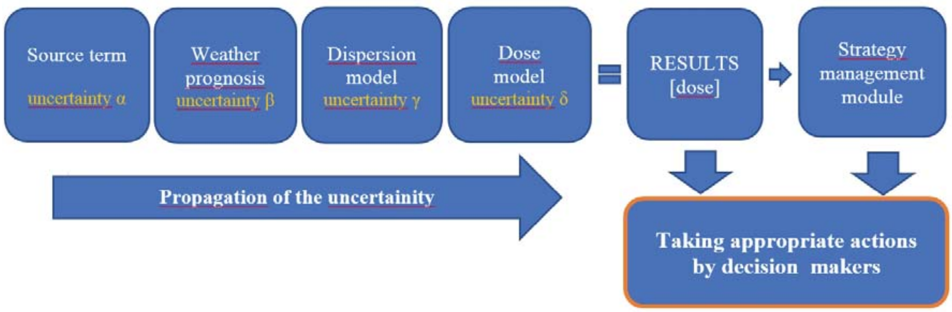

Fig. 5. Simplified scheme of the propagation of uncertainty in decision support systems [9]

Figures 6 and 7 present uncertainties resulting from the use of various input data, and models. Figure 7 shows the difference between two dispersion models (same input data) in long distance simulation over complex topography. First model is local scale puff diffusion model “RIMPUFF”, and the second model is lagrangian puff particle model “DIPCOT” (designed for simulations over complex terrain). Figure 7 presents hypothetical scenario of areas contaminated by I-131 after a nuclear accident. In cases A and B the same dispersion model was used (Rimpuff), but with numerical weather data from different providers, the results are different and cover other residential areas of the population. One of the proposed methods to solve the problem of uncertainty of the result in emergency situation is to merge together received in two cases results to get maximum possible affected area. The real monitoring data result from dispersion experiments with chemical tracers (ex. SF6) or from real accident can be used to validate system. Figure 8 [10] shows real data monitoring results (Cs-137 deposition) after Fukushima accident and prognosis from the RODOS system. Both results are consistent, the range of the contaminated area and an order of magnitude of contaminations are at an acceptable levels of uncertainty. This example presents potential ability of the RODOS system to be used as a tool for supporting decision making in real accident cases and for emergency preparedness.

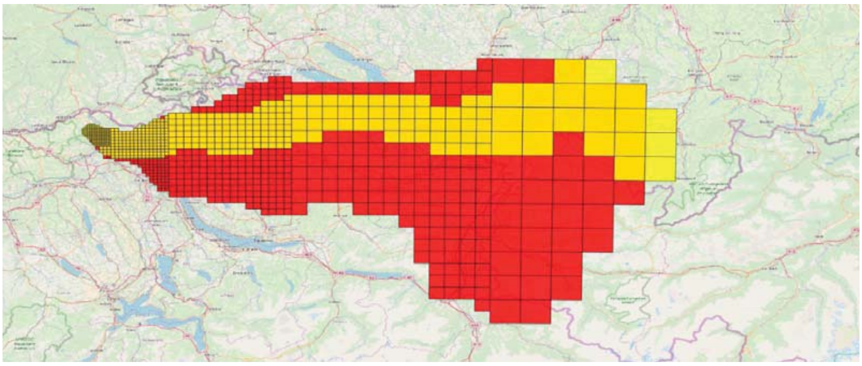

Fig. 6. Comparison of the simulation results from different RODOS dispersion models in very complex topography. Release (fictious) from a Swiss nuclear power plant Gosgen. Yellow – DIPCOT model, Red – Rimpuff model

a) b)

c)

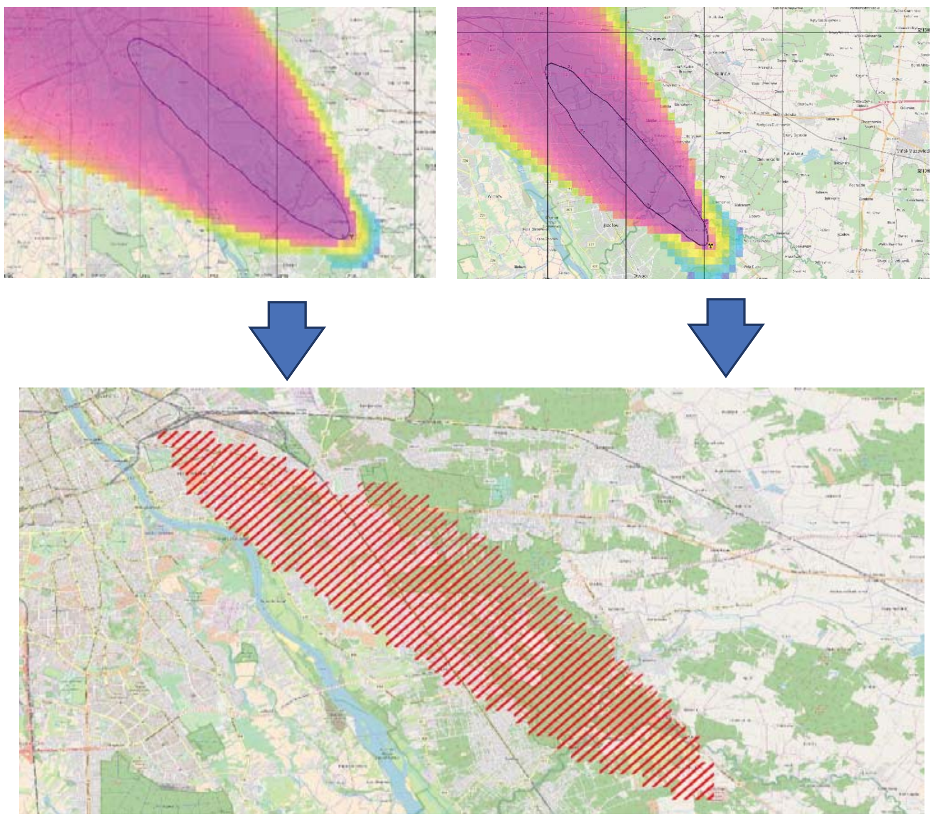

Fig. 7. Hypothetical scenario of contaminated areas with I-131 after nuclear accident (the source term is overestimated and fictitious). Cases a and b – prognosis with numerical weather data from different providers, c – maximum possible area affected by distribution of stable iodine for the public

a) b)

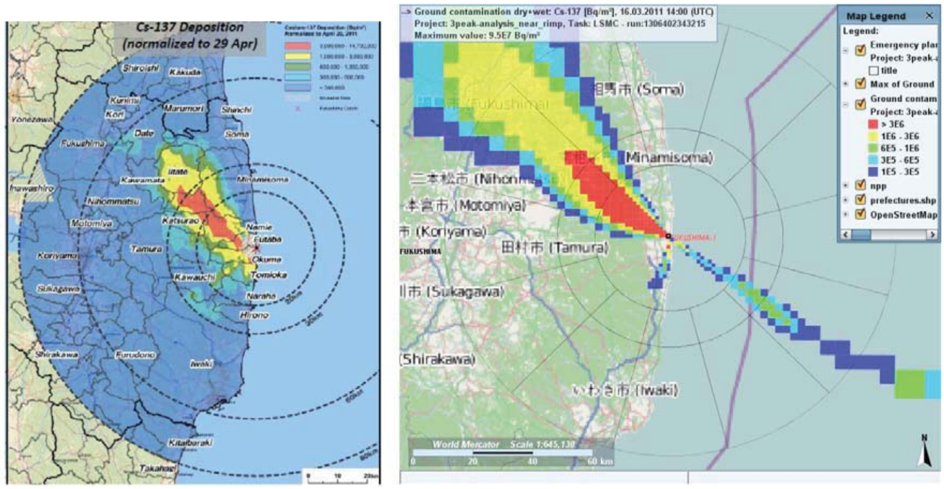

Fig. 8. Deposition of the Cs-137 isotope after Fukushima accident:
a – radiological measurment results, b – RODOS system results [10]

5. CONCLUSION

DSSs have a key role in emergency management in project, operational and decommission phases. In project phase is uses to determine emergency zones and size of area of limited use. In normal operational phase DSS is useful for radiological environmental impact assessment (from routine noble gases discharges). But they play the most essential role during severe accidents especially for design extension conditions, when operator of DSS can calculate prognosis of the evaluation of radiological situation during the release or even before (when the accidental situation is in progress). This information significantly improve emergency management and help choose appropriate measures to carry out during emergency situation.

Nowadays decision support systems can be used for a back calculations functionality for estimation of possible source of the radionuclide release, based on the result of the environmental measurements. Error size can significantly affects the selection of appropriate countermeasure actions. Therefore in emergency management following severe nuclear accident it is advisable to follow the environmental monitoring results to better assess the real situation – in this respect it should be mentioned that the RODOS system enables also usage of monitoring data once they are available.

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WYKORZYSTANIE SYSTEMU WSPOMAGANIA DECYZJI „RODOS” W PRZYPADKU AWARII REAKTORA JĄDROWEGO ZE SCENARIUSZEM UWOLNIENIENIA SUBSTANCJI PROMIENIOTWÓRCZYCH DO ATMOSFERY

ADAM SYLWESTER JAROSZEK

STRESZCZENIE *Systemy wspomagania decyzji cieszą się coraz większą popularnością ze względu na szybkie dostarczanie informacji o rozwoju sytuacji radiacyjnej po awarii jądrowej z uwolnieniem izotopów promieniotwórczych do powietrza atmosferycznego. Systemy te są wykorzystywane jako narzędzie bezpośrednio stosowane w sytuacji awaryjnej oraz jako narzędzie do przeprowadzenia przed inwestycyjnych obliczeń z zakresu planowania awaryjnego.*

Artykuł przedstawia podstawowe funkcjonalności systemu wspomagania decyzji RODOS. Program służy do przeprowadzania prognoz rozwoju zdarzeń radiacyjnych z uwolnieniem izotopów promieniotwórczych do atmosfery w wyniku awarii w elektrowniach jądrowych.

Słowa kluczowe: *bezpieczeństwo jądrowe, systemy wspomagania decyzji, izotopy promieniotwórcze, planowanie awaryjne, dyspersja zanieczyszczeń w powietrzu atmosferycznym, awarie jądrowe*