Radiological Emergency Planning Zones for SMRs: A JRODOS-Based Assessment

NATIONAL CENTRE FOR NUCLEAR RESEARCH
ŚWIERK

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National Centre for Nuclear Research (NCBJ), Poland

•Largest nuclear research institute in Poland (>1200)
•Located in **Świerk near Warsaw**
•Research in **nuclear energy, radiation safety, physics and nuclear technologies**
•Operation of the **MARIA research reactor** – one of the most powerful research reactors in Europe
•Production of **radioisotopes for medicine and industry**
•Development of **nuclear safety analyses and emergency preparedness tools**
•Participation in **international projects and collaborations (IAEA, EU programmes)**
•Research on **nuclear reactor safety, severe accidents and radiological consequences**

MARIA is currently the **only operational research nuclear reactor in Poland**, with a **thermal power of 30 MW**. Its construction began in **June 1970** at the **Institute of Nuclear Research in Świerk**. The reactor achieved **first criticality in December 1974**.

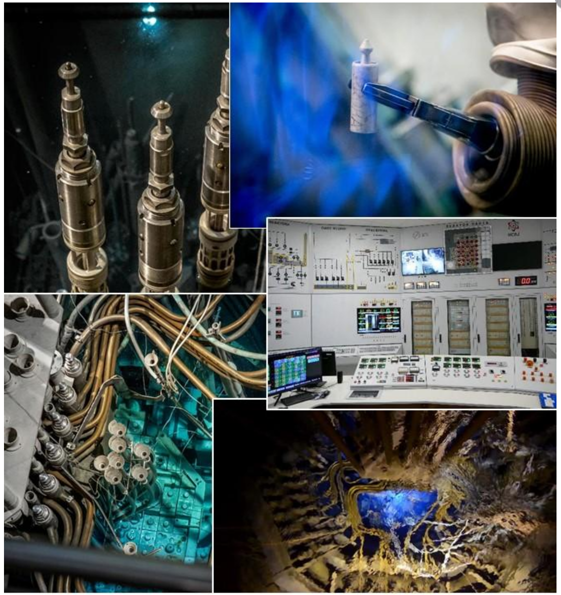
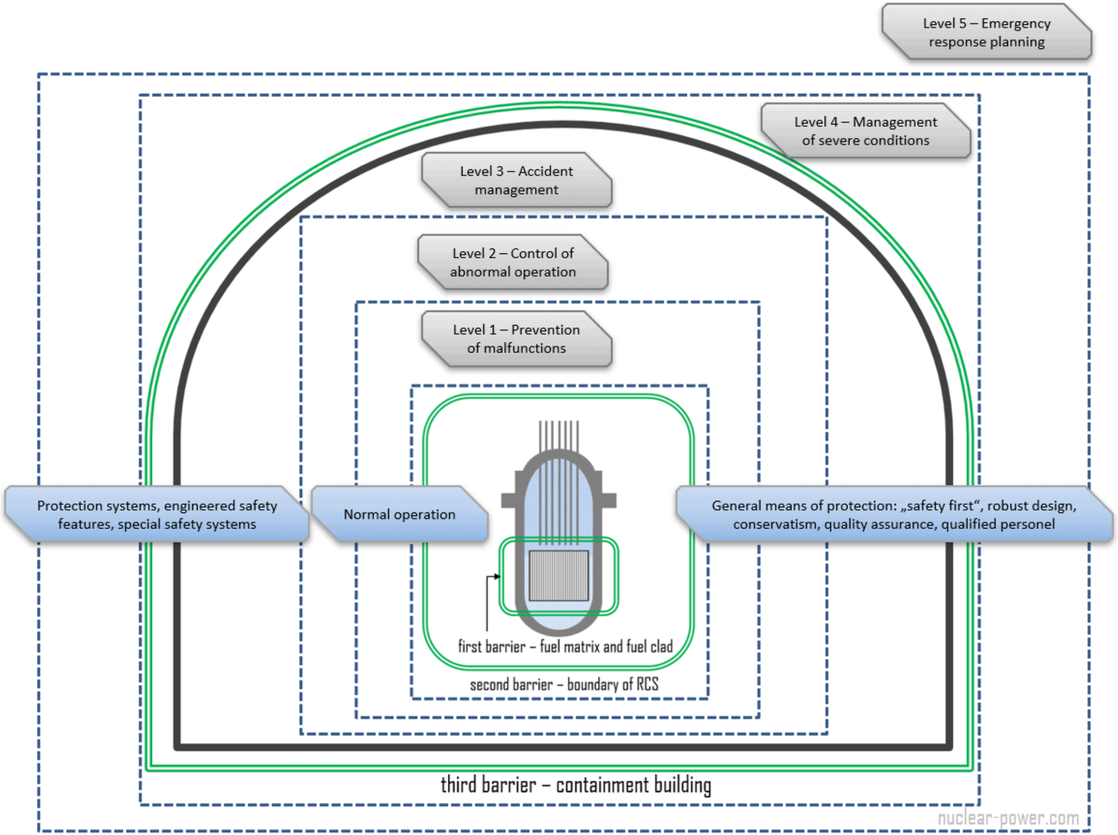


Fig. 1. View of the MARIA research reactor.

Fig. 2. NCBJ campus.

Nuclear Safety – Defence-in-depth Principle



source:[1] https://www.nuclear-power.com/nuclear-power/reactor-physics/nuclear-safety/defence-in-depth-principle/

Fig. 3. Schematic of the Defence-in-Depth methodology.

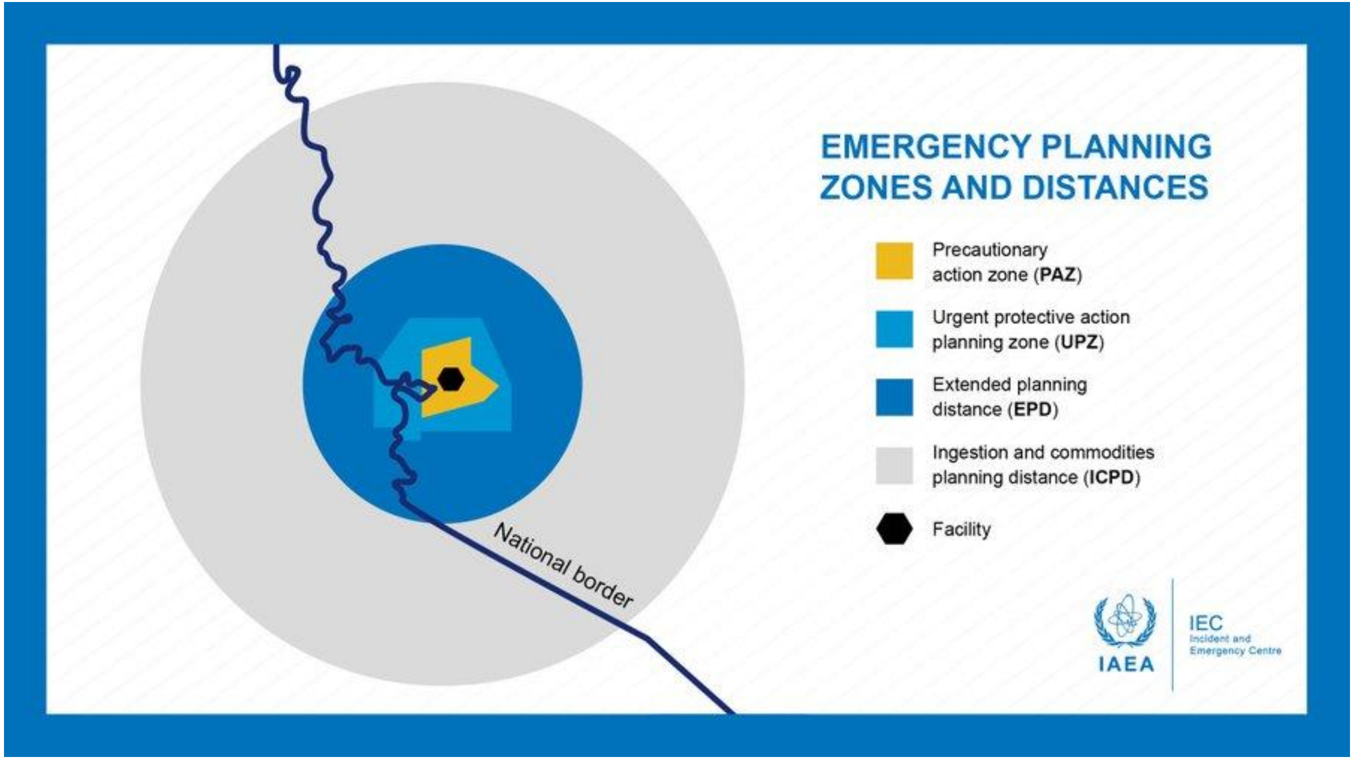
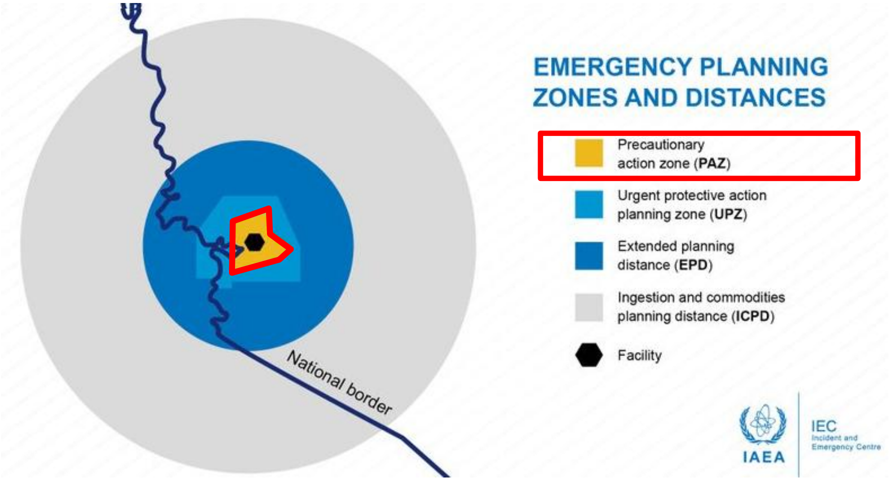


Fig. 4. Schematic of Emergency Planning Zones and distances recommended by the IAEA.

Precautionary Action Zone (PAZ)

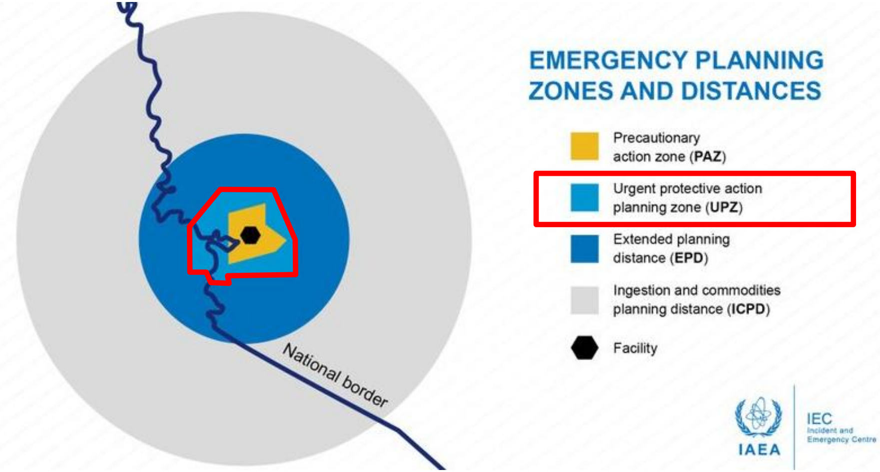
For EPC I facilities, arrangements shall be made to take urgent protective actions and other response actions **before any significant release of radioactive material occurs**, based on plant conditions (i.e., conditions leading to the declaration of a **general emergency**), in order to avoid or minimize **severe deterministic effects**.



Facility type	Thermal power (MWth)	PAZ
EPC I – Reactors	≥ 1000 MWth	3–5 km
EPC I – Reactors	100–1000 MWth	3–5 km

Urgent Protective Action Planning Zone (UPZ)

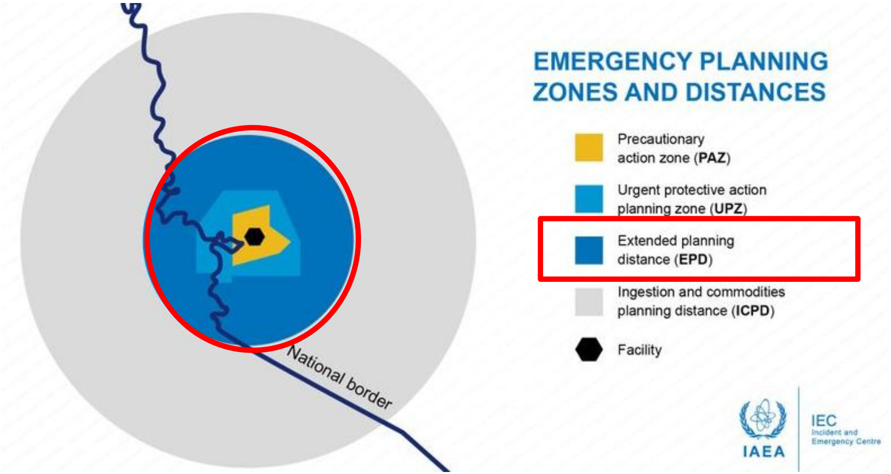
For EPC I and EPC II facilities, arrangements shall be made to initiate urgent protective actions and other response actions, **if possible before any significant release of radioactive material occurs**, based on conditions at the facility, and **after a release**, based on monitoring and assessment of the off-site radiological situation, in order to reduce the risk of **stochastic effects**.



Facility type	Thermal power (MWth)	UPZ
EPC I – Reactors	≥ 1000 MWth	15-30 km
EPC I – Reactors	100–1000 MWth	15-30 km
EPC II – Reactors	10-100 MWth	0.5-5 km
EPC II – Reactors	2-10 MWth	0.5 km

Extended Planning Distance (EPD)

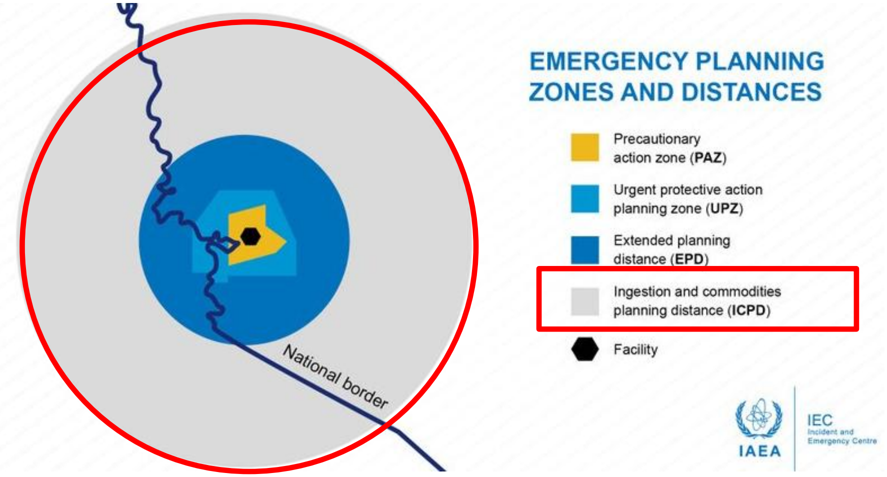
For EPC I and EPC II facilities (beyond the UPZ), arrangements shall be made to conduct monitoring and assessment of the off-site radiological situation in order to identify areas where, within a time period that allows effective risk reduction, **stochastic effects** can be reduced by implementing protective and other response actions **within a day to a week, or up to a few weeks**, following a significant radioactive release.



Facility type	Thermal power (MWth)	EPD
EPC I – Reactors	≥ 1000 MWth	100 km
EPC I – Reactors	100–1000 MWth	50 km

Ingestion and Commodities Planning Distance (ICPD)

For EPC I and EPC II facilities (beyond the EPD), arrangements shall be made to implement response actions to protect the food chain and water supply, as well as commodities other than food, from contamination following a significant radioactive release, and to protect the public from the ingestion of contaminated food, milk and drinking water and from the use of non-food commodities that may be contaminated following a significant radioactive release.



Facility type	Thermal power (MWth)	**ICPD**
EPC I – Reactors	≥ 1000 MWth	300 km
EPC I – Reactors	100–1000 MWth	100 km

Emergency Planning Zones – Key Principles

Zone boundaries should be easy to identify in the field.
• Use natural and existing features as boundaries (rivers, roads, railways, embankments, slopes).
• Avoid cutting through residential areas or population clusters (industry, schools, prisons, hospitals).
• Include entire facilities or settlements within a single zone to reduce social impacts.
• Urgent Protective Action Zone May be divided into sectors.
• Sectoring helps apply actions only in areas actually at risk.

Evacuation and Logistics
•<u>Consider efficient implementation of emergency actions when defining zones.</u>
•Prioritize clear evacuation routes.
•Avoid moving people into inner zones during an emergency.
•Minimize time spent by evacuees in outer zones.

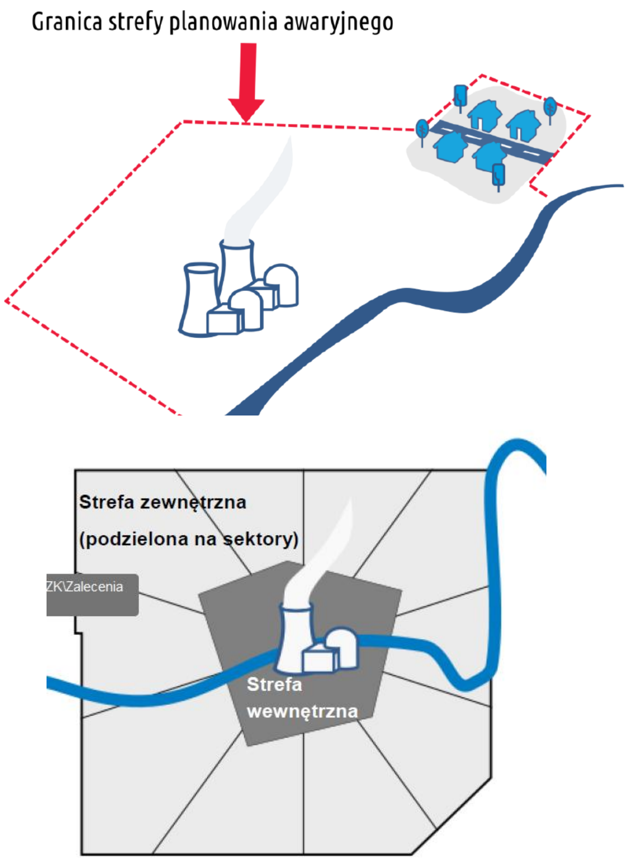
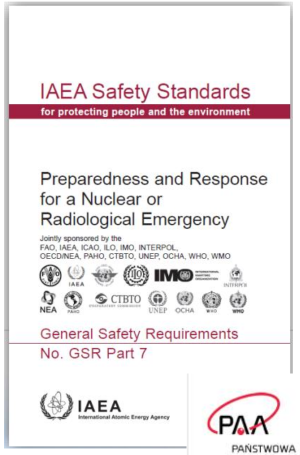


Fig. 6. Model of the emergency planning zones recommended by the Polish National Atomic Energy Agency (PAA).

Protective Action Planning Zone and Extended Planning Distance [2]

Precautionary Action Zone (PAZ)	[only for Category I facilities] Criterion: For external exposure over any 10-hour period post-accident: • For the red bone marrow, an equivalent dose ≥1 Sv. • For the skin – calculated as an average over any 100 cm^2 of exposed area – an equivalent dose at a depth of 0.4 mm ≥10 Sv. For internal exposure over any 30-day period: • For the red bone marrow: • From isotopes with atomic number Z ≤ 89, an equivalent dose ≥2 Sv. • From isotopes with atomic number Z ≥ 90, an equivalent dose ≥0.2 Sv. • For the thyroid, an equivalent dose ≥2 Sv. • For the lungs, an equivalent dose ≥30 Sv.
Urgent Protective Action Planning Zone (UPZ)	for Category I and II facilities Criterion: •Projected effective dose (without ingestion) ≥ 100 mSv •equivalent thyroid dose ≥ 50 mSv within 7 days.
Extended Planning Distance (EPD)	for Category I and II facilities Criterion: Projected effective dose ≥ 100 mSv over 1 year (including ingestion).
Ingestion and Commodities Planning Distance (ICPD)	for Category I and II facilities Criterion: Projected effective dose ≥ 10 mSv over 1 year (from ingestion of food and water).



How Do We Determine Emergency Planning Zones and Distances?

Atmospheric transport of radionuclides must be modeled. The analysis is based on **national regulations and dose criteria**.
Simulation results are used to determine **how „far” dose criteria levels can be reached**, which forms the basis for defining zone boundaries and distances.
Site-specific meteorological data are used to model atmospheric dispersion.

Source term evaluation includes:

- Release height
- Magnitude of release + Duration
- Radionuclide composition

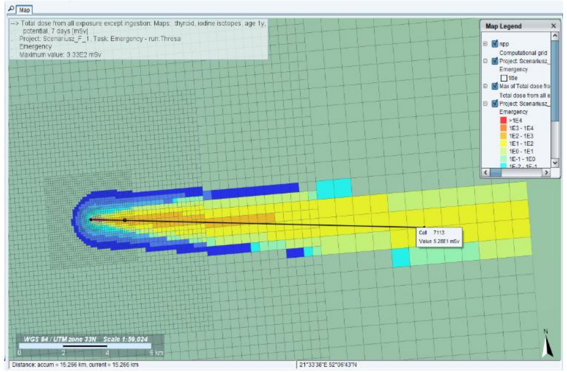


Fig. 7. Results of the radionuclide transport model simulations.

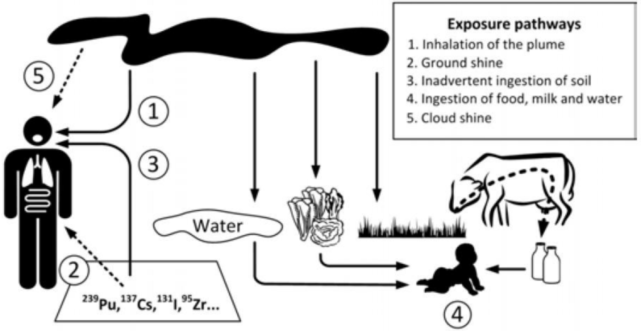


Fig. 8. Schematic of radionuclide transfer pathways in the environment.

METHODOLOGY FRAMEWORK

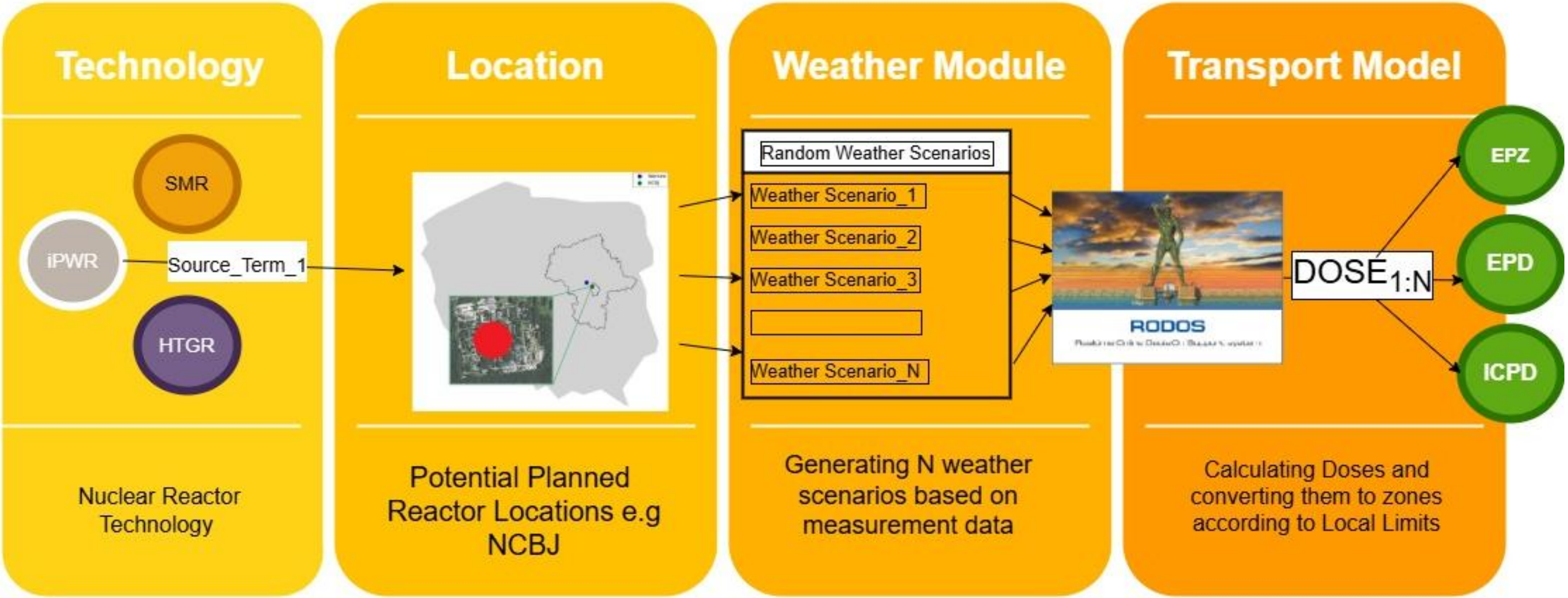
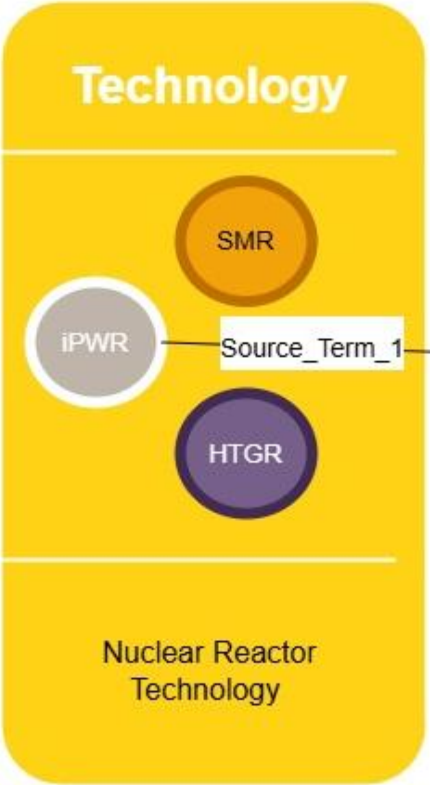
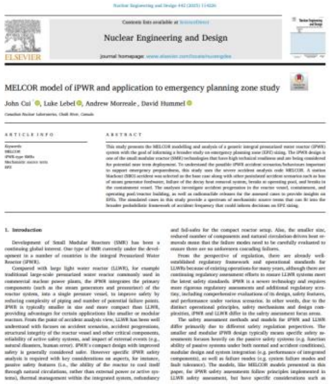


Fig. 8. Methodological framework for the determination of Protective Action Planning Zones (PAPZs) for Category II facilities using the JRODOS system.

Integral Pressurized Water Reactor (iPWR)



- The analyzed plant is a generic iPWR with a thermal power of about ~100 MWth.
- It features a compact steam generator (SG).
- Although generic, the design incorporates features typical of advanced Light Water Small Modular Reactors (LW-SMRs):
- Integral Reactor Pressure Vessel (RPV)
- Compact Steam Generator


Nuclear Engineering and Design

MELCOR model of iPWR and application to emergency planning zone study

John Cui, Luke Lebel, Andrew Morreale, David Hummel

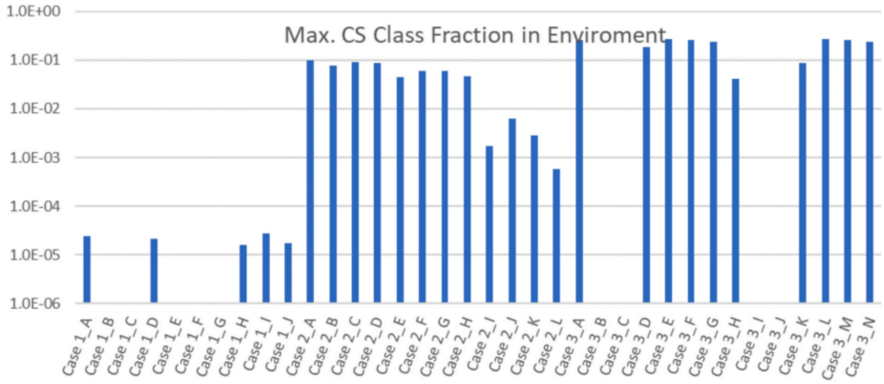


Fig. 12. Maximum Fractions of Class Cs in Environment.

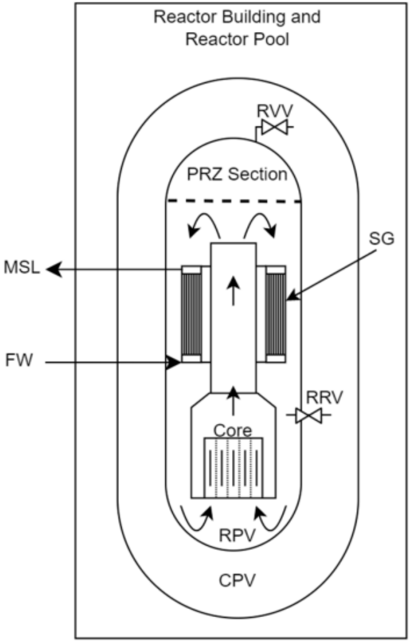
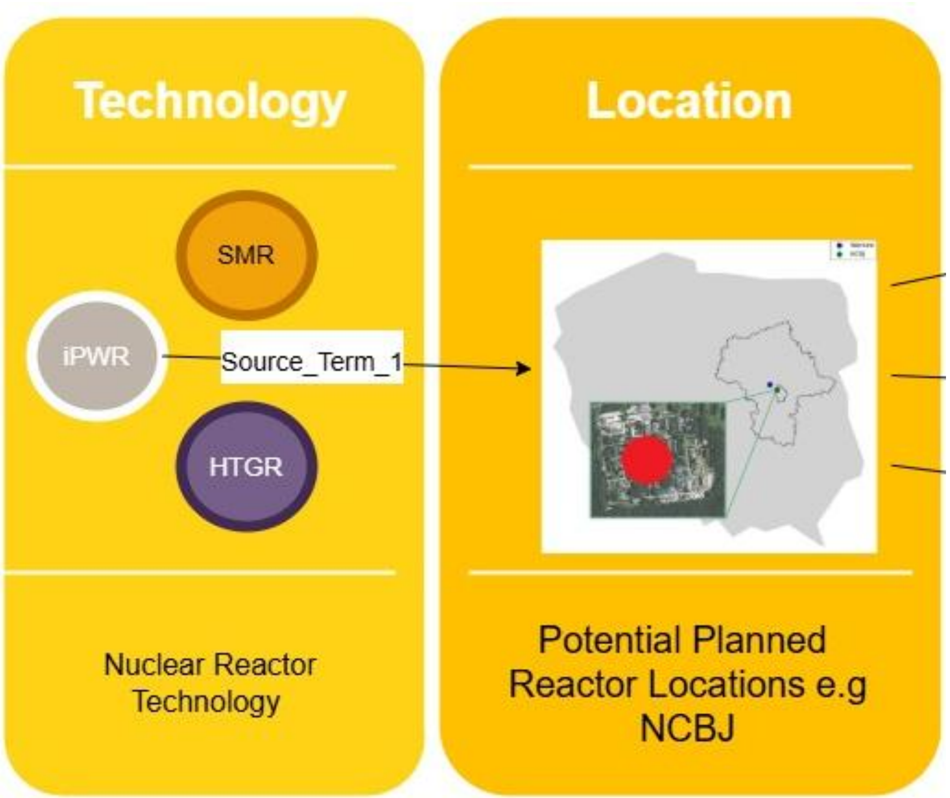
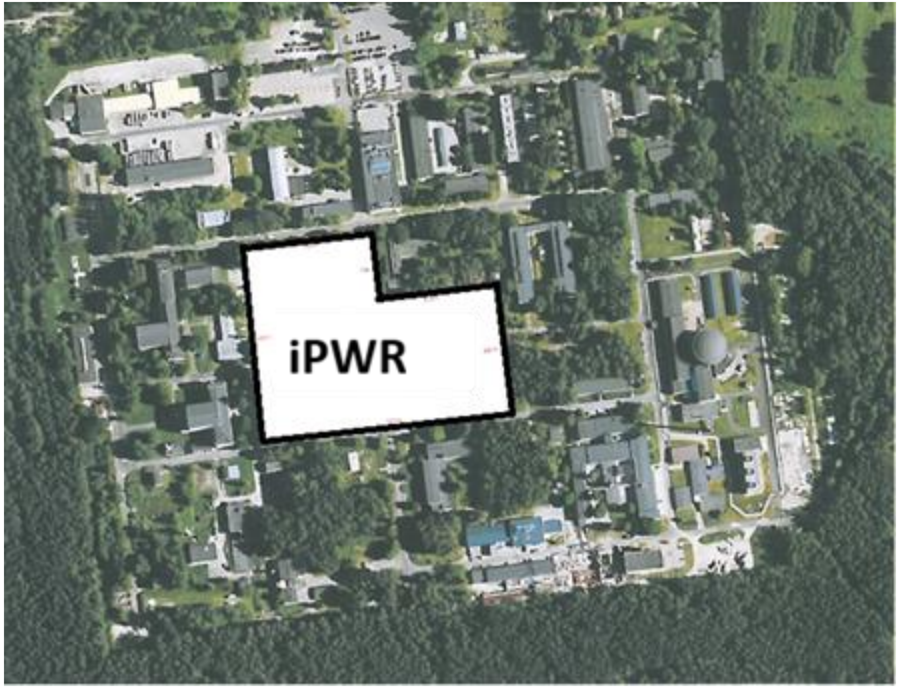


Fig. 9. Schematic diagram of the **integral Pressurized Water Reactor (iPWR)**. [3]

National Centre for nuclear research Campus





Methodology for Emergency Scenario Analysis

- **Probabilistic approach** used to account for meteorological variability.
  - **Meteorological data:** at least **3 years of historical data** required.
  - **Precipitation:** real **historical precipitation data** can be included in the calculations.

Simulation of Emergency Scenarios

  - Calculations performed for **1,000 different random release scenarios**.
  - Each scenario considers **different meteorological conditions**.

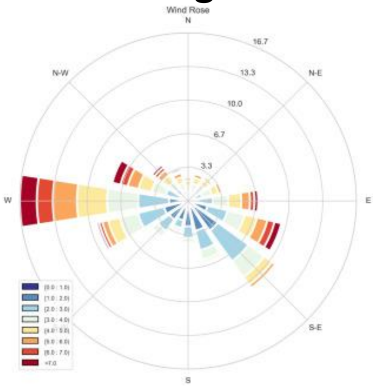
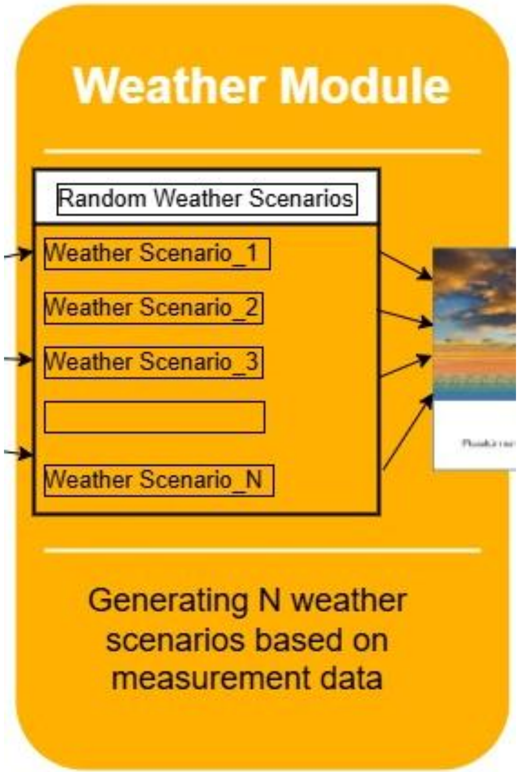


Fig. 10. Wind rose chart for NCBJ SWIERK location. Data from 2013–2022.



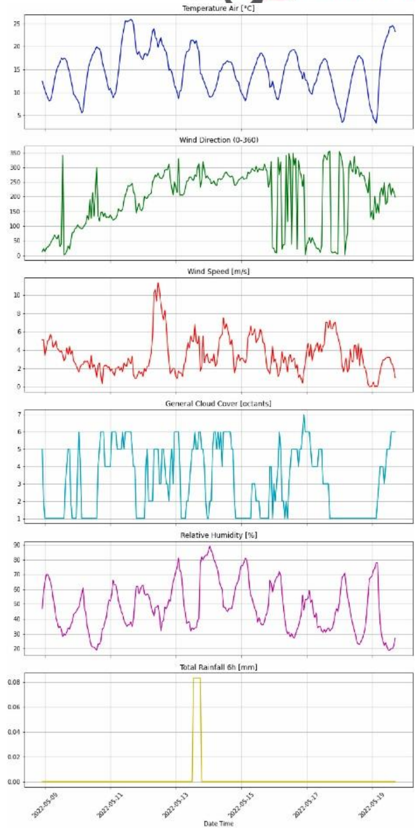
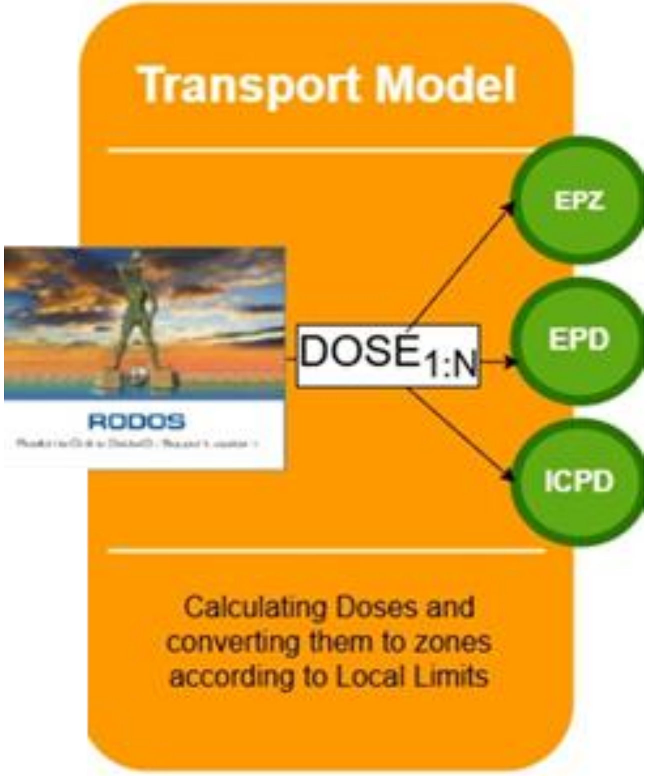


Fig. 11. Weather data scenario for a randomly selected state from May 8, 2022, 22:00 to May 19, 2022, 10:00. The weather sequence includes air temperature, wind direction, wind speed, general cloud cover, relative humidity, and total rainfall over 6 h.

JRODOS - Decision Support Systems

- JRODOS is designed to assist decision-makers in mitigating the consequences of radioactive releases after a nuclear incident, applicable in national or regional emergency control centers. [3]
- **Local-Scale Models**: RMPP: Meteorological pre-processor, RIMPUFF: Puff diffusion model for short-range dispersion. Dipcot: Lagrangian model for local dispersion.
- **Long-Range Models**: MATCH: Eulerian model for long-range atmospheric dispersion. **LASAT**: Lagrangian model for long-range scenarios, with some limitations.
- **Radionuclide Transfer Modeling**: DEPOM: Models deposition from the atmosphere to the ground and food products. FDMT: Calculates radionuclide transfer through the food chain, requiring customization based on regional climate, agriculture, and dietary habits



Step-by-Step Statistical Procedure

1. **Dose Calculations on Spatial Grid**
   1. Results stored on a **dense numerical grid** (from the **JRODOS system**).
2. **Determination of Representative Values (95th Percentile)**
   1. For each grid point and dose type, the **95th percentile** value was calculated from N=1000 results:
      1. All dose values sorted in ascending order.
      2. Top **5% of extreme values removed**.
      3. The **highest remaining value** taken as the 95th percentile.
3. **Identification of Threshold Exceedance Areas**
   1. Points where dose values exceeded defined thresholds
   2. **Geometric Boundary Determination**
   3. A minimum convex polygon drawn around all exceedance points.
   4. Defines the **outer boundary** of the emergency planning area and corresponding distances.

Results:

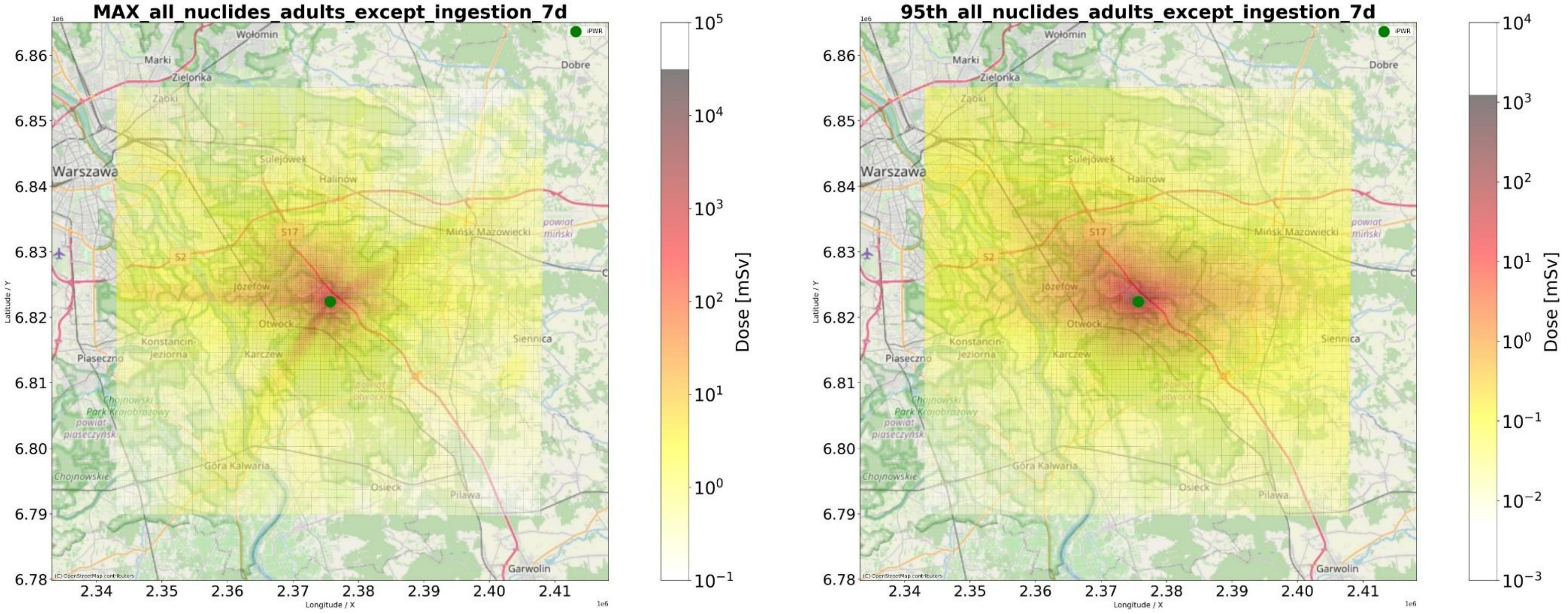


Fig. 13. Spatial distribution of the total effective dose for adults (excluding ingestion, 7-day integration) obtained from N = 1000 model realizations: **(left)** maximum dose at each grid node; **(right)** 95th percentile of the dose distribution, illustrating the smoothed spatial pattern after exclusion of extreme values.

Urgent Protective Action Zone

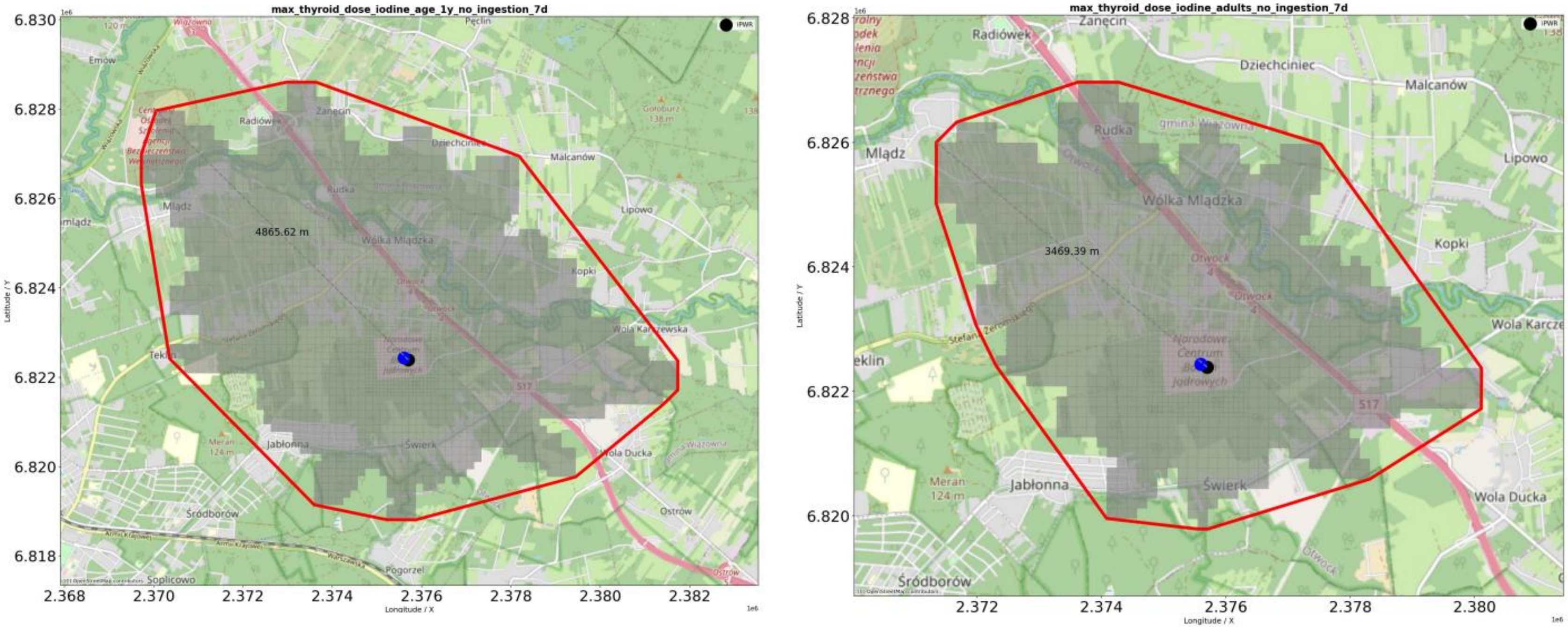
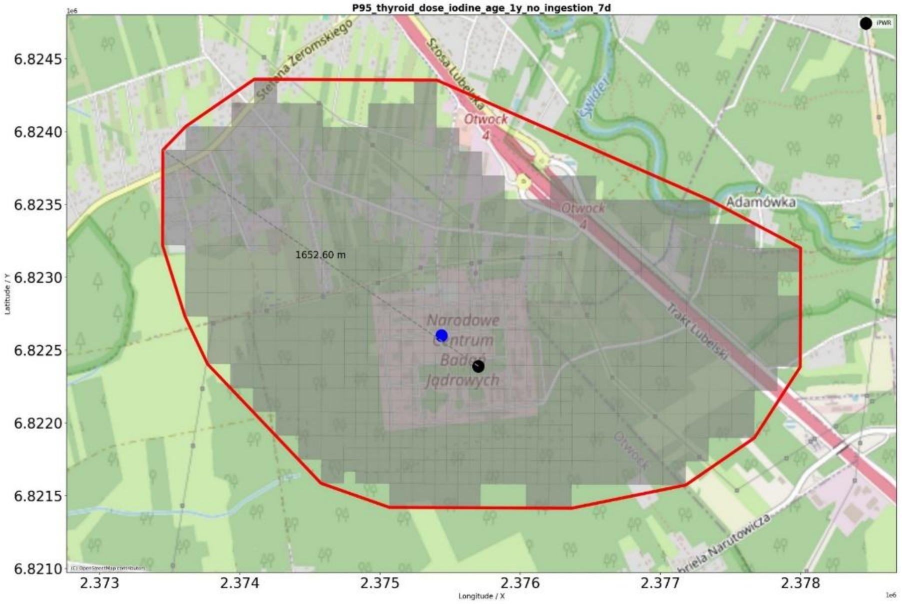


Fig. 14. Equivalent thyroid dose from iodine isotopes (no ingestion, 7 days): exceedance areas for one-year-old children (left) and adults (right).

Urgent Protective Action Zone



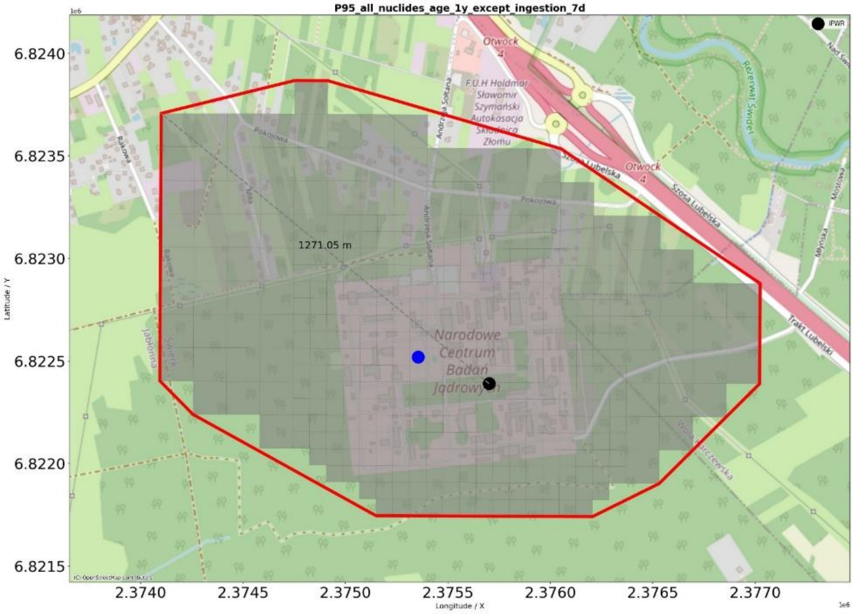


Fig. 14. Urgent Protective Action Zone: spatial distribution of the 95th percentile of projected doses for one-year-old children at 7 days after release: (left) effective dose from all radionuclides excluding ingestion pathways; (right) equivalent thyroid dose from iodine isotopes excluding ingestion pathways.

Summary of exceedance distances for planning zones

Planning Zone/Dist.	Dose Type	Adults Dist. – Max [m]	Adults Dist. – P95th [m]	Children Dist. – Max [m]	Children Dist. – P95th [m]
UPZ	Total dose – all nuclides – excluding ingestion – 7 days	2213.60	933.02	3284.88	1652.60
UPZ	Thyroid dose – iodine – excluding ingestion – 7 days	3469.39	1155.12	4865.62	1652.60
EPD	Total dose – all pathways – all products – 1 year	25636.48	4466.78	21646.11	4186.14
UCPD	Ingestion dose – all nuclides – 1 year	>56544.80	18417.92	>56544.80	14794.54

UPZ – Urgent Protective Action Planning Zone (≥100 mSv effective dose or ≥50 mSv thyroid dose); EPD – Extended Planning Distance (≥100 mSv total dose including ingestion); UCPD – Ingestion and Commodities Planning Distance (≥10 mSv ingestion dose).

Remerk: Urgent Protective Action Planning Zone (UPZ) for MARIA Reactor

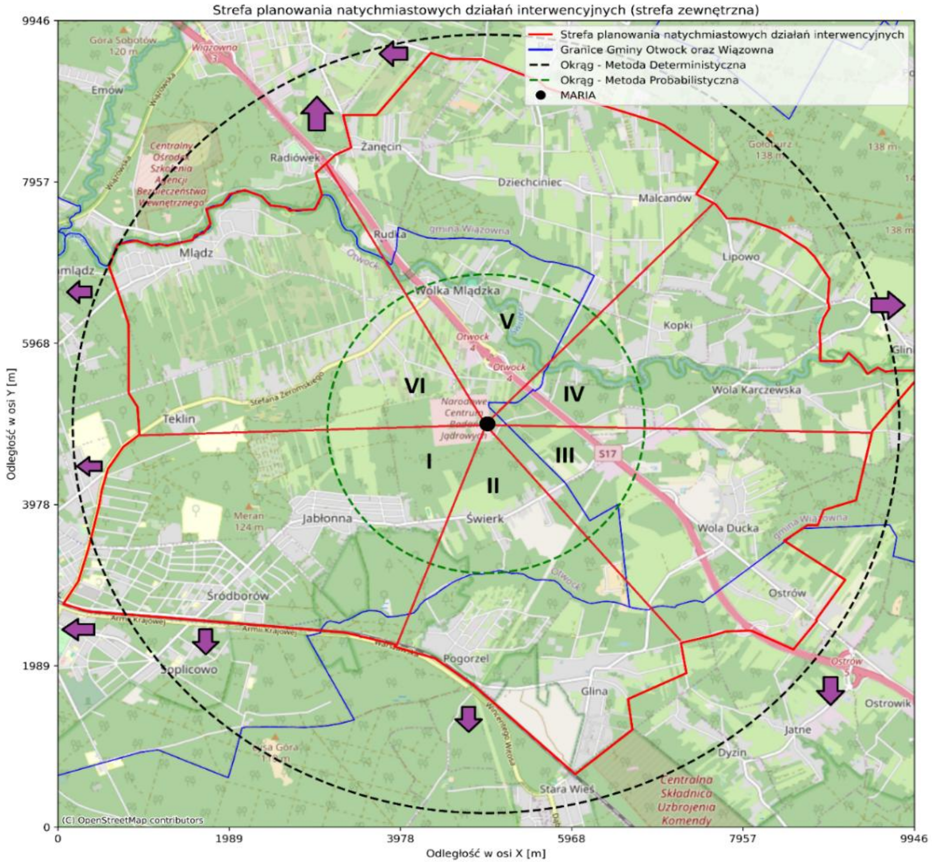


Figure 15. Emergency Planning Zone (internal zone) obtained from the deterministic and probabilistic methods. The area was defined on the basis of the **thyroid equivalent dose** resulting from the **inhalation of radioactive iodine isotopes** during the **first 7 days following the radiological event**.

Key Considerations for Small Modular Reactors: Weather Scenario and Source Term Determination

Weather Scenarios: Meteorological conditions have a major influence on zone calculations. Conservative assumptions can substantially enlarge predicted impact areas.

Regulatory Guidance: Authorities should establish standardized weather scenarios for each site to ensure consistency and prevent disputes regarding “worst-case” assumptions.

Source Term: Accurate estimation of the source term is critical. MELCOR-based analyses provide more realistic and precise release estimates compared to overly conservative literature values.

Improved Modeling: Verification of source term data using modern computational codes is essential to achieve realistic assessments of accident consequences.

Fig. 16. View of the MARIA research reactor core.

References

[1] https://www.nuclear-power.com/nuclear-power/reactor-physics/nuclear-safety/defence-in-depth-principle/

[2] International Atomic Energy Agency. (2015). *Preparedness and response for a nuclear or radiological emergency* (IAEA Safety Standards Series No. GSR Part 7). Vienna: IAEA.

[3] Malicki, M., Darnowski, P., & Lind, T. (2024). *An iPWR MELCOR 2.2 Study on the Impact of the Modeling Parameters on Code Performance and Accident Progression*. **Energies**.

[4] Barescut, J. et al. (2011). JRODOS: Platform for improved long term countermeasures modelling and management. Radioprotection, 46(6), S731–S736.