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DETERMINATION OF POTENTIAL AREAS OF INFLUENCE ON THE ROMANIAN TERRITORY OF UKRAINIAN NUCLEAR POWER PLANTS IN THE CONTEXT OF THE CRISIS GENERATED BY THE RUSSIAN-UKRAINIAN CONFLICT

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Abstract. *In the context of the crisis generated by the Russian-Ukrainian conflict, radiological situation forecasts were made within the National Institute of Research and Development for Physics and Nuclear Engineering "Horia Hulubei" (IFIN-HH) for all nuclear power plants in Ukraine. Therefore, the resident decision support software systems for radiological and nuclear emergencies were used, with the main purpose of identifying potential areas of influence on the territory of Romania generated by Ukrainian power plants, as consequence of military actions. In the absence of pertinent and confirmed information, two hypothetical scenarios were considered by which the radioactive material could be dispersed into the atmosphere, for which appropriate accident source terms were built, using methods validated and approved by the international organizations in the field. The monitoring of the radiological situation of the Ukrainian nuclear power plants was carried out over a period of several months starting from the first day of the conflict outbreak. In the paper are presented comparative results obtained with two software systems for a representative case at the Zaporozhe Nuclear Power Plant, the largest nuclear power plant in Europe, situated in the center of several disputes.*

Keywords: Decision-making support systems; Situation forecasts; Potential areas of radiological risk; Total effective dose equivalent (TEDE)

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1. Introduction

It cand be said that wars have a durable influence on almost every aspect of modern society and the history of conflicts is inseparable from the history of humanity. It is very difficult to understand the present-day world without first acknowledging how war has influenced the lives of people. The Russian Revolution led to communism political system, the American Civil War finished slavery, World War II changed the global power balance. From the Crusades to the Mongol Invasions, from the French Revolution to the Vietnam War and recent wars like the so-called "War Against Terrorism", conflicts have direct and powerful impacts upon our lives, they can create and dismantle empires, can destroy nations, and create new states, claim numerous lives, erase cultures, obliterate families, communities, and even entire civilizations. But war can also stimulate scientific innovation, earn oppressed people the right to freedom, and show the potential for courage, principles, and heroism in ordinary people [1]. Although it may seem easy to talk about warfare and conflicts in an academic fashion, one should always remember the many tragic and uncontrollable developments: the lives lost, the exorbitant expense, and the collateral damage inflicted upon civilians, architecture, and the environment.

One example of such resounding conflict was The Cuban Missile Crisis. It is the most significant event in the modern history of nuclear conflicts after World War 2. It was a confrontation that lasted more than one month between the United States and the Soviet Union, (16 October and 20 November 1962), which escalated into a international nuclear crisis. It debuted with Soviet Union deployments of nuclear ballistic missiles in Cuba, that were matched by United States deployments of similar missiles in Italy and Turkey. Despite the short time frame, the Cuban Missile Crisis remains a defining moment in international security and nuclear war preparation. The confrontation is often considered the closest the Cold War came to escalating into a full-scale nuclear war.[2]

Not only in conflicts, but in times of peace as well, the impact of nuclear accidents has been a topic of debate since the first nuclear reactors were constructed in 1954 and has been a key factor in public concern about nuclear facilities. Technical measures to reduce the risk of accidents or to minimize the amount of radioactivity released to the environment have been adopted, however human error, as well as mal-intentions and sabotage remain an issue.

A nuclear and radiation accident is defined by the International Atomic Energy Agency (IAEA) as "an event that has led to significant consequences to people, the environment or the facility. Examples include lethal effects to individuals, large radioactivity release to the environment, reactor core melt."[3]. The prime example of a 'major nuclear accident' is one in which a reactor core is damaged and significant amounts of radioactive isotopes are released, such as in the Chernobyl disaster in 1986 [4] [5] and Fukushima nuclear disaster in 2011 [6].

Nowadays, Ukraine is a country that relies to a large extent on nuclear power. Ukraine operates four nuclear power plants: Khmelnytskyi NPP, Rivne NPP, South Ukraine NPP, and Zaporizhzhia NPP, with a total of 15 reactors located in Volhynian and South Ukraine regions. The largest nuclear power plant in Europe is the Zaporizhzhia Nuclear Power Plant. The total installed nuclear power capacity was over 13 GWe, ranking 7th in the world in 2020. More exactly, nuclear power supplied over 20% of Ukraine's energy in 2019 [7] due to ENERGOATOM, a Ukrainian state enterprise, that operated all four active nuclear power stations in Ukraine.

In February 2022, Russia launched a military offensive against Ukraine. On 24 February Ukraine informed the IAEA that Russian forces had taken control of all facilities of the Chernobyl nuclear power plant, which is not functional since year 2000. Control of the site was returned to Ukrainian personnel on 31 March. Also, in the early hours of 4 March, the Zaporizhzhia plant in southeastern Ukraine became the first operating civil nuclear power plant to come under armed attack. Fighting between forces overnight resulted in a projectile hitting a training building within the site of the six-unit plant. Russian forces then took control of the plant. Reportedly, the reactors were not affected and there was no environmental release radioactive material. Widespread blackouts have resulted, and external power supply to all four of the country's nuclear plants has been affected [8]. The International Atomic Energy Agency (IAEA) is currently monitoring the developments in the country with respect to its nuclear facilities and is providing regular updates on the situation [9]. The AIEA cited many violations of the Zaporizhzhia NPP safety because the physical integrity of the plant has not been respected in the ensuing confrontation [10].

In the context of the crisis generated by the Russian-Ukrainian conflict, radiological situation forecasts were made within the National Institute of Research and Development for Physics and Nuclear Engineering "Horia Hulubei" (IFIN-HH) for all nuclear power plants in Ukraine. Therefore, the resident decision support software systems for radiological and nuclear emergencies were used, with the main purpose of identifying potential areas of influence on the territory of Romania generated by Ukrainian power plants, as consequence of military actions.

2. Assessment tools

Decision support systems (DSS), such as dose projection tools, for estimating radiation doses, are essential in preparing and responding to nuclear and radiological emergencies. Users of decision-making systems are the regional, national, and international institutions and organizations responsible for emergency management. The assessments of the possible radiological consequences of the scenarios as described were conducted by running two of the computer codes available with IFIN-HH/DFVM: RODOS (*Real-Time Online Decision Support System for the Management of Nuclear Emergencies*) – the reference computer code in development under the EC auspices [11] and CBRNE Software (*Chemical, Biological, Radiological, Nuclear, and Explosives Software*) – a domestic product in standing development and maintenance [12].

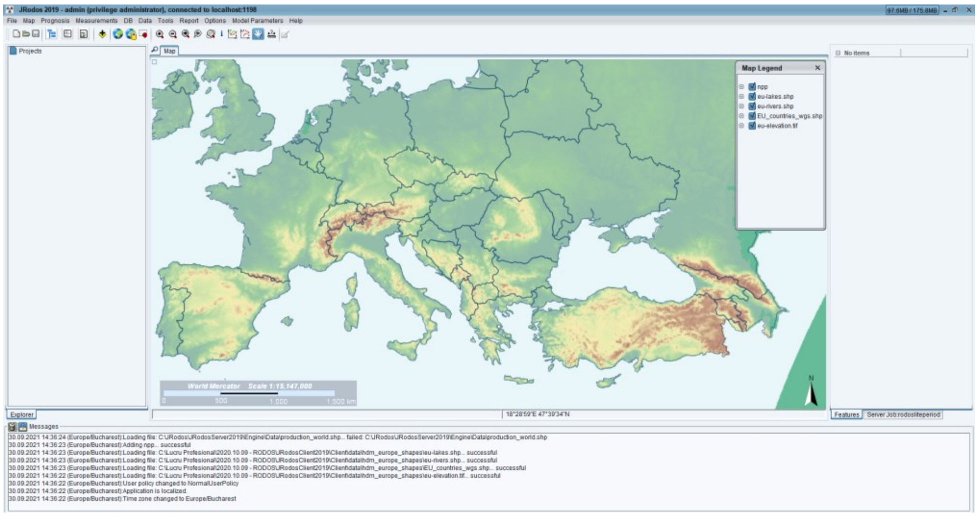
2.1. JRodos System

The European Realtime Online Decision Support System for nuclear emergency management (RODOS) [12] 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 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 like EURANOS [13] and NERIS-TP [14].

In more recent times, a Java-based successor version of RODOS was issued in 2009 under the name JRodos [15]. It operates on modern information technology platforms and shows good performance and operational stability. 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. 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 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. In case of a nuclear accident, 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.

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, allowing to download such data for a user-specified period.

In the RODOS-Lite data entry interface (Figure 1), the input parameters are introduced in order to initialize the calculation sequence.



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30.09.2021 14:36:24 (Europe/Bucharest):Loading file: C:\JRodos\JRodosServer2019\Engine\Data\production_world.shp... failed: C:\JRodos\JRodosServer2019\Engine\Data\production_world.shp
30.09.2021 14:36:23 (Europe/Bucharest):Adding npp... successful
30.09.2021 14:36:23 (Europe/Bucharest):Loading file: C:\Lucru Profesional\2020.10.09 - RODOS\JRodosClient2019\Client\data\hdm_europe_shapes\eu-lakes.shp... successful
30.09.2021 14:36:23 (Europe/Bucharest):Loading file: C:\Lucru Profesional\2020.10.09 - RODOS\JRodosClient2019\Client\data\hdm_europe_shapes\eu-rivers.shp... successful
30.09.2021 14:36:23 (Europe/Bucharest):Loading file: C:\Lucru Profesional\2020.10.09 - RODOS\JRodosClient2019\Client\data\hdm_europe_shapes\EU_countries_wgs.shp... successful
30.09.2021 14:36:22 (Europe/Bucharest):Loading file: C:\Lucru Profesional\2020.10.09 - RODOS\JRodosClient2019\Client\data\hdm_europe_shapes\eu-elevation.tif... successful
30.09.2021 14:36:22 (Europe/Bucharest):User policy changed to NormalUserPolicy
30.09.2021 14:36:22 (Europe/Bucharest):Application is localized.
30.09.2021 14:36:22 (Europe/Bucharest):Time zone changed to Europe/Bucharest
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Fig. 1. JRodos Graphical User Interface, RODOS-Lite.

Input data in JRodos models can be national weather data online from weather towers or numeric data for global weather forecast such as those from the United States National Center for Environmental Predictions (NOAA-NCEP) available through the NOMADS online service [16]. Thus, this data can be downloaded for the desired period as numerical forecast data up to 120 hours (5 days) or as retroactive reanalysis data. The downside is that the spatial resolution is lower disregarding local conditions, although it has been substantially improved in recent years. The models of transport and atmospheric dispersion for the close field (LSMC) on a radius of up to 800 km around the emission point, implemented in JRodos are of several types, namely: models of Gaussian "puff" such as RIMPUFF (developed within Risø, Roskilde) [17] and the particle model for complex terrain DIPCOT (developed within Demokritos, Athens) [18] and the commercially developed Lagrangian aerosol transport simulation model LASAT [19]. The models for the distant field on long distances of several thousand kilometers are: the Eulerian multi-scale model for transport and atmospheric chemistry MATCH developed by the Swedish Meteorological and Hydrological Institute [20].

2.2. CBRNE Software

CBRNE Software system (Figure 2) is an open software platform of MS&V type (Modeling, Simulation and Visualization). Developed within IFIN-HH/DFVM as part of a research project in the field of national security [21], designed for anticipatory, prognostic assessment of CBRNE events (chemical, biological, radiological, nuclear, and explosive), comprising functions for diagnosis of effects and consecutive recommendation of response measures for an open and scalable variety of event scenarios. The system is designed as a physically distributable component in autonomous but interconnected and monitored installation instances in the local network, providing expert services to the various compartments of an Emergency Operations Center (EOC). The platform consists of an open, updatable structure, comprising thematic module executables; utilities for data acquisition, updating, editing, and pre-processing data libraries; documentary collections and administrative facilities. Installed on PC class computers under a widely used operating system, the platform integrates analytical tools for developing event scenarios, tracking their phenomenology in carrying out the processes involved, evaluating the situations created, calculating exposures of different types and of harmful effects and potential damage, involving a suite of data libraries expert information, operating interfaces, executable modules, and communication interfaces.

Fig. 2. CBRNE Software. Dispatcher Page.

CBRNE Software uses primary meteorological forecast data on intervals between 8 to 72 hours, acquired in real time from public weather services sites such as: temperature (ºC); direction (deg.) and wind speed (m/s) at 10 mAG; cloudiness (%); precipitation (mm equivalent rain). Data derived by pre-processing of primary data consists of atmospheric stability classes (Pasquill A-F). The trajectory of radioactive/toxic clouds released from sources in the event of an accident or sabotage is modeled, in the platform's applications, by a model originated by the authors of CBRNE Software based on the model of air traffic control tower.

Thus, the atmospheric releases of the sources are considered to be sequences of 'puffs' of relatively short duration and close in time, of equal intensity throughout the duration of the release, transported individually to heights prescribed by conventional *plume rise models*, of the barometric wind (at 10 m height from the ground) corrected with the height (*wind shear*) measured by the meteorological station closest to the center of each puff in the respective time step. Emphasizing the analogy, weather stations work as 'air control towers' of aircraft, which successively take over the direction of their navigation.

This approach proved to be the most efficient in terms of accuracy/time balance of calculation, on computers of PC class and current use, the accuracy deriving from the fact that the raw data is not coming from numerical models, but from direct measurements.

As providers of weather data, CBRNE Software uses three public sources: World Weather Online [22], VentuSky [23] and FreeMeteo [24].

3. The Radiological Assessment

3.1. Postulated Scenarios

Assessment of situation for Ukraine NPP was made with JRODOS System and CBRNE software platform, both resident at IFIN-HH/DFVM with the purpose of determining the potential areas of influence on the Romanian territory in case of a nuclear accident. The narrative of the considered scenarios involved the unintentional hitting of the *active zones* of the nuclear installations, followed by the release of radioactive material into the atmosphere. Two such release pathways were considered: the reactor itself – *reactor scenario* and spent fuel pool – *spent fuel pool scenario* [25].

The radiological situation for all four active nuclear power plants in Ukraine (Khmelnitsky, Rivne, South Ukraine, and Zaporozhe) as well as the decommissioned Chernobyl Power Plant (Figure 3), has been assessed for several months from the start of the conflict. The assessments were performed daily starting at 11:00 a.m. over a 24-hour monitoring interval.

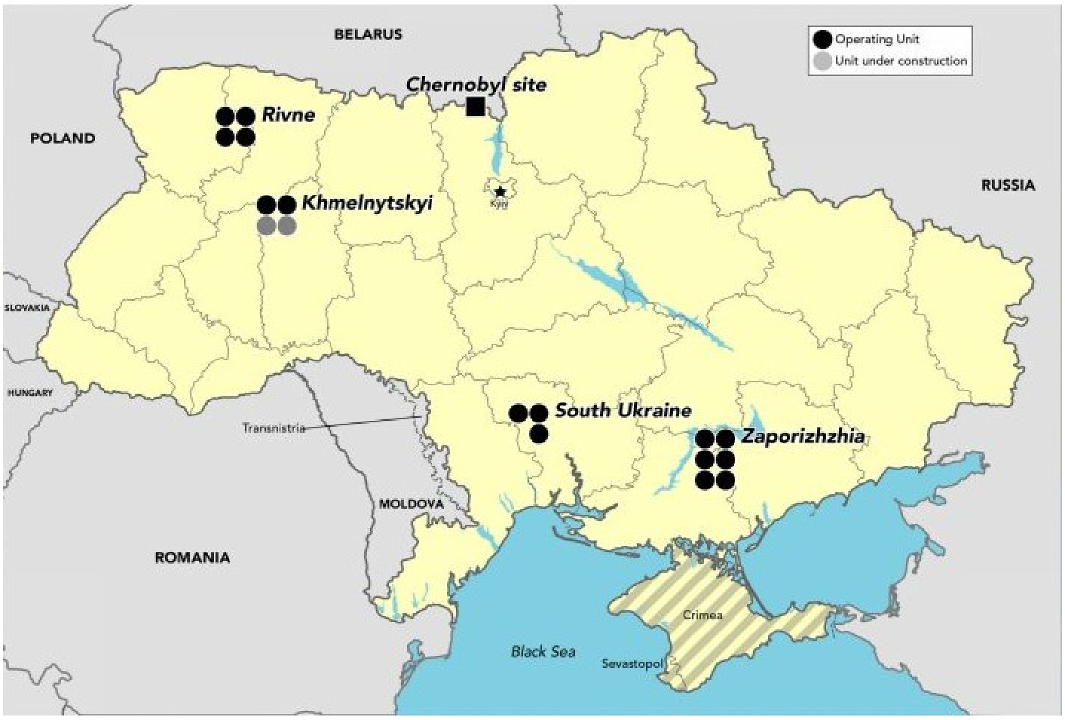


Fig. 3. Location of Ukraine's NPP Map [26].

3.2. Source Term Estimation

The source terms have been inferred based on the assumptions of the considered scenarios, in the absence of a source term confirmed by the operator of the nuclear objective. The calculated doses were only informative, having the role of rapid identification (*screening*) of the vulnerabilities to the national territory induced mainly by the daily weather conditions. Therefore, *the computer assisted dose projection assessments were oriented towards identification of the potential impact areas on the national territory* [27].

The determination of the source terms derives from the methodology accredited by the U.S. nuclear regulatory body – U.S. Nuclear Regulatory Commission adopted in nuclear accident response manuals [28, 29, 30], assimilated and recommended by the technical document series (IAEA TECDOC) of the International Atomic Energy Agency [31].

Known as *'The Four-Factors Rule'* (4FRule) [32], this is a simplified solution, practical and providing sufficient degrees of confidence in making decisions to respond to abnormal nuclear events. The four factors rule finds specific expression in the *'Release Pathways'* of the seven types of Light Water Reactors (LWR) that dominate the nuclear-electric industry in the world.

For each of these scenarios, using the dedicated module of the CBRNE-Software platform, medium severity source terms were built. The scenarios assumptions used for the assessment are presented in Table 1, considering a VVER type reactor with a capacity of 1000 MWe (VVER-1000) and the on-site spent fuel pool (SPFP). Activity values (Bq) per nuclide for both scenarios are shown in Table 2.

Table 1. The scenarios assumptions considered for both scenarios.

Scenario	Type of accident	Release duration (hrs)	Release height (m)	Total activity (Bq)
Reactor	Containment bypass, gap release	1	10	4.63E+17
Spent fuel pool	Gap release, 1 batch affected, no fire	4	10	5.79E+17

Table 2. Values of activity (Bq) per nuclide for both scenarios.

Nuclide	Activity (Bq)	
	Reactor Containment bypass, gap release	Spent fuel pool gap release, 1 batch affected, no fire
Kr-85	2.07E+14	2.59E+14
Kr-85m	8.88E+15	1.11E+16
Kr-87	1.74E+16	2.18E+16
Kr-88	2.52E+16	3.15E+16
I-131	3.15E+16	3.92E+16
I-132	4.44E+16	5.55E+16
I-133	6.29E+16	7.88E+16
I-134	7.03E+16	8.81E+16
I-135	5.55E+16	6.96E+16
Xe-131m	3.70E+14	4.63E+14
Xe-133	6.29E+16	7.88E+16
Xe-133m	2.22E+15	2.78E+15
Xe-135	1.26E+16	1.58E+16
Xe-138	6.29E+16	7.88E+16
Cs-134	2.78E+15	3.47E+15
Cs-136	1.11E+15	1.39E+15
Cs-137	1.74E+15	2.18E+15
TOTAL	4.63E+17	5.79E+17

3.3. JRODOS Assessment

For the assessment with JRodos, a general configuration was used for global applications and NOMADS historic diagnostic data (Grib2 type), for 26 August 2022, 11 AM consisting of:

- Creation of a new project using only near-field Local Scale Model Chain model (LSMC), specifying the type of event (accident in a nuclear power plant) and the location ("Ukraine", "Zaporozhe-1") from a list of available reactors.
- Defining of the Source Term by introducing data for the following parameters: the time interval between the end of the chain reaction and the beginning of the emission (0 h), the start of the emission, the activity emitted in the form of sums of activities by categories of radionuclides (iodine isotopes, noble gases and aerosols), the emission height above the ground (30 m), the thermal power released in [MW], the volume of the vertical flow emitted to the atmosphere in [m^3/s] and the emission ventilation surface into the atmosphere in [m^2].
- Specifying the weather forecast range of 24 hours after the start of the release and defining the provider of the weather data, as well as the selected atmospheric dispersion model (RIMPUFF [17]). In addition, the default network type and range for calculations were selected (800 km).
- Running the calculation forecast automatically and successively by submitting all the input data to the code. JRodos shows the results in the form of a situation map (Figure 4) with information grouped into several layers that are selected from the legend. Calculated values are displayed as a result tree in the program interface.
- Displaying the results using custom user defined maps. Although the system provides a default set of simple maps, for this assessment, 'OpenStreetMap' maps provided by the Terrestris internet service [33] were employed to generate the detailed background.

The JRodos assessments are presented below for Scenario 1 (reactor containment bypass) and Scenario 2 (spent fuel pool gap release) in Figures 4 and 5 respectively. Hence, the meteorological situation for the 24 h interval (26.08.2022; 11:00h – 27.08.2022; 11:00h) is considered for Zaporizhzhia NPP, using numerical prognosis data from NOMADS Global Service (NOAA).

The prognosticated maximum value of the *Total Effective Dose Equivalent* (TEDE) in mSv at the end of the 24 h interval is emphasized near source, as well as over national territory of Romania using a zoom on the map view. Results could 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 contaminant cloud.

The calculations were performed using the atmospheric dispersion gaussian model RIMPUFF with 144 calculation timesteps of 10 min and a range of 800 km. The release time is 1 h for reactor scenario and 4 h for spent fuel scenario.

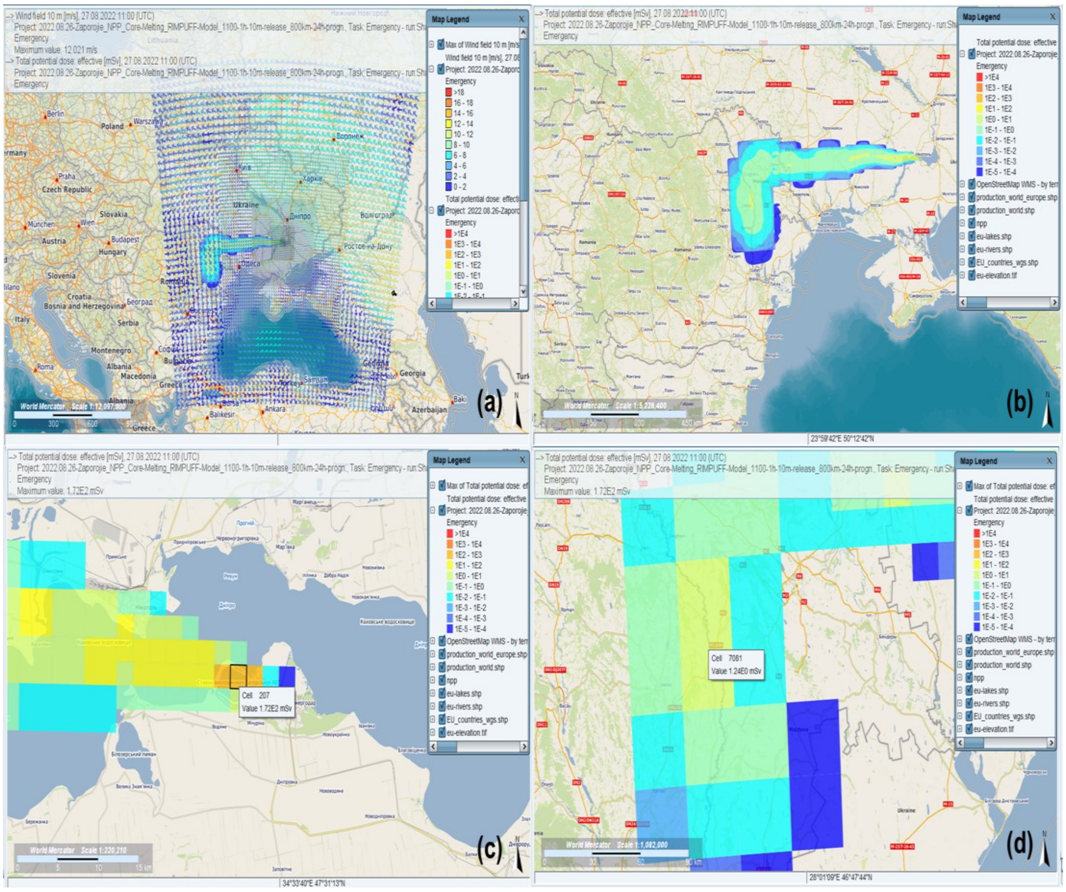


Fig. 4. JRodos assessment. Scenario 1 – Reactor containment bypass, gap release. (a) Meteo wind field [m/s] at 10 m for 24 hrs.; (b) Total Effective Dose Equivalent isopolygones; (c) Maximum value of TEDE (mSv) near source: 1.72E+02; (d) Maximum value of TEDE (mSv) potential affected area: 1.24E+00

In the case of nuclear accidents there can be a delay between the end of chain reaction and the beginning of chain reactions, but this is not always the case depending on the accident scenario. For simplifying reasons, we choose a scenario without this delay.

The RIMPUFF atmospheric dispersion model is a local-scale puff diffusion model developed by Risø DTU National Laboratory for Sustainable Energy of Denmark [17]. It is a model to help emergency management organizations deal with chemical, biological and radiological releases to the atmosphere. It is in operational use in several European national emergency centers for preparedness and prediction of nuclear accidental releases, chemical gas releases, and for airborne virus spread. RIMPUFF uses parameterized formulas for puff diffusion, wet and dry deposition, and gamma dose radiation. Its range of applications covers distances up to ~1000 km from the point of release. RIMPUFF calculates instantaneous atmospheric dispersion considering the local wind variability and the local turbulence levels. The puff sizes represent instantaneous relative diffusion and is calculated from similarity scaling theory. Puff diffusion is parameterized for travel times in the range from a few seconds and up to one day. Wet and dry deposition is also calculated as a function of local rain intensity and turbulence levels.

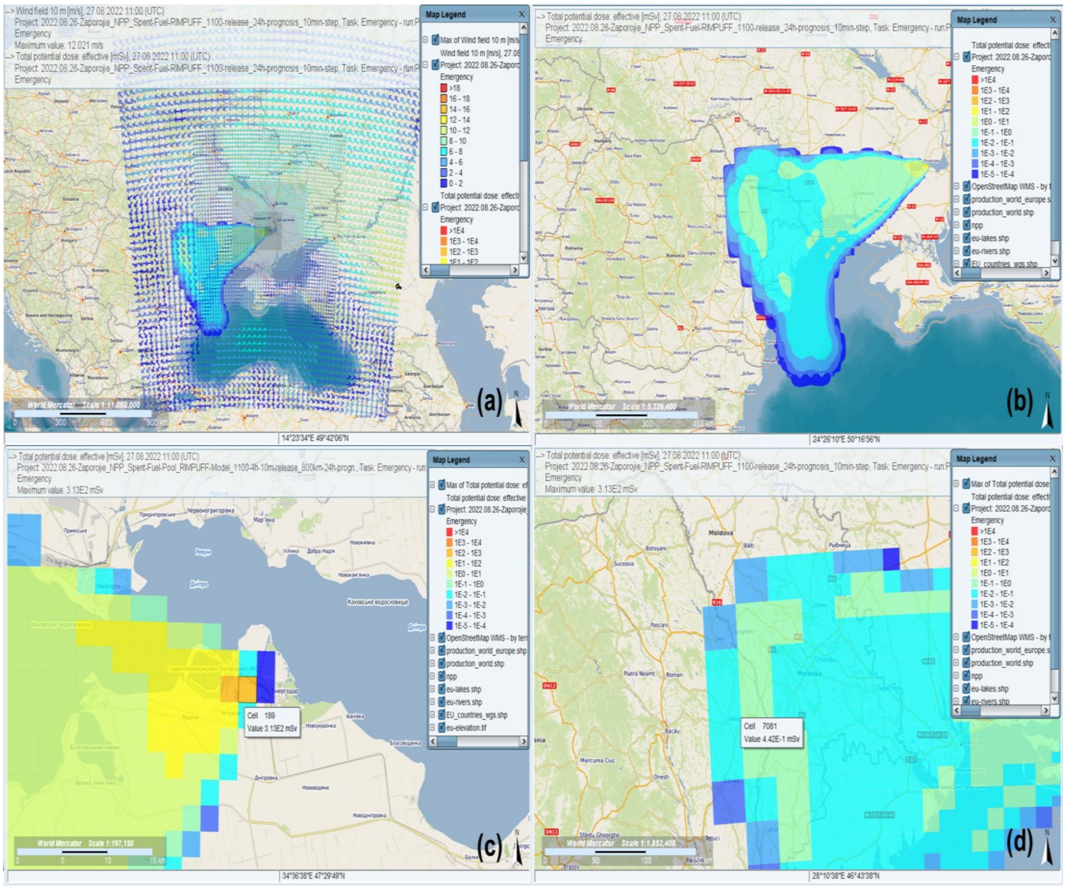


Fig. 5. JRodos assessment. Scenario 2 – Spent fuel pool gap release, 1 batch affected, no fire. (a) Meteo wind field [m/s] at 10 m for 24 hrs.; (b) Total Effective Dose Equivalent isopolygones; (c) Maximum value of TEDE (mSv) near source: 3.13E+02; (d) Maximum value of TEDE (mSv) potential affected area: 4.42E-01

3.4 CBRNE Assessment

For this study, the thematic module *'Nuclear Accidents'* of CBRNE Software was run, which addresses issues related to nuclear risks and threats that integrate, among others, the *'Situation Forecasts'* application, part of the software platform's portfolio. The core function of this application is to iteratively forecast, as frequently as the user decides (including around the clock), over time windows spanning from 8 to 72 hours, the virtual radiological impact of hypothetical *atmospheric radioactive releases from nuclear facilities anywhere in the World*, as the assumed releases are driven cross-country by the true meteorology of the regions (winds, atmospheric stability, precipitations). The working sequence consisted of:

- Identifying the site of an event by using an interactive list from the code's data library, which contains 168 nuclear sites accompanied by a set of primary information.
- The geolocation of position for the radioactive emission source in the environment through geographical coordinates determined with the help of an interactive map of the entire globe, offered by the code in several web versions through whose manipulation (zoom, click) the user can establish with the necessary accuracy the position of the radioactive atmospheric emission source.
- Acquisition of the meteorological forecast by collecting anticipatory data on wind, precipitation and atmospheric stability regime using one of the weather sites over a time interval of 8 – 72 hours.
- Selecting the source term by using a predefined source term implying a dedicated module of the platform, stored in the data library of the code.
- Other adjustable input data, depending on the degree of knowledge of the situation. The user changes certain input parameters such as: the activity multiplication factor, the emission duration, the height, and diameter of the exhaust stack, etc.

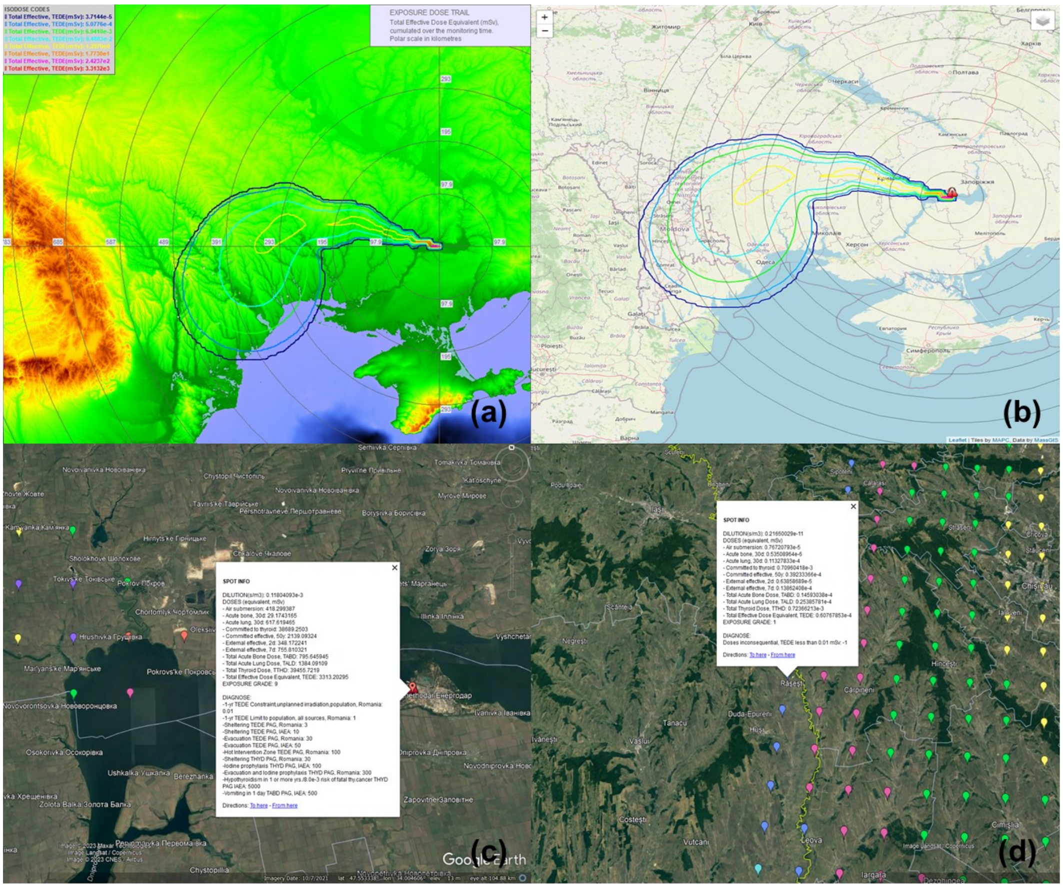
The results obtained with the help of the assessment engines are delivered to the interface by the viewing facilities of the platform in two ways:

- *Situation maps* – present the areas of influence of the sources of radioactive air emissions in their geographical context as isodose maps of the Total Effective Dose Equivalent (TEDE) or as grids of interrogable spots (values for dilution factors as well as values for a variety of doses). These are offered in the form of: 2D base map (Base Map) that can also be used in the off-line mode in which only TEDE isodoses are represented; 3D maps in several visual expressions according to the user's preferences.
- *Text files* – the complete input/output file attached to the situation maps, the diagnosis resulting from the interactive query (click) of the location of a

community, or by retrieving (marking on the map) of a community listed in the file.

At the end of the evaluations, all the executive applications of the platform provide a *'Situation Report'* (SitRep) which is a summary document of the application representing a web-publishable compilation on the integrated server of the Platform, which reproduces in a logical sequence the main elements of the code output such as: the presentation of the nuclear objective that constitutes the source of radioactive air emissions, base map, complementary maps or links to them and the full I/O file (input/output) of the reported case.

SitRep is an HTML5/JavaScript document accessed by browsers that preserves, at the level of published maps, the interactivity of its components.



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SPOT INFO

DILUTION(s/m3): 0.11804093e-3
DOSES (equivalent, mSv)
- Air submersion: 418.299387
- Acute bone, 30d: 29.1743165
- Acute lung, 30d: 617.619465
- Committed to thyroid: 38689.2503
- Committed effective, 50y: 2139.09324
- External effective, 2d: 348.172241
- External effective, 7d: 755.810321
- Total Acute Bone Dose, TABD: 795.645945
- Total Acute Lung Dose, TALD: 1384.09109
- Total Thyroid Dose, TTHD: 39455.7219
- Total Effective Dose Equivalent, TEDE: 3313.20295
EXPOSURE GRADE: 9

DIAGNOSE:
-1-yr TEDE Constraint,unplanned irradiation,population, Romania: 0.01
-1-yr TEDE Limit to population, all sources, Romania: 1
-Sheltering TEDE PAG, Romania: 3
-Sheltering TEDE PAG, IAEA: 10
-Evacuation TEDE PAG, Romania: 30
-Evacuation TEDE PAG, IAEA: 50
-Hot Intervention Zone TEDE PAG, Romania: 100
-Sheltering THYD PAG, Romania: 30
-Iodine prophylaxis THYD PAG, IAEA: 100
-Evacuation and Iodine prophylaxis THYD PAG, Romania: 300
-Hypothyroidism in 1 or more yrs./8.0e-3 risk of fatal thy.cancer THYD PAG IAEA: 5000
-Vomiting in 1 day TABD PAG, IAEA: 500

Directions: To here - From here
```

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SPOT INFO

DILUTION(s/m3): 0.21650029e-11
DOSES (equivalent, mSv)
- Air submersion: 0.76720793e-5
- Acute bone, 30d: 0.53508964e-5
- Acute lung, 30d: 0.11327833e-4
- Committed to thyroid: 0.70960418e-3
- Committed effective, 50y: 0.39233366e-4
- External effective, 2d: 0.63858689e-5
- External effective, 7d: 0.13862408e-4
- Total Acute Bone Dose, TABD: 0.14593038e-4
- Total Acute Lung Dose, TALD: 0.25385781e-4
- Total Thyroid Dose, TTHD: 0.72366213e-3
- Total Effective Dose Equivalent, TEDE: 0.60767853e-4
EXPOSURE GRADE: 1

DIAGNOSE:
Doses inconsequential, TEDE less than 0.01 mSv: -1

Directions: To here - From here
```

Fig. 6. CBRNE Software assessment. Scenario 1 – Reactor containment bypass, gap release. (a) TEDE (mSv) footprint on ground over 24 hrs.; (b) TEDE (mSv) isodoses map. (c) Maximum value of TEDE (mSv) near source: 3.31E+03; (d) Maximum value of TEDE (mSv) potential affected area: 6.07E-05

Fig. 6 and Fig. 7 display the results of CBRNE Assessments for Scenario 1 (reactor containment bypass) and Scenario 2 (spent fuel gap release) respectively.

The situation maps after 24 hours since accident are presented using real meteorological data from 26-27 August 2022.

The Figures illustrates: (a) the footprint over ground, (b) TEDE isodose map, (c) maximum value of TEDE near source and (d) maximum value of TEDE for the potential affected area in Romania.

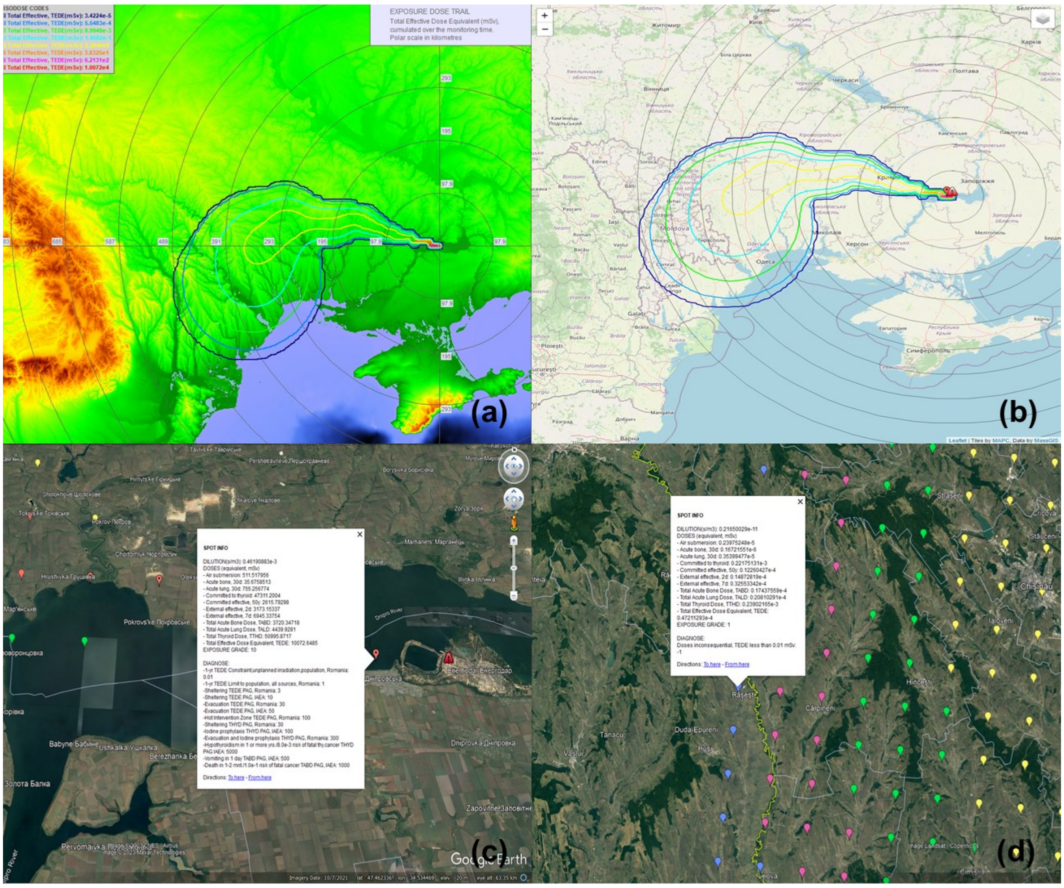

Fig. 7. CBRNE Software assessment. Scenario 2 – Spent fuel pool gap release, 1 batch affected, no fire. (a) TEDE (mSv) footprint on ground over 24 hrs.; (b) TEDE (mSv) isodoses map. (c) Maximum value of TEDE (mSv) near source: 1.00E+04; (d) Maximum value of TEDE (mSv) potential affected area: 4.72E-05

3.5. Intercomparison of Results

For an easier comparison, the situation assessment maps of the assessments for both scenarios are shown in Fig. 8.

Also, for comparison we have added the dose equivalent values for: *Total Effective Dose Equivalent* (TEDE), *Total Acute Bone Dose* (TABD), *Total Acute Lung Dose* (TALD), and *Total Dose to the Thyroid* (TTHD) also calculated by all software, doses that are considered to be of importance in taking the necessary countermeasures. The assessment dose values for both scenarios are summarized in Tables 3 and 4. We emphasize the fact that in this kind of assessment, the intervention dose level is considered by the first responders.

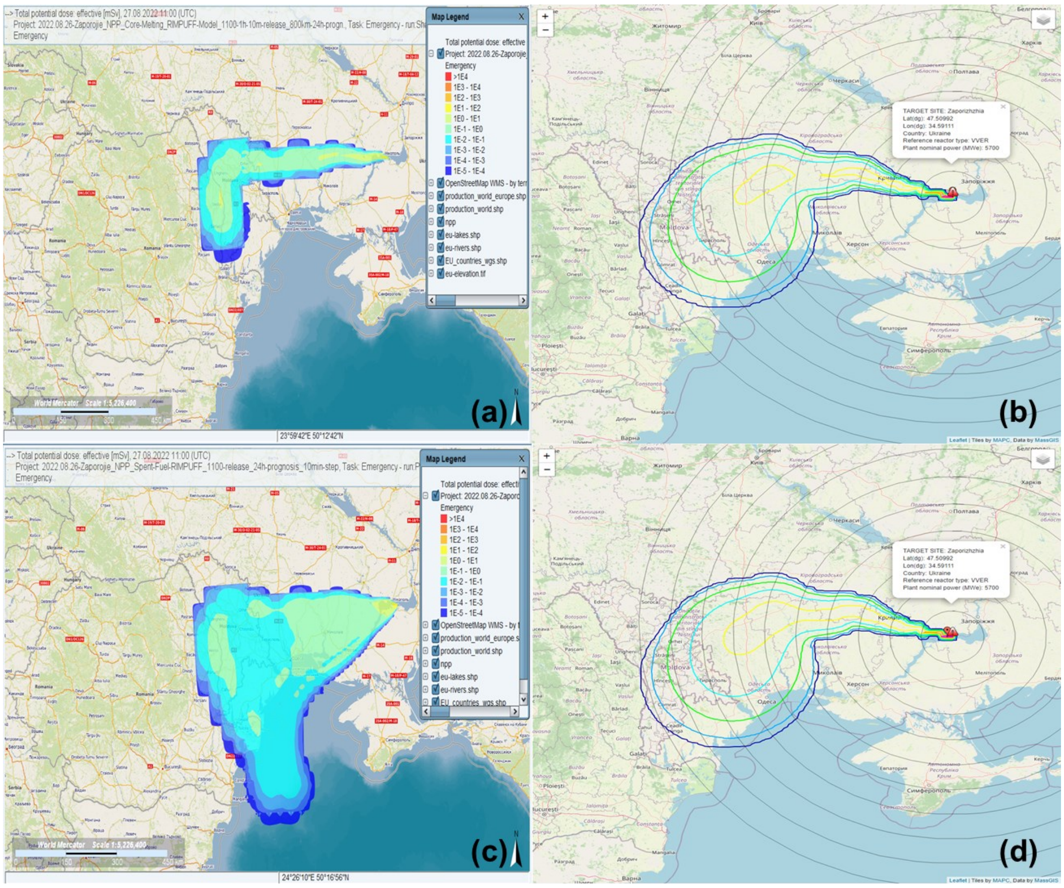

Fig. 8. Exposure dose trail comparison. (a) JRodos assessment. Scenario 1 – Reactor containment bypass, gap release.; (b) CBRNE assessment. Scenario 1 – Reactor containment bypass, gap release. (c) JRodos assessment. Scenario 2 – Spent fuel pool gap release, 1 batch affected, no fire; (d) CBRNE assessment. Scenario 2 – Spent fuel pool gap release, 1 batch affected, no fire.

Table 3 Scenario 1 – Reactor containment bypass. Maximum dose values

Software	Doses (mSv)							
	near source				potential affected area			
	TABD	TALD	TTHD	TEDE	TABD	TALD	TTHD	TEDE
CBRNE	7.95E+02	1.38E+03	3.95E+04	3.31E+03	1.45E-05	2.53E-05	7.23E-04	6.07E-05
JRODOS	2.05E+00	4.58E+01	2.90E+03	1.72E+02	7.71E-02	1.41E-01	2.27E+01	1.24E+00

Table 4 Scenario 2 – Spent fuel pool gap release. Maximum dose values

Software	Doses (mSv)							
	near source				potential affected area			
	TABD	TALD	TTHD	TEDE	TABD	TALD	TTHD	TEDE
CBRNE	3.72E+03	4.44E+03	5.09E+04	1.00E+04	1.74E-05	2.08E-05	2.39E-04	4.72E-05
JRODOS	3.84E+01	8.24E+01	5.26E+03	3.13E+02	2.74E-02	5.02E-02	8.09E+00	4.42E-01

4. Conclusion

Potentially affected areas from nuclear power plants in Ukraine were assessed with two different decision support systems JRodos and CBRNE Software.

The reason behind the results comparison is given by one of the declared objectives of this paper, namely, to correlate the assessments performed with J-RODOS and CBRNE. Moreover, with regards to the visual and numerical results presented, those are the protective quantities (i.e. equivalent and effective doses) oriented towards preemptive/immediate intervention: the Total Effective Dose Equivalent (TEDE), Acute Lung, Acute Bone and Thyroid (TTHD) – all in (mSv). Therefore, the situational maps in the paper render the affected area in respect to the projected TEDE from the time integrated concentration over the monitoring time (considered the most important dose for protective actions).

Although, the potential exposure areas assessed with both software have some slight differences, the maximum values of TEDE are similar, being of the order of $10^2 \div 10^4$ mSv. The difference arises from various factors including, yet not limited to: the analytical dispersion models adopted; additional models employed for modeling the various physical phenomena occurring during release and transport (e.g. plume rise, wet and dry deposition); the selection of numerical algorithms employed in various phases of the computation (e.g. methods for solving the numerical definite integrals); the actual algorithms for the implementation of the models (grid generation, time sampling, etc.); the programing language (floating point operation and precision); and last but not least the potential differences in the radiological support data (dose conversion factors).

Therefore, it can be considered that assessments made with domestic developed support systems, such as, for example, CBRNE Software, may prove useful, congruent, and non-conflicting with the JRodos system which is recognized nationally and internationally as the reference Decision Support System (DSS) for the management of global nuclear emergencies.

Last but not least, given the very low levels of doses assessed with both systems in the potentially affected areas it can be concluded that the influence of Ukraine's NPPs over the national territory of Romania − in case of an accident using real *unfavorable meteorological data* (wind direction towards Romanian territory) and the *experts best guess source term scenarios* − is negligible and poses no risk to both the public and the environment.

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