RADIOLOGICAL RISK IN THE CONTEXT OF THE CHALLENGES BROUGHT BY THE ADOPTION OF NEW NUCLEAR TECHNOLOGIES IN ROMANIA'S NATIONAL ENERGY MIX

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Abstract. *Romania is at a pivotal point in its energy transition, increasingly prioritizing Small Modular Reactor (SMR) technology within its national energy mix. While SMRs offer a decentralized, low-carbon alternative to conventional large-scale nuclear power plants and fossil fuels, their integration introduces distinct radiological safety paradigms. This paper evaluates the current implementation landscape in Romania, focusing on the transition from traditional safety assessments to the challenges posed by SMR-specific source terms. Specifically, we analyse the radiological risk under hypothetical accident scenarios, examining how passive safety systems and reduced core inventories influence emergency planning zones (EPZ) and national regulatory compliance. The findings highlight the critical need for an updated radiological protection framework that aligns with the modular and innovative nature of these emerging nuclear technologies*

Keywords: decision-support systems; situation forecasts; potential areas of radiological risk; total effective dose equivalent (TEDE).

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1. Introduction

The global nuclear landscape is currently witnessing a paradigm shift with the emergence of integrated Pressurized Water Reactors (iPWRs) [1]. Defined by a compact design where the primary coolant system and its major components—such as the pressurizer, steam generators, and reactor coolant pumps—are enclosed within a single pressure vessel, iPWRs represent the core of Small Modular Reactor (SMR) technology [1]. While several vendors, including Holtec, mPower, and Westinghouse, are advancing their respective designs, the NuScale Power module stands out as the most mature technology, having achieved significant licensing milestones both in the United States and internationally [1][2].

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Romania is positioned at the forefront of this energy transformation. Facing the dual challenge of ensuring energy security while meeting stringent European Union decarbonization targets, the country has identified SMRs as a critical component of its future energy mix. Unlike conventional large-scale reactors, SMRs offer enhanced flexibility, scalability, and—most importantly—advanced passive safety features that significantly reduce the risk of environmental impact in the event of a transient. [3]

A milestone in this national strategy was the agreement between SN Nuclearelectrica SA and NuScale Power for the development of a flagship SMR plant at the former Doicești thermal power site [4]. This pilot project, designed for a total capacity of 462 MW, is intended to provide clean energy to approximately 400,000 households. [4] The regulatory transition reached a decisive point in August 2023, when the National Commission for Nuclear Activities Control (CNCAN) issued an official approval letter certifying the compliance of the Basic Licensing Document with national safety requirements [5].

However, the adoption of such innovative technology is not without complex challenges. Beyond the financial and public acceptance hurdles, the integration of SMRs into Romania's national energy grid requires a rigorous re-evaluation of the radiological risk framework. The modular nature and reduced core inventory of these units necessitate a shift from traditional emergency planning zones (EPZ) to more localized, data-driven safety perimeters [6].

This paper aims to analyse the current state of SMR implementation in Romania, focusing on the radiological safety implications and the specific regulatory challenges posed by a hypothetical nuclear accident within this new technological context.

2. Technical Characteristics of the NuScale SMR

2.1. Design Overview and Core Technology

The NuScale Power Module (NPM) is an integrated Pressurized Water Reactor (iPWR) that represents a significant departure from traditional loop-type PWRs. The design consolidates the reactor core, a helical coil steam generator (HCSG), and a pressurizer within a single Reactor Pressure Vessel (RPV) [7]. The RPV is a high-pressure vessel with a height of approximately 20 m and an outer diameter of 2.8 m, constructed from heavy-section carbon steel with internal stainless-steel cladding to prevent corrosion. [6] (Fig. 1)

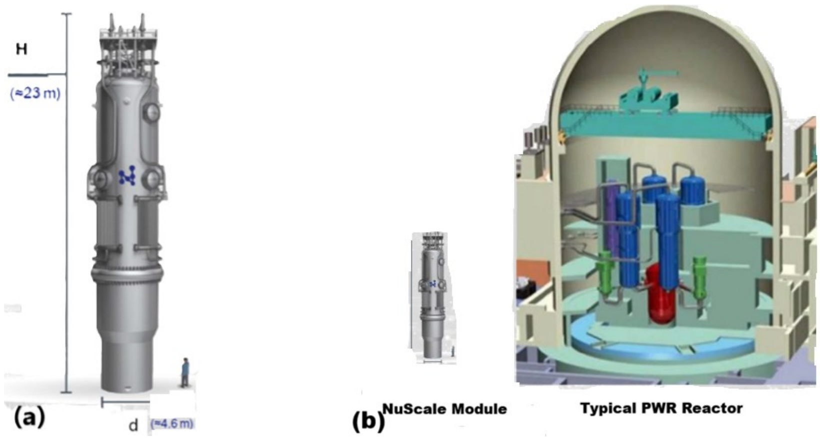

Fig. 1 Dimensions of a NUSCALE SMR module (a) and comparison with a typical PWR reactor (b) [8]

To facilitate a rigorous radiological safety analysis, it is essential to establish the baseline design parameters that define the NuScale Power Module's operational envelope. The following table (Table 1) synthesizes the key technical specifications that directly influence the reactor's source term and its thermal-hydraulic behaviour during transient events.

Specifically, the rated thermal power (250 MWt) and the compact core geometry are the primary factors in determining the inventory of volatile fission products. Furthermore, the significant volume of the ultimate heat sink (the reactor pool) and the high design pressure of the containment vessel (CNV) are critical variables in calculating the safety margins for severe accident mitigation. These specifications represent the 'VGY' (Standard Design) configuration, which serves as the reference model for the hypothetical accident scenarios analysed in the subsequent sections of this study.

By eliminating Reactor Coolant Pumps (RCPs) (see Table 2) the design of NuScale SMR modle (Fig. 2) removes the risk of "Loss of Flow" accidents and simplifies the NSSS by reducing the number of penetrations and large-diameter piping, which are primary LOCA (Loss of Coolant Accident) initiators in conventional plants.

Table 1. Technical Specifications for "VOYGR-6" standard design [9]

VOYGR Operating period	60 years	Moderator	Light water
Thermal power (per module)	250 MWt	Number of steam generators ConfigurationCirculation	2 bundles of independent tubes integrated into the reactor vessel Single-pass helical unit. Secondary fluid inside the tubes Natural
Electrical power	77 MWe (gross)	Length of the operating cycle until fuel resupply	18-24 months
Thermal Efficiency	>30%	Scheduled outage duration	10 days
Reactor type	Pressurized light-water cooled and moderated reactor	Containment parameters Design Temperature Design Pressure Nominal Operating Pressure Vessel diameter Vessel Height	 316 ^{o}C 5.5 MPa 12.7 MPa 4.6 m 23.3 m
Core Fuel type Enrichment No. of fuel elements Cell Geometry Core height Fuel cladding	Ceramic Pellets UO_2 <4.95% 37 (17x17 pins standard PWR shortened, 2 m Zircaloy-4	Primary System Parameters Design Temperature Design Pressure Nominal Operating Pressure	 343 ^{o}C 152 bars 12.7 MPa
Cooling agent	Light water	Secondary system parameters Design Temperature Feedwater temperature Turbine Inlet Pressure	 343 ^{o}C 93 ^{o}C 35 bars
Capacity factor	>95%	Thermodynamic cycle	Rankine
Operating mode	Basic Task	Utilization mode	Distributed or centralized
Burn Level at fuel discharge	>30 MWd/kg	Neutron Liquid Absorbent	Gadolinium
Reactivity control mode	Control bars, boric acid	Reactor Shutdown Mode	Control bars
Power Conversion System	Steam	Pumps number	0
Residual Heat Extraction Systems	Passive DHRCP/ECSS	Plant area	160 000 m^2
Envelope	Below ground level immersed in water in a concrete basin	Control room and spent fuel tank Reactor building	Underground First Level seismically protection and against plain crush

Another defining characteristic of the NuScale design is its exclusive reliance on natural circulation for primary coolant flow during all modes of operation. The physics of this process is driven by the density differential between the "hot leg" (riser) and the "cold leg" (downcomer) as follows: [10]

- The Riser: Water heated by the reactor core decreases in density and travels upward through a central riser column.

- Heat Exchange: At the top of the riser, the fluid is diverted downward through the HCSG, where it transfers heat to the secondary side.

- The Downcomer: As the water cools, its density increases, causing it to descend through the annular space between the riser and the RPV wall, eventually returning to the core inlet.

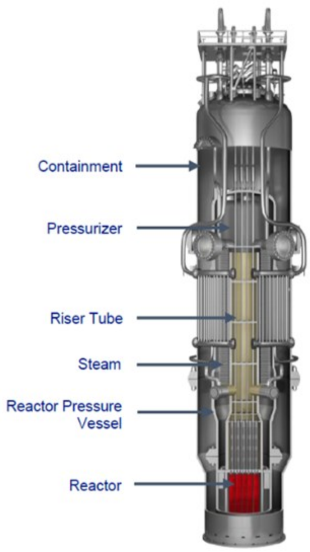

Fig. 2. NuScale SMR Module schematic [10]

2.2 Advanced Helical Coil Steam Generator (HCSG)

The Advanced Helical Coil Steam Generator (HCSG) consists of two independent sets of tube bundles wrapped around the riser. This configuration provides a high heat transfer surface area within a compact volume. Feedwater enters the tubes at the bottom, boils, and exits as superheated steam at the top. This "once-through" design allows for a rapid response to load changes and ensures that the primary and secondary systems remain physically separated by robust tube walls, acting as a critical barrier against the transport of activated corrosion products or fission products.

2.3 High-Pressure Containment Vessel (CNV) and Vacuum Technology

The RPV is housed within a cylindrical steel Containment Vessel (CNV), measuring 23.3 m in length and 4.6 m in diameter. The CNV is a safety-grade structure designed to withstand an internal pressure of 5.5 MPa. During normal operation, the annular space between the RPV and CNV is maintained at a deep vacuum (< 0.1 psia). This vacuum serves three critical functions:

- Thermal Insulation: It eliminates the need for conventional fiberglass or reflective insulation on the RPV, which could potentially debris-clog the ECCS strainers during an accident.
- Oxygen Exclusion: The absence of air prevents the formation of combustible hydrogen-oxygen mixtures following a core-damage event, significantly enhancing severe accident resilience.
- Steam Condensation: In the event of a safety valve discharge, the vacuum facilitates near-instantaneous steam condensation on the cold, submerged walls of the CNV, rapidly lowering the pressure.

2.4 Passive safety systems: DHRS and ECCS

The NuScale safety philosophy is centred on "passive" functionality, meaning the systems rely on gravity and natural convection rather than pumps, AC/DC power, or operator intervention [10]:

- Decay Heat Removal System (DHRS): In the event of a secondary side isolation, the DHRS opens valves to allow steam from the HCSG to flow to passive condensers submerged in the reactor pool. The heat is rejected to the pool, and the condensate returns to the HCSG by gravity.
- Emergency Core Cooling System (ECCS): The ECCS consists of three Reactor Vent Valves (RVVs) on the RPV head and two Reactor Recirculation Valves (RRVs) above the core. In a LOCA or total loss of power, these valves open. Steam vents into the CNV, condenses, and the liquid level rises until it reaches the RRVs, creating a continuous natural circulation loop that keeps the fuel submerged indefinitely.

2.5 Severe Accident Mitigation and Defence-in-Depth

The underground placement of the NuScale modules in a stainless steel-lined concrete pool (the Reactor Pool) provides a massive heat sink. This pool contains enough water to absorb the decay heat of a full 12-module plant for over 30 days without any makeup water (Fig. 3).

From a radiological risk perspective, this configuration offers [11]:

- Physical Protection: Enhanced resistance to aircraft impacts and external hazards.

- Source Term Limitation: The small core size (approx. 1/20th of a large PWR) means the inventory of volatile fission products (like I-131 and Cs-137) is drastically reduced, supporting the argument for smaller Emergency Planning Zones (EPZ) in Romania's national energy mix.

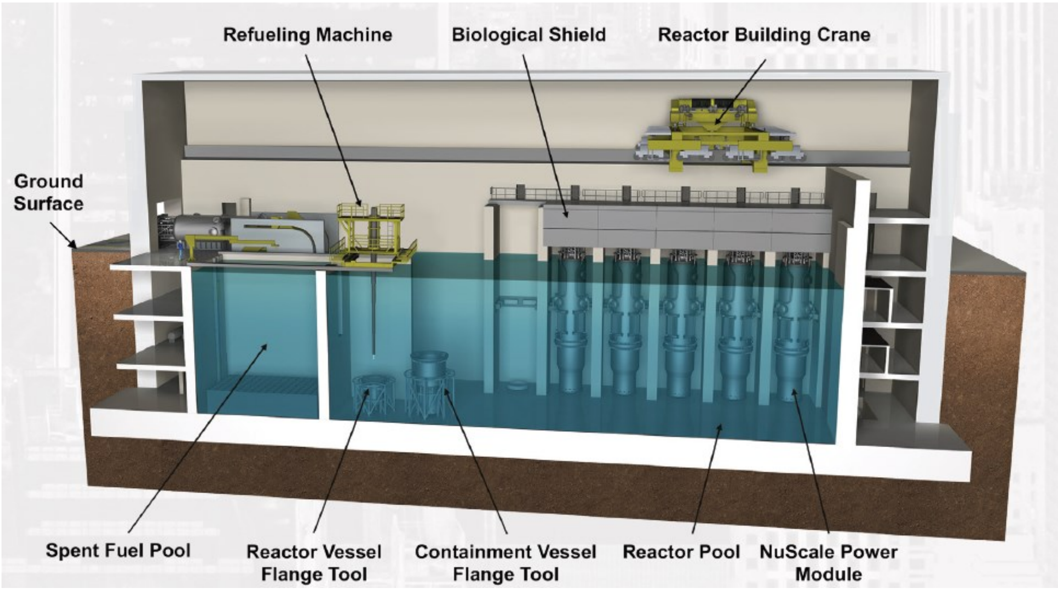

Fig. 3. Transversal view of the reactor building [10]

The NuScale architecture characterized by an integral design introduces a robust defence-in-depth strategy specifically aimed to minimize and passively reduce the radiological and environmental source term [12]:

- Reduced Inventory: Each 77 MWe module contains a significantly smaller fuel inventory compared to large-scale reactors, inherently limiting the potential fission product release.

- Below-Ground Installation: As illustrated in Figure 3, the modules are located below ground level in a stainless steel-lined concrete basin. This configuration provides superior seismic resistance, physical security, and a massive heat sink capable of absorbing decay heat for over 30 days.

- Fission Product Barriers: The design maintains five distinct barriers against the release of radioactivity: the fuel pellet, the fuel cladding, the Reactor Pressure Vessel (RPV), the Containment Vessel (CNV), and the biological shield/reactor building. (Fig. 4)

- Enhanced In-Vessel Retention (IVR): The internal steam generators provide a vast surface area that acts as a passive heat sink and a site for aerosol deposition (plate-out). This ensures that a significant fraction of radionuclides is trapped within the vessel before reaching the containment.

- Thermal Inertia and Grace Periods: The high primary water-to-power ratio provides a superior thermal buffer. This delay allows for the natural decay of short-lived isotopes (e.g. I131) before any potential release to the environment.

- Passive Scrubbing: The elimination of active pumps and the reliance on natural circulation reduce the energetic driving forces that would otherwise accelerate the transport of radioactive materials through containment leak paths.

3. Radiological risk evaluation

3.1 Source Term Analysis in iPWR SMRs

The "source term" represents the most critical variable in assessing the consequences of a nuclear accident. It defines the quantity, timing, and physical-chemical form of the radionuclides released. In this study, we distinguish between two primary stages [1]:

- Initial Source Term (Core Inventory): The total radionuclide inventory present within the fuel matrix, cladding gaps, and primary coolant during steady-state operation.
- Environmental Source Term (Release Fraction): The portion of the initial inventory that successfully breaches all five physical barriers, pellets, cladding, reactor pressure vessel (RPV), and the high-pressure containment vessel (CNV) and reactor building [8], to be discharged into the atmosphere. (Fig. 4)

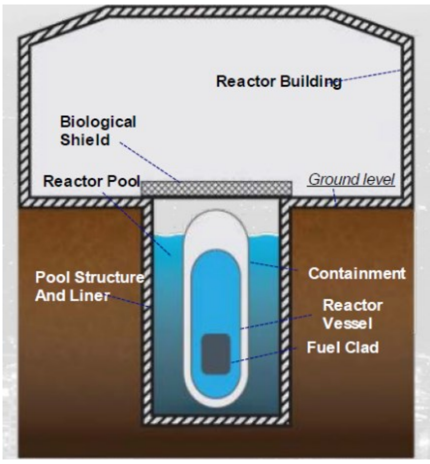

Fig. 4. The five barriers: fuel pellets, fuel cladding, RPV, CNV, building [8]

Estimating the source term for an iPWR SMR requires a multi-staged computational approach. While the underlying nuclear physics is similar to conventional PWRs, the integral geometry significantly influences the transport and attenuation of fission products.

The steady-state isotopic inventory is determined using depletion and transmutation codes such as ORIGEN. The focus is directed toward high-volatility fission products (e.g., Iodine, Caesium, and Noble Gases) and long-lived actinides. Due to the lower power density characteristic of SMRs compared to large-scale reactors, the isotopic ratios and the decay heat profile exhibit distinct signatures that favour longer "grace periods" before cladding failure.

To evaluate the progression of both Design Basis Accidents (DBAs) and Beyond Design Basis Accidents (BDBAs), the physical degradation of the core is modelled in three phases [1]:

- Gap Release: The immediate discharge of fission products accumulated in the fuel-cladding gap upon initial cladding rupture.
- In-Vessel Release: The release of radionuclides during fuel overheating and melting prior to vessel breach.
- Ex-Vessel Release: In the highly unlikely event of vessel failure, this phase involves Molten Core-Concrete Interaction (MCCI). However, in the NuScale design, the submerged steel containment effectively mitigates this phase by ensuring external cooling of the vessel.

3.2 Accident Consequences Modelling and JRODOS Integration

JRODOS (Real-time Online Decision Support System) is a comprehensive multi-user system designed to provide coherent support for atmospheric dispersion and environmental impact assessment across all stages of a nuclear emergency. To evaluate the radiological impact on the exclusion zone and surrounding communities, the derived source term was integrated into the JRODOS framework. [13]

The use of JRODOS in this analysis provides a standardized, European-validated platform for decision-making. The system's modular architecture allows for the integration of [14][15]:

- Local GIS Data: Accurate digital elevation models and land-use maps for the Dâmbovița County region.
- Source Term Presets: Tailored input files reflecting the NuScale core inventory and release fractions calculated in the previous sections.
- Optimization of Protective Actions: The software enables a comparative analysis of different countermeasure strategies (e.g., evacuation vs. sheltering), ensuring that the proposed emergency plan for Doicești is optimized for the specific radiological footprint of an SMR.

The simulation utilized the JRODOS atmospheric transport modules (RIMPUFF) [13] to model the plume's trajectory and the deposition of radionuclides (I131, Cs137 etc.) onto the soil. These models account for local meteorological conditions—including wind speed, stability classes, and precipitation—to provide a realistic mapping of the radioactive cloud's evolution from the Doicești site [16].

The modelling focused on several critical dose indicators to assess the biological risk and the necessity for protective actions (e.g., sheltering or iodine thyroid blocking) [17]:

- Total Effective Dose Equivalent (TEDE): Represents the sum of external and internal dose equivalents, providing a global measure of the radiological risk to an individual.
- Total Absorbed Bone Marrow Dose (TABD): Critical for assessing deterministic effects and acute radiation syndrome risks.
- Total Absorbed Lung Dose (TALD): Used to evaluate the impact of inhaling aerosolized alpha and beta emitters.
- Total Absorbed Thyroid Dose (TTHD): A primary metric for the NuScale SMR context, evaluating the uptake of radioiodine by the thyroid gland, especially important for the paediatric population.

The results are visualized through high-resolution situational awareness maps. These maps allow for the identification of the Precautionary Action Zone (PAZ) and the Urgent Protective Action Planning Zone (UPZ). Given the reduced source term and the passive safety features of the NuScale iPWR, the modelling aims to demonstrate whether the radiological consequences remain confined within a significantly smaller perimeter compared to traditional large-scale nuclear power plants [6].

The transition to iPWR SMR technology in Romania necessitates a re-evaluation of the traditional Emergency Planning Zone (EPZ) boundaries [6]. Utilizing the results generated by JRODOS, this study evaluates the feasibility of a "scalable EPZ"—a concept where the zone size is proportional to the reduced source term and the enhanced passive safety of the NuScale design involving:

- Data-Driven Zoning: Unlike the fixed 15–30 km radii typical for large-scale reactors, the JRODOS maps for the Doicești site demonstrate that under most BDBA (Beyond Design Basis Accident) scenarios, the projected doses (TEDE and TTHD) fall below the intervention levels prescribed by CNCAN within a much smaller perimeter, potentially limited to the site boundary.
- Regulatory Harmonization: This approach aligns with the newest IAEA and NRC recommendations, which advocate for "performance-based" safety perimeters. By integrating local topography and real-time meteorological data from JRODOS, Romania can implement a safety framework that protects the public without imposing unnecessary land-use restrictions around SMR parks.

3.3 Hypothetical Accident Scenario and Meteorological Parameterization

To quantify the radiological impact, the study defines four distinct simulation cases based on varying atmospheric stability conditions and wind profiles. The source term release is centred at the coordinates 45.001303 N, 25.398137 E (Doicești, Dâmbovița County). The dispersion is modelled using the RimPuff Gaussian puff model within JRODOS, which is particularly effective for assessing the early phase of an atmospheric release. [18]

3.3.1Meteorological Sensitivity Cases

The overall wind direction is set at 320 degrees, representing a conservative "worst-case" vector directed toward high-density population centres, including Târgoviște and Bucharest. The release height is fixed at 10 m (ground-level release simulation) with a duration of 1 hour [19].

Meteorological Sensitivity Cases are summarised in Table 2

Table 2. Meteorological Sensitivity Cases

Case	Stability Class	Wind Speed	Modelling Range	Description
Case 1	A (Extremely Unstable)	1 m/s	40 km	Daytime scenario with strong vertical mixing; represents rapid but localized dispersion.
Case 2	F (Stable)	3 m/s	100 km	Nighttime inversion scenario; limits vertical mixing, causing the plume to stay concentrated for longer distances.
Case 3	D (Neutral)	4 m/s	200 km	Representative of average/high wind speed conditions in Romania; focuses on long-range transport.
Case 4	Integrated	Variable	200 km	A 24-hour composite simulation integrating the dynamics of the first three cases to assess cumulative impact.

3.3.2 Rationale for Case Selection

Rationale for Case Selection are listed below:

- The RimPuff Model: By selecting the Gaussian puff approach without precipitation, the study establishes a "dry deposition" baseline, which is typically more conservative for long-range air concentration calculations.[19] [20]
- Geographic Risk: The 320-degree orientation is chosen to test the robustness of emergency plans for the Dâmbovița-Bucharest corridor, the most critical socio-economic axis in the region [18] [19] [20]
- Release Height (10 m): This is a very "conservative" (safe) assumption. In a real SMR building, if the release happens through a stack, it might be

higher, which would actually decrease the dose at the site boundary. By choosing 10m, we are aiming for the maximum possible risk. [18] [19]

- Case 4 (Integration): This case is vital for understanding the Total Effective Dose Equivalent (TEDE) over a full diurnal cycle (day/night transition) [18] [19]

- Atmospheric Stability (Pasquill-Gifford): The selection of Classes A, D, and F ensures a comprehensive envelope of potential environmental outcomes. Class F is of particular interest for radiological protection, as the lack of turbulence often results in the highest ground-level concentrations at significant distances from the source. [21]

4. Results and Discussions

The radiological impact of the four simulated accident scenarios was quantified through a series of high-resolution spatial maps and dose-distance profiles generated by the JRODOS platform.

By integrating the NuScale-specific source term with the local topography of the Doicești site, the results provide a comparative visualization of how atmospheric stability and wind profiles dictate the footprint of a potential release.

The analysis focuses on the distribution of Total Effective Dose Equivalent (TEDE) and Total Thyroid Dose (TTHD), benchmarks that are critical for determining the efficiency of the "scalable EPZ" concept.

In the following sections, we examine the geographical extent of the plume for each case, evaluating the distance at which radiological values fall below the intervention thresholds established by the National Commission for Nuclear Activities Control (CNCAN).

This spatial assessment is essential for defining the necessary precautionary and urgent protective action planning zones within the context of Romania's evolving nuclear energy landscape.

4.1 Numerical Results and Comparative Analysis of Calculated Doses

The results presented in Table 3 demonstrate the significant influence of atmospheric stability on the dispersion of radionuclides from the Doicești site.

A primary observation is the rapid attenuation of the radiological impact as a function of distance, even under the most conservative meteorological assumptions.

Table 3. Calculated Doses (JRodos Software)

Case No.	Area	Bone Marrow (TABDmax) [mSv]	Lungs (TALDmax) [mSv]	Thyroid (TTHDmax) [mSv]	Total (TEDEmax) [mSv]
1	Doicești (Source)	3.41E+00	3.10E+01	5.70E+02	3.53E+01
	Târgoviște	1.24E-03	1.05E-02	1.50E-01	1.05E-02
	Bucharest	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2	Doicești (Source)	7.18E00	6.68E+01	1.26E+03	7.75E+01
	Târgoviște	3.46E-02	3.23E-01	7.92E+00	3.47E-01
	Bucharest	4.10E-03	4.14E-02	5.63E-01	3.24E-02
3	Doicești (Source)	3.09E-01	2.75E+00	4.95E+01	3.08E+00
	Târgoviște	6.73E-03	5.87E-02	8.62E-01	5.59E-02
	Bucharest	2.45E-04	2.43E-03	2.85E-02	1.92E-03
4	Doicești (Source)	4.02E-01	3.15E+00	5.43E+01	3.45E+00
	Târgoviște	1.67E-03	1.33E-02	2.03E-01	1.00E-02
	Bucharest	1.17E-05	1.11E-04	1.53E-03	1.02E-04

Key Findings by Scenario:

- Case 1 (Stability Class A - Unstable): In contrast, the highly unstable atmosphere of Case 1 results in lower peak doses compared to Case 2. While the thyroid dose at Doicești remains significant (570 mSv), the impact on Bucharest is negligible (0.00 mSv), illustrating how strong vertical turbulence and daytime convection effectively dilute the plume.
- Case 2 (Stability Class F - Stable): This scenario represents the "worst-case" radiological impact at the source. The TEDEmax reaches 77.5 mSv at Doicești, and the TTHDmax (Thyroid Dose) peaks at 1,260 mSv. This is consistent with stable nighttime conditions, where vertical mixing is suppressed, keeping the plume concentrated near ground level. However, even in this case, the dose at Târgoviște drops to 0.347 mSv, well below the annual public limit of 1 mSv.
- Case 3 (Neutral) & Case 4 (Integrated): These cases show much lower peak values at the source (TEDE approx. 3.08 – 3.45 mSv), reflecting more common atmospheric conditions in Romania. For these scenarios, the radiological

footprint at the Târgoviște and Bucharest levels remains several orders of magnitude below any regulatory intervention threshold.

4.2 Impact on Emergency Planning:

A critical finding of this study is that Bucharest remains virtually unaffected in all simulated scenarios, with the highest TEDE recorded being only 0.0324 mSv (Case 2), which is less than the dose received from a single dental X-ray.

The high Thyroid Dose (TTHD) at the Doicești source (up to 1,260 mSv) highlights that while the general population is safe, Urgent Protective Actions (such as Iodine Thyroid Blocking - ITB) would be strictly necessary for personnel and residents in the immediate vicinity of the plant. However, the data supports the "scalable EPZ" [6] argument, as the urgent intervention levels are not reached at the Târgoviște perimeter, suggesting that the emergency planning zone could be confined to a radius significantly smaller than those used for traditional 1000 MWe reactors.

The results obtained must be interpreted in relation to the radiological safety standards and intervention levels established by the National Commission for Nuclear Activities Control (CNCAN). According to the Romanian regulations for emergency preparedness, the urgent protective action threshold (e.g., sheltering) is typically set at a generic level of 10 mSv (TEDE).

It is important to emphasize that the doses calculated at the Doicești source, which exceed this threshold, correspond to a Beyond Design Basis Accident (BDBA) scenario. Such events represent the most extreme hypothetical conditions, characterized by an extremely low probability of occurrence, far beyond the standard safety envelopes.

Our simulations indicate that even under these severe conditions, the impact at the Târgoviște perimeter (max 0.347 mSv in Case 2) remains well below the intervention level. Furthermore, the maximum recorded Total Thyroid Dose (TTHD) at the source (1,260 mSv) significantly exceeds the 100 mGy threshold for iodine administration on-site, but its precipitous decline to 7.92 mSv at the Târgoviște level confirms that the radiological risk is effectively contained by distance. These findings provide a quantitative basis for proposing a restricted Emergency Planning Zone (EPZ) for NuScale SMRs in Romania, demonstrating that public safety is maintained even in the most improbable accident sequences.

4.3 Spatial Analysis of Case 1 Situational Map (Stability Class A)

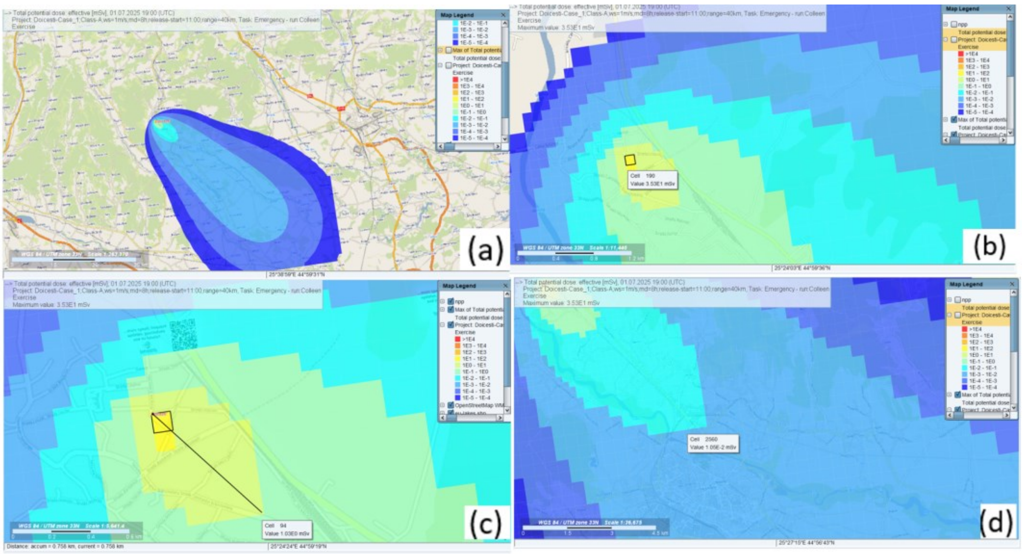

Fig. 5. Case 1. General cloud form (a), TEDEmax @ Doiceşti (source) (b), TEDEmax @ Târgoviște (c), TEDEmax @ Bucharest (d)

Figure 5 illustrates the spatial distribution of the Total Effective Dose Equivalent (TEDE) for the first scenario. Under Stability Class A conditions, extremely instable, characterized by strong solar insolation and low wind speeds (1 m/s) the plume exhibits a characteristic broad, "conical" dispersion pattern:

- Source Impact (Doiceşti): As seen in Figure 5(b), the maximum dose is concentrated in the immediate vicinity of the release point, reaching 35.3 mSv. The color gradient indicates that the area exceeding the 10 mSv intervention threshold is strictly limited to the site boundary and its closest surroundings.
- Târgoviște Perimeter: Moving toward Târgoviște (Fig. 5c), the plume's effective dose drops precipitously to 0.0105 mSv. The JRODOS situational map confirms that at this distance, the radiological impact is practically indistinguishable from the natural background radiation.
- Distal Impact (Bucharest): In Figure 5(d), the simulation confirms a zero-dose result for the Bucharest area. The unstable atmospheric conditions promote vertical mixing, which effectively "breaks up" the plume before it can reach major population centres at the 80–100 km range.

This scenario validates the "inherent safety" argument of the NuScale SMR: even in a Beyond Design Basis Accident (BDBA), the radiological footprint under unstable daytime conditions is highly localized, providing a strong technical basis for the reduction of the Precautionary Action Zone (PAZ).

4.4 Spatial Analysis of Case 2 Situational Map (Stability Class F)

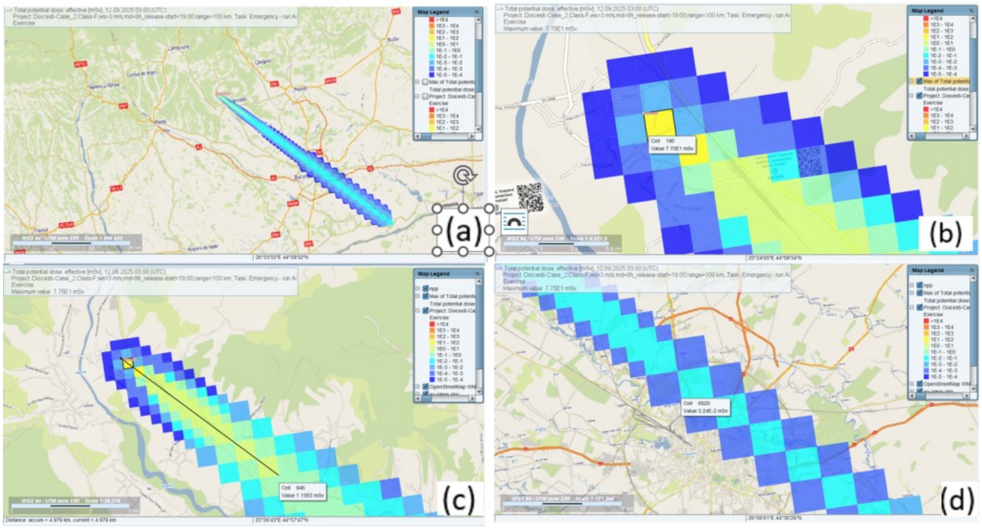

Fig. 6. Case 2 General cloud form (a), TEDEmax @ Doicești (source) (b), TEDEmax @ Târgoviște (c), TEDEmax @ Bucharest (d)

Figure 6 presents the radiological footprint for the most conservative meteorological scenario (Case 2), characterized by a highly stable atmosphere and a wind speed of 3 m/s. Unlike the previous case, the plume geometry is significantly more elongated and narrower, reflecting the lack of vertical and horizontal mixing typical of nighttime temperature inversions.

- Maximum Source Impact: The simulation records the highest TEDEmax at the Doicești source point, reaching 77.5 mSv. As shown in Figure 6(b), the dose is concentrated in a tight perimeter, but the values are more than double those of Case 1, highlighting the risk of localized high exposure under stable conditions. This is due to "accumulation effect" in nocturnal thermal inversion.
- Plume Persistence (Târgoviște): At the Târgoviște level (Fig. 6c), the TEDEmax is 0.347 mSv. Although this value remains safely below the 1 mSv public limit, the situational map clearly shows that the plume maintains its coherence over much longer distances than in Case 1, with a clearly defined trajectory toward the South-East.
- Long-Range Transport (Bucharest): Figure 6(d) illustrates the impact at the 100 km range (Bucharest). Even in this "worst-case" stability scenario, the maximum effective dose is only 0.0324 mSv. While the dose is non-zero (unlike Case 1), it is still radiologically insignificant for the general population, being equivalent to approximately one-third of the dose received during a standard chest X-ray.

4.5 Spatial Analysis of Case 3 Situational Map (Stability Class D)

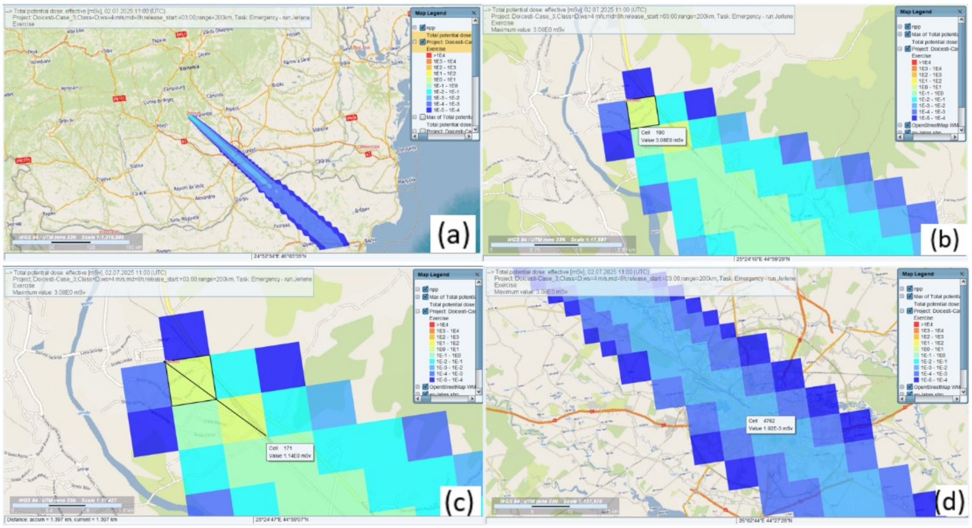

Fig. 7. Case 3 General cloud form (a), TEDEmax @ Doicești (source) (b), TEDEmax @ Târgoviște (c), TEDEmax @ Bucharest (d)

Figure 7 illustrates the radiological consequences for Case 3, characterized by neutral atmospheric stability and sustained wind speeds, meteorological condition predominant for Romania. This scenario demonstrates a balanced dispersion pattern, where the plume maintains a moderate width while being transported over a significant range toward the South-East.

- Impact at Source (Doicești): The TEDEmax recorded at the release point is 3.08 mSv. As shown in Figure 7(b), the dose is significantly lower than in the previous cases, illustrating how higher wind speeds (4 m/s) facilitate the rapid removal and dilution of radionuclides from the immediate site vicinity.
- Târgoviște Perimeter: For the Târgoviște area (Fig. 7c), the simulation indicates a maximum effective dose of only 0.0559 mSv. This value is approximately 20 times lower than the annual public dose limit, confirming that under neutral conditions, the radiological risk to nearby urban centres is negligible.
- Long-Range Assessment (Bucharest): In Figure 7(d), the impact at the 200 km range is analysed. The results show a TEDEmax of 0.00192 mSv. This result is statistically insignificant, representing a fraction of the daily dose received from natural background radiation.

4.6 Spatial Analysis of Case 4 Situational Map (Integrated 24h Scenario)

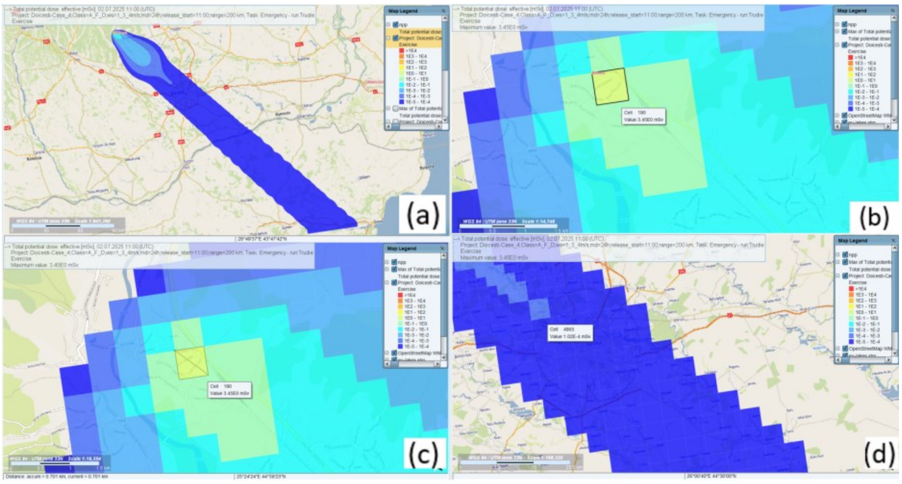

Fig. 8. Case 4 General cloud form (a), TEDEmax @ Doicești (source) (b), TEDEmax @ Târgoviște (c), TEDEmax @ Bucharest (d)

Figure 8 illustrates the integrated radiological impact over a 24-hour period, effectively combining the meteorological dynamics of the previous three cases. This scenario provides the most realistic estimation of the total potential exposure following a prolonged release, accounting for diurnal atmospheric transitions.

- Cumulative Impact at Source: The integrated TEDEmax at the Doicești source is 3.45 mSv. As shown in Figure 8(b), the cumulative dose remains well below the 10mSv urgent intervention threshold, even when accounting for a full day of exposure. This highlights the significant safety margins provided by the SMR's reduced source term.
- Regional Dispersion Profile: In Figure 8(c), the plume's footprint at the Târgoviște level shows a TEDEmax of 0.0100 mSv. The integrated mapping reveals that the radiological "buffer" between the plant and the nearest city is substantial, with cumulative values representing only 1% of the annual public dose limit.
- Long-Range Integrity: At the 200 km range (Fig. 8d), the cumulative impact is negligible, with a TEDEmax of only 0.000102 mSv. This result confirms that even a continuous release over 24 hours under varying conditions does not pose a threat to the Bucharest metropolitan area or other distant population centres.

4.7 Summary of Findings from Situational Maps

The Case 1 scenario validates the "inherent safety" argument of the NuScale SMR: even in a Beyond Design Basis Accident (BDBA), the radiological footprint under unstable daytime conditions is highly localized, providing a strong technical basis for the reduction of the Precautionary Action Zone (PAZ).

The Case 2 scenario confirms that even under the most unfavourable meteorological conditions (Class F), the radiological consequences of a NuScale SMR BDBA in Romania do not reach intervention levels for the nearest major urban centres. This evidence supports the technical possibility of implementing performance-based Emergency Planning Zones that are much smaller than the current 15–30 km standards.

The Case 3 scenario reinforces the conclusion that the inherent safety features of the NuScale SMR—combined with typical atmospheric behaviour—result in a highly manageable radiological footprint. Even with a modelling range extended to 200 km, the plume's impact remains well below any level that would trigger urgent protective actions for the general public.

The spatial analysis across all four cases leads to several critical conclusions for Romania's nuclear strategy:

- Strict Localization: High radiological values are confined to the immediate vicinity of the Doicești site.
- Thyroid Protection: While the TTHD at the source can be significant in severe cases (Case 2: 1,260 mSv), it drops below intervention levels before reaching Târgoviște (7.92 mSv).
- Scalable EPZ Validation: The JRODOS simulations consistently show that the 1 mSv and 10 mSv perimeters do not extend to major urban centres, providing the necessary technical justification for a reduced Emergency Planning Zone.

5. Conclusions

This paper evaluated the radiological risk associated with the adoption of NuScale Small Modular Reactor (SMR) technology within Romania's national energy mix, using the Doicești site as a primary case study. The integrated analysis—spanning from reactor technical specifications to advanced atmospheric dispersion modelling in JRODOS—leads to the following fundamental conclusions:

- Inherent Safety and Localized Impact: The results demonstrate that due to the reduced radionuclide inventory and passive safety systems, the radiological consequences of a Beyond Design Basis Accident (BDBA) remain highly concentrated near the source. Even under the most unfavourable meteorological conditions (Stability Class F), the Total Effective Dose Equivalent (TEDE) at the Târgoviște perimeter remains below 0.35 mSv, which is significantly lower than the annual public dose limit of 1 mSv.
- Validation of the Scalable EPZ Concept: Spatial simulations confirm that Emergency Planning Zones (EPZs) can be recalculated and significantly

restricted compared to conventional large-scale reactors. Data indicates that intervention thresholds for sheltering or evacuation are not reached outside the immediate vicinity of the Doicești site, facilitating the integration of these plants near industrial zones or existing communities.

- Protection of Major Urban Centres: The study proves that the radiological impact on the Bucharest metropolitan area is negligible across all four analysed cases, with values comparable to natural background radiation. This finding is crucial for increasing public acceptance and dismantling exaggerated risk perceptions regarding the distance between nuclear sites and the capital city.
- Necessity for Regulatory Adaptation: While iPWR SMR technology offers superior safety margins, its successful implementation in Romania depends on updating CNCAN regulations to reflect the specificities of modular designs. The use of decision support tools like JRODOS has proven indispensable for evidence-based emergency planning.[5]

In summary, the adoption of NuScale technology at Doicești represents a safe and viable step toward the decarbonization of the Romanian energy sector. The enhanced radiological safety of these units allows for greater siting flexibility, positioning Romania as a potential regional leader in the operation of next-generation nuclear technologies.

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