

ESTIMATION OF RADIOLOGICAL CONSEQUENCES FOR A HYPOTHETICAL RADIOACTIVE RELEASE AT CERNAVODA NPP

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Abstract. *An analysis regarding the release and atmospheric transport of radionuclides in case of a hypothetical nuclear incident at Cernavoda Nuclear Power Plant was performed in the present paper. For that purpose, the computer code JRodos (Real-Time Online Decision Support System for Offsite Emergency Management in Europe) was implied.*

Keywords: Radioactive effluents; NPP atmospheric release; Numerical weather data predictions Radionuclide modelling

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1. Introduction

The full implications of a serious radiation accident became apparent for the first time with the Chernobyl Accident in May 1986. As response, many ‘Post Chernobyl’ actions were initiated within the European Union’s research and development programmes and related activities in regulation and monitoring, inducing much research to ensure that emergency management processes become better designed to meet future challenges. Decision support systems (DSS) for emergency management after nuclear or radiological accidents or incidents are used in the specific case of a release of radioactive material. Their main task is to provide all the information required to decide on measures to protect the population quickly, continuously, consistently, and comprehensively. Users of decision-making systems are the regional, national and international institutions and organizations responsible for emergency management.

The European Realtime Online Decision Support System for nuclear emergency management (RODOS) [1] is a synthesis of many innovative methods and techniques. Forecasting modules predict how contamination would spread following atmospheric and aquatic releases of radiation. A set of models calculate the best estimate of the current and evolving radiological situation in contaminated inhabited and agricultural areas. Dose models predict the dose to

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individuals and communities for all exposure pathways not related to ingestion, both with and without the application of countermeasures. In the almost three decades that have passed since the beginning, hundreds of scientists and software engineers, emergency managers and stakeholders in many European countries were involved in the multitude of projects underpinning the engineering of the system [2]. In recent years the Java-based successor version of RODOS was issued in 2009. Named JRodos, it operates on modern information technology platforms, shows good performance and operational stability and is user friendly in operation and administration.

2. JRodos simulation models

JRodos simulation models account for atmospheric transport and deposition phenomena and the resulting terrestrial exposure pathways after an accidental release of radioactive material into the environment (Fig. 1). The released volumes of air follow the wind flow. With growing distance, the initial nuclide concentration is diluted because uncontaminated air gets mixed in and the cloud will spread until it reaches an inversion lid. The passing cloud causes external exposure by gamma irradiation and internal exposure by inhalation of radioactive air near ground. Dry and especially wet deposition processes lead to a radioactive contamination of surfaces, causing external exposure by gamma irradiation. In addition, material deposited onto natural surfaces can finally end up in the human food chain and lead to internal exposure by ingestion of contaminated food products.

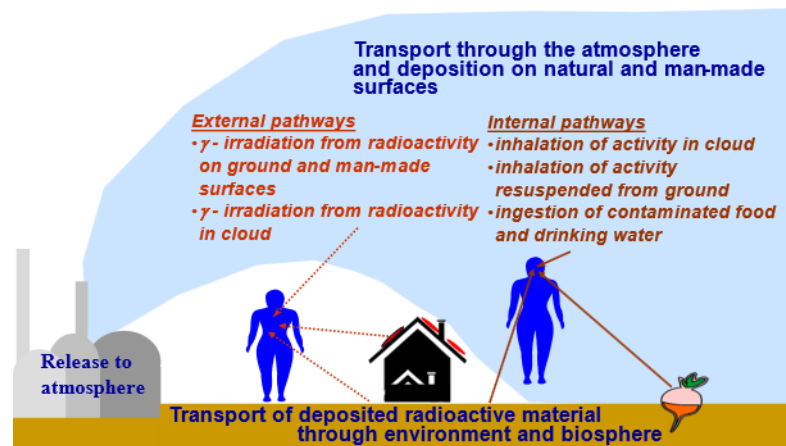


Fig. 1. Atmospheric transport, deposition phenomena and terrestrial exposure pathways.

Fig.2 illustrates the models or model chains in JRodos dealing with such effects and indicates which phases of an accident they cover. The threat phase begins with the point in time when the possibility of a relevant release is realized and

ends when the event is brought under control or with the onset of a major release in the wake of the event. The release phase ends when all significant releases have terminated and there is no more deposition of airborne material from the travelling radioactive cloud.

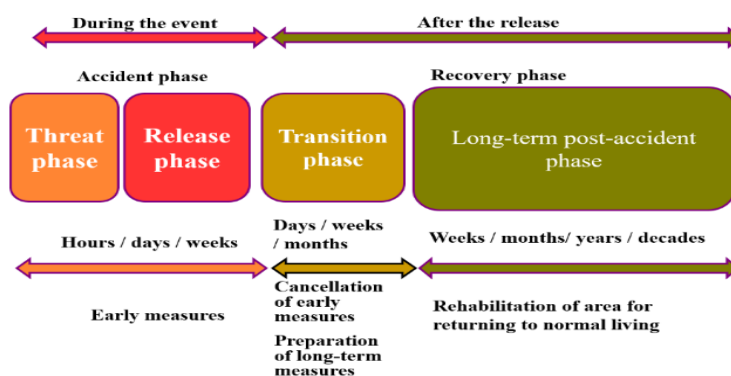


Fig. 2. JRodos models and model chains and the corresponding NPP accident phases.

JRodos contains several Atmospheric Transport and Deposition Models, some applicable on the local scale in the order of one hundred km, others to distances of some thousand kilometers. Meteorological data from national or global weather services can be used. For local scale applications, data like wind speed and direction can directly type in by hand via the user interface. (Fig. 3).

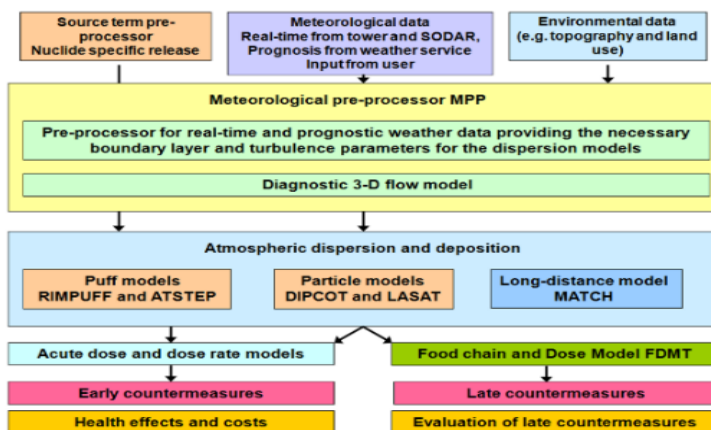


Fig. 3. Assessment of radiological situation – JRodos models.

3. Source term estimation

The environmental and safety assessment of nuclear fuel involves a detailed analysis of the pathways for radionuclides released from used fuel into atmosphere, as well as the transport of these nuclides through biosphere. These analyses provide the information required to estimate the source term for radiological dose consequences and risks to man and the environment in case of dispersion to the atmosphere [3].

The radionuclide inventories have been calculated using the radionuclide generation and depletion code ORIGEN-S for a Bruce-A reactor fuel 1 Canada Deuterium Uranium [4]. ORIGEN-S code was publicly released as part of the SCALE (Standardized Computer Analyses for Licensing Evaluation) modular code system that was developed at the Oak Ridge National Laboratory (ORNL) [5].

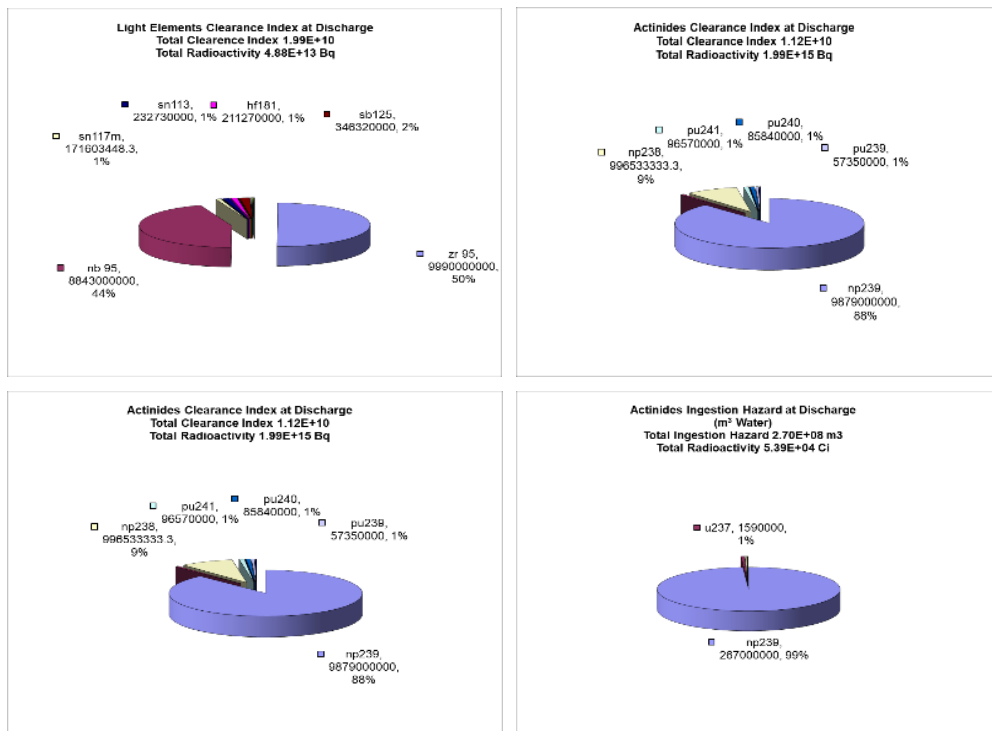


Fig. 4. CANDU inventory calculated with ORIGEN-S code at discharge from reactor.

Knowing the detailed radionuclide inventory in the used fuel at discharge from reactor, it is possible to over-conservatively estimate the source term in case of radiological emission (Table 1) [6]. In JRodos, a few nuclides are missing from the radionuclide list, because the program does not have all corresponding libraries for dose conversion factors. Moreover, the most important omission, in the special case of CANDU fuel, is the lack of H-3 (tritium) and C-14 environmental transport models latest edition of JRodos 2019 [7]. This is important issue to be addressed in future versions of the code currently under development, because of rather large of percentage they pose from the total activity.

Table 1) Calculated source term.

Nuclide	Activity [kBq]	Half-life [d]	DCF _{Fe,50} [mSv/h]/ [kBq/m ³]	DCF _{bone} [mSv/h]/ [kBq/m ³]	DCF _{lung} [mSv/h]/ [kBq/m ³]	DCF _{thyd} [mSv/h]/ [kBq/m ³]	DCF _{gi} [mSv/h]/ [kBq/m ³]	DCF _{fai} [mSv/h]/ [kBq/m ³]
Ag-110m	1.92e07	2.5e02	9.12e-03	2.30e-04	1.51e-03	0.00e00	9.29e-06	4.57e-04
Ba-137m	9.55e08	1.8e-03	0.00e00	0.00e00	0.00e00	0.00e00	2.08e-06	9.68e-05
Ba-140	6.14e10	1.3e01	6.12e-03	1.54e-04	1.18e-03	0.00e00	6.84e-07	2.91e-05
Ce-141	5.62e10	3.3e01	3.84e-03	2.21e-05	1.17e-03	0.00e00	2.49e-07	1.12e-05
Ce-144	2.09e10	2.8e02	4.32e-02	1.02e-04	8.90e-03	0.00e00	6.55e-7	1.23e-5
Cs-134	5.29e08	7.5e02	7.92e-03	2.01e-04	8.20e-04	0.00e00	5.33e-06	2.54e-04
Cs-136	6.18e08	1.3e01	1.44e-03	2.26e-04	8.10e-04	0.00e00	7.31e-06	3.58e-04
Cs-137	9.77e08	1.1e04	5.52e-03	1.20e-04	8.60e-04	0.00e00	1.98e-06	9.18e-05
Eu-154	2.33e07	3.2e03	6.36e-02	1.38e-04	2.36e-03	0.00e00	4.21e-06	2.07e-04
Eu-155	2.29e07	1.8e03	8.28e-03	2.04e-05	4.50e-04	0.00e00	1.93e-07	7.70e-06
I-129	2.86e02	5.7e09	4.32e-02	5.66e-06	1.92e-04	8.52e-01	7.02e-08	1.01e-06
I-131	3.62e10	8.0e00	8.88e-03	2.38e-05	5.66e-04	1.80e-01	1.31e-06	6.08e-05
I-132	5.22e10	9.6e-02	1.13e-04	1.68e-05	3.24e-04	1.68e-03	7.92e-06	3.78e-04
I-133	7.14e10	8.7e-01	1.80e-03	2.74e-05	8.64e-04	3.36e-02	2.22e-06	9.94e-05
Kr-85	8.25e07	3.9e03	1.98e-07	0.00e00	0.00e00	0.00e00	0.00e00	9.17e-07
La-140	6.25e10	1.7e00	1.32e-03	2.16e-04	2.60e-03	0.00e00	7.78e-06	4.00e-04
Mo-99	6.44e10	2.8e00	1.07e-03	1.24e-04	2.04e-03	0.00e00	6.41e-07	2.52e-05
Nb-95	4.96e10	3.5e01	1.80e-03	7.00e-05	5.40e-04	0.00e00	2.62e-06	1.26e-04
Pm-147	2.48e09	9.6e02	6.00e-03	9.40e-06	4.40e-04	0.00e00	1.01e-10	3.12e-08
Pr-144	2.18e10	1.2e-02	2.16e-05	0.00e00	0.00e00	0.00e00	5.87e-07	9.54e-06
Pr-144m	2.96e08	5.0e-03	0.00e00	0.00e00	0.00e00	0.00e00	3.78e-08	7.92e-07
Rb-86	1.47e07	1.9e01	1.12e-03	2.17e-04	1.88e-03	0.00e00	6.01e-07	1.78e-05
Rh-106	1.31e10	3.5e-04	0.00e00	0.00e00	0.00e00	0.00e00	1.24e-06	3.82e-05
Ru-103	5.59e10	3.9e01	2.88e-03	6.10e-05	9.10e-04	0.00e00	1.62e-06	7.49e-05
Ru-106	8.33e09	3.7e02	3.36e-02	2.39e-04	9.80e-03	0.00e00	1.24e-6	3.82e-5
Sb-124	3.85e06	6.0e01	7.68e-03	2.82e-04	3.10e-03	0.00e00	6.12e-06	3.10e-04
Sb-126	1.31e07	1.2e01	3.36e-03	0.00e00	0.00e00	0.00e00	9.79e-06	4.61e-04
Sb-127	3.59e09	3.9e00	2.04e-03	0.00e00	0.00e00	0.00e00	2.43e-06	1.12e-04
Sn-123	1.71e07	1.3e02	9.72e-03	0.00e00	0.00e00	0.00e00	2.34e-07	2.51e-06
Sr-89	3.03e10	5.1e01	7.32e-03	2.20e-04	3.92e-03	0.00e00	2.47e-07	1.57e-06

Sr- 90	6.66e08	1.1e04	4.32e-02	2.36e-04	3.30e-03	0.00e00	5.90e-09	3.54e-07
Tb-160	4.88e06	7.2e01	8.40e-03	0.00e00	0.00e00	0.00e00	3.82e-06	1.87e-04
Tc- 99m	5.70e10	2.5e-01	2.28e-05	3.62e-06	3.52e-05	0.00e00	4.10e-07	1.89e-05
Te-127	3.40e09	3.9e-01	1.56e-04	0.00e00	0.00e00	0.00e00	3.71e-08	1.20e-06
Te-127m	4.03e08	1.1e02	8.88e-03	1.32e-04	1.57e-03	0.00e00	3.08e-08	4.03e-07
Te-129	1.17e10	4.8e-02	4.44e-05	0.00e00	0.00e00	0.00e00	4.10e-07	1.03e-05
Te-129m	2.29e09	3.4e01	7.92e-03	2.72e-04	3.92e-03	0.00e00	2.05e-07	5.62e-06
Te-131	2.97e10	1.7e-02	3.36e-05	0.00e00	0.00e00	3.16e-03	1.71e-06	6.91e-05
Te-131m	8.14e09	1.3e00	1.13e-03	1.26e-04	1.64e-03	4.33e-02	4.82e-06	2.36e-04
Te-132	5.11e10	3.3e00	2.40e-03	9.90e-05	6.40e-04	3.00e-02	8.89e-06	4.21e-04
Xe-131m	3.96e08	1.2e01	0.00e00	0.00e00	0.00e00	0.00e00	0.00e00	1.33e-06
Xe-133	6.77e10	5.2e00	5.19e-07	0.00e00	0.00e00	0.00e00	0.00e00	5.00e-06
Xe-133m	2.12e09	2.2e00	0.00e00	0.00e00	0.00e00	0.00e00	0.00e00	4.58e-06
Y - 90	7.29e08	2.70e00	1.80e-03	9.30e-05	4.52e-03	0.00e00	3.96e-07	2.85e-06
Y - 91	3.89e10	5.90e01	1.07e-02	9.90e-05	4.10e-03	0.00e00	2.69e-07	2.24e-06
Zr- 95	5.33e10	6.4e01	5.76e-03	2.05e-04	1.06e-03	0.00e00	2.53e-06	1.21e-0

4. Data input and calculation results

Current JRodos world-wide usage implies that it can tackle radioactive releases anywhere on the globe. It cannot not be taken for granted that appropriate national meteorological data would be available for running JRodos. Therefore, the program offers an interface for using the freely available and globally applicable numerical weather forecast and reanalysis data from the NOMADS service of US National Centers for Environmental Prediction (NCEP) [8], allowing to download such data for a user-specified period.

For the present evaluation, a general JRodos configuration was used for global applications and NOMADS Grib2 forecast data at 0.5g resolution downloaded in advance for 24 hours from the date of April 24, 2021. In the RODOS-Lite data entry interface (Fig. 5), a series of tabs were filled in to initialize the calculation sequence.

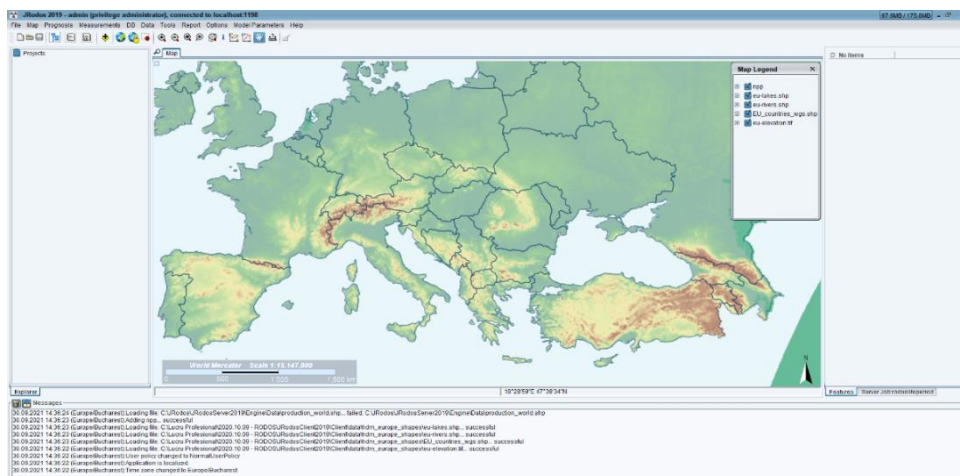


Fig. 5. JRodos Graphical User Interface, RODOS-Lite.

First a new project was created using only near-field Local Scale Model Chain (LSMC) in exercise mode for data input and calculation (Table 2).

Table 2) Protocol data input.

Run mode	interactive
Model chain	LSMC
Run id	generated
Run type	Exercise
Editing user	admin
Comment	none

In the "Site" tab, the type of event (accident in a nuclear power plant) was specified, "Romania" was selected from the list of available countries "Romania", then unit "Cernavoda-2" from the list of available reactors (Table 3).

Table 3) Site data input.

Site	CERNAVODA
Country	Romania
Coordinates (long/lat)	28.06 / 44.322
Number of used rings	5
Calculation area	
Radius	800 km
Grid Size	2000 m
Timestep	60 min

In the "Source Term" tab, JRodos also required the following information: the time interval between the end of the chain reaction and the beginning of the emission (0h), the start of the emission (date 24.04.2021, time 10:00), the activity emitted in the form of sums of activities by categories of radionuclides (iodine isotopes, noble gases and aerosols) according to Table 4, the emission height above the ground (50 m), the thermal power released in [MW], the volume of the vertical flow emitted to the atmosphere in [m³/s] and the emission ventilation surface into the atmosphere in [m²]. The last 3 parameters basically refer to the plant stack and are already predefined in JRodos. (Table 4).

Table 4) Source term data input.

Unit	CERNAVODA-1
Coordinates (long/lat)	28.06 / 44.322
Name of source term	User defined or imported/loaded run
Start of release	22.04.2021 10:00 [EEST]

Delay before start of release	0.00 h
End of chain reaction	22.04.2021 10:00 [EEST]
End of release	22.04.2021 11:00 [EEST]

In the "*Weather*" tab, the forecast range for 24 hours after the start of the broadcast was specified for a step-by-step calculation of 1 hour time, as well as the defined provider for the weather data and the selected atmospheric dispersion model (ADM) (Table 5).

Table 5) Weather data input.

Prognosis earliest start of release	22.04.2021 10:00 [EEST]
Duration	24 h
End	23.04.2021 10:00 [EEST]
Provider	nomadg2pr
Weather data timestamp	21.04.2021 06:00 [UTC]
Adapt prognosis time	Yes
Use diagnostic meteo data when possible	Yes
Use radar precipitation data when possible	Yes
Dispersion model	RIMPUFF

In the "*Run*" tab, the preset for "*Exercise*" was used. In addition, the default network type (5 rings) and the distance on which the calculations are performed (800 km) were selected (Table 2). Finally, in the "*Summary*" tab, a synopsis of the input data was displayed and the calculation sequence was initialized (*Submit*).

The forecast calculations were done automatically and successively for the atmospheric transport model (RIMPUFF) [9] in the near field (LSMC). On a quad core laptop, the duration of the calculations was about 5 minutes with these configurations.

JRodos shows the results in the form of a situation map with information grouped into several *layers* that be selected from the legend. The calculated values are displayed as a result tree in the "*Projects*" section of the interface. After installation the system contains a simple set of maps, but custom user maps from the internet can be added by user. In this case, the "*OpenStreetMaps*" maps [10] provided by the Terrestriis service was used to generate the detailed background.

JRodos contains tools for saving the map completely as an image (static or as an animated sequence for time-dependent results) and for saving individual map

layers as *shape* files. It is also possible to automatically generate results reports and access the model results from another GIS software.

In Fig. 7 the prognosticated value of the total effective gamma dose flow rate in mSv/h at the end of the 24-hour interval is shown. The results can be displayed statically in single steps of 1 hour or rendered dynamically for 24 h to study the trajectory and evolution on the map of the cloud of contaminants. It can be noted that the maximum dose obtained is $1.25E-03$ mSv/h, which is quite low given the postulated accident parameters.

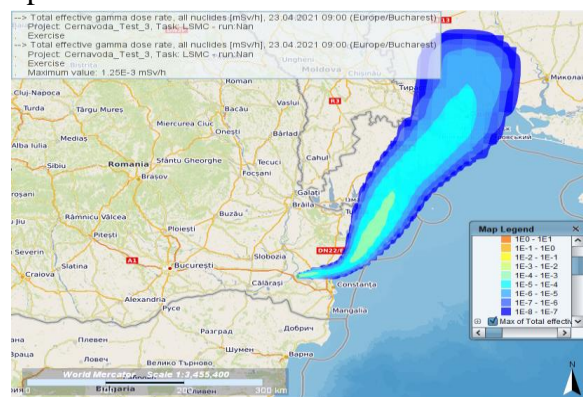


Fig. 7. Total effective gamma dose rate, 24 h after emission[mSv/h].

In Fig. 8 one can observe on the situation map the wind field at 10 m height in [m/s] (a) and the atmospheric stability category (b).

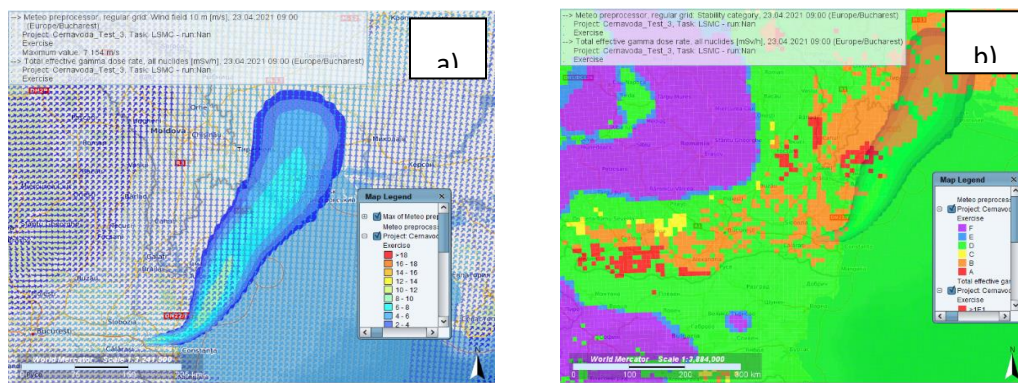


Fig. 8. Wind field at 10 m [m/s] (a) and atmospheric stability category (b).

Other results of interest are the situational map of the ground contamination for I-133 in Bq/m^3 (Fig. 9.a) and the cloud arrival time in h (Fig 9.b).

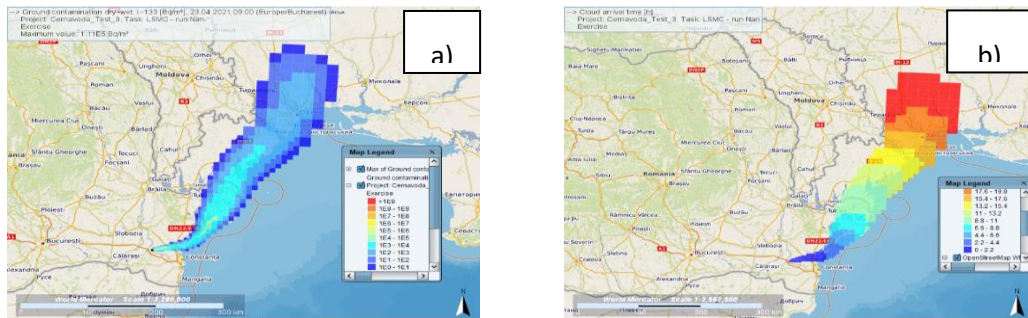


Fig. 9. Ground contamination, I-133 [Bq/m³] (a) and cloud arrival time [h] (b).

5. Conclusion

In the present paper an analysis regarding the release and atmospheric transport of nuclear material in case of a potential nuclear accident at Cernavoda CANDU Nuclear Power Plant was performed. In the case of the proposed scenario, the trajectory of the contamination cloud was determined based on numerical weather prediction data for the 24 hours after emission. The evaluation was performed as an exercise for testing the available software tools in case of real radiological emission. Using an estimated source term, useful information necessary to the authorities in charge was determined such as: total effective gamma dose, the ground contamination, and cloud arrival time. The maximum dose rate obtained was $1.25\text{E-}03$ mSv/h.

Acknowledgment

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