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Hazard Assessment of NPP Krško for Republic of Croatia

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ABSTRACT

While Croatia does not have nuclear power plant on its territory, NPP Krško in Slovenia is just 10 km from the Croatian border. It is important for Croatia to include NPP Krško in comprehensive hazard assessment. This article will present hazard assessment based on calculations using RODOS. Real-time weather prepared by Croatian National Weather Service and collected by the State Office for Radiological and Nuclear Safety over the years will be used. Scenario resulting in the large release from the NPP will be analysed. Results from hundreds of calculations will be statistically analysed and compared to the current protection zones in Croatia around the NPP Krško.

Keywords: *emergency, protective actions, planning zones, NPP, hazard assessment*

1 INTRODUCTION

Nuclear power plants are safe facilities, with probability of serious accident in range of once every 20 000 years or less. However, the impact of such serious accident can be severe, so, despite very low probability, risk of such an accident is moderate, and warrants mitigation measures, especially for the protection of the population.

Urgent protective actions are primarily evacuation, sheltering and iodine thyroid blocking. Their aim is to reduce or prevent external exposure to the radioactive cloud, as well as external exposure to the deposited radioactive material and internal exposure through inhalation. Urgent protective actions include also decontamination of individuals, urgent medical assistance, prevention of inadvertent ingestion of radionuclides and prevention of ingestion of contaminated food and drinks.

This article will consider only first group of urgent protective actions, evacuation, sheltering and iodine thyroid blocking.

1.1 Description of protective actions

Evacuation is protective action where the whole population from affected area is urgently relocated to a safer area. Evacuation needs to be done in a matter of hours and usually is performed by the people themselves, with authorities ensuring open roads and evacuation of vulnerable individuals.

Sheltering is protective action where people shelter themselves in their own homes or in predefined shelters. It is more effective in big buildings with thick walls. Thick walls should reduce cloud-shine, and people should close all ingresses (duck-taping doors and windows, for example) to prevent or reduce internal exposure by inhalation.

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Sheltering cannot last longer than 48 hours.

Iodine thyroid blocking (ITB) is protective action where high amount of stable iodine is taken in order to saturate the thyroid gland and prevent the accumulation of radioactive iodine that enters the body through inhalation.

Current IAEA recommendations and Croatian legislature do not have intervention levels for urgent protective actions, instead relying on overarching strategy based on reference levels. This strategy will be developed in Croatian Emergency preparedness and response plan for nuclear and radiological emergencies. Until then, IAEA recommendations valid before reference levels were developed have to be used. Intervention levels considered in this paper are set in Table 1.

Table 1: Intervention levels for urgent measures

Measure	Level (mSv)
Evacuation	100, averted over 7 days
Sheltering	10, averted over 2 days
ITB, adults	100, thyroid dose averted over 7 days
ITB, children	100, thyroid dose averted over 7 days

1.2 Protection zones

In order to ensure proper effectiveness, all the urgent protective measures have to be activated and implemented as soon as possible, ideally close before or just after the release of radioactive cloud. For that to be possible, both authorities and people need to know in advance what are actions to be performed, where are locations affected and when to perform the actions. For that reason, protection zones (and distances) are set. In each protection zone prospective protective actions should be known in advance, as well as triggers to start the actions. International organizations work on establishing optimal zones, especially after the Fukushima [1], [2].

1.2.1 Protection zones in Croatia

Closest Croatian territory to the NPP Krško is 10 km from the reactor. That means that Croatia does not need to have the first recommended zone, *Precautionary Action Zone*, PAZ, that is typically up to 5 km from the NPP.

Urgent Protective Action Zone (UPZ) in Croatia is set up to the distance of 20 km form NPP Krško. This is the zone where sheltering and ITB are expected in case of serious accident, and evacuation should be planned.

Extended Planning Distance (EPD) in Croatia is set between 20 km and 100 km from NPP Krško. In this zone evacuation is not expected, except for the hot spots, and general plans exist for sheltering and ITB.

Ingestion and Commodities Planning Distance (ICPD) is zone where only agricultural measures are expected.

Immediate restriction of use of drinking water from open sources (wells and similar) as well as restriction of consummation of fresh food and feed exposed to open air is expected for all the zones.

Distance is first parameter in determination of the zones. Actual zones follow municipal boundaries.

2 HAZARD ASSESSMENT

Protective zones presented in Chapter 1.2.1 were set based on international recommendations ([1], [2]). The aim of this article is to repeat calculations similar to the ones made by international organizations, but for Croatian specific situation, and to see if internationally recommended protection zones are adequate. Maximum sheltering time is 48 hours, but usually sheltering is considered for 24 hours (time used in calculation is this paper).

As a tool in emergencies, Croatia uses RODOS (Real-time On-line DecisiOn Support) system. One of the capabilities of RODOS system is calculation of spread of radioactive cloud based on the meteorological data. One of the functions of RODOS system is the ability to continuously run calculation for selected NPP, using selected source-term data and up-to-date weather prognosis.

State Office for Radiological and Nuclear Safety has an agreement with Croatian Meteorological and Hydrological Service to get prognosis for the next 48 hours in RODOS-usable format. The past agreement assumed availability of new prognosis every 12 hours, and since 2018 it has changed to the new prognosis every 6 hours.

To check the validity of current protection zones, this article will simulate release from NPP Krško for all prognosis available for the year 2017. Maximum distance predicted for sheltering, ITB and evacuation will be collected, analysed and compared to current zones.

3 INPUT DATA FOR CALCULATION

3.1 Source Term

Specific source terms prepared for NPP Krško were not available for this paper. Instead, generic source term was taken. Source term was selected from program InterRAS. Source term was for generic PWR, 1994 MWt, for scenario core melt – dry containment leak. Source term consists of 47 radionuclides.

3.1.1 InterRAS

InterRAS (International radiological assessment system) was developed for IAEA by the US NRC. It is a version of NRC RASCAL (**R**adiological **A**ssessment **S**ystem for **C**onsequence **A**na**L**ysis) code prepared for international use. InterRAS is simple to use with limited options, but quite powerful. Weather has to be set manually and it uses Gaussian puff atmospheric dispersion model. It has generic core inventories for major reactor types, expected release coefficients based on the scenario (conservative ones) and calculates decay.

3.2 Weather

Meteorological data used was received from Croatian Meteorological and Hydrological Service. Every day prognoses were received after 06:00 UTC and 18:00 UTC, consisting of last 6 hours of real meteorological data and 48-hour prognosis. Since data were collected and stored automatically, some data were not stored because of server error.

For this paper, calculations were started at 06:00 UTC every day for which data exists. In all, 341 calculations were made.

3.3 Scenario

Standard release scenarios, including the most severe ones, last for days. On one hand, it is important to simulate longer-time release, because of changing weather conditions. On the other hand, this article is considering only measures that need to be implemented as soon as possible, and calculations were set up so that protection measures started at the ideal time – at the start of release. Since only urgent protective actions are assessed, the calculation time was set at 24 hours.

Five-hour uniform release interval was selected as interval large enough to enable effects from changing weather, while still short enough that the whole inventory can be released and transferred through the atmosphere. Five-hour uniform interval was realized as 10 half-hour intervals with same source term, meaning that there is no decay calculated for any of the intervals up to the time it is released from the NPP.

Recently, Germany and Sweden analysed their protective zones using similar method. Selected source term compares well to the data available for Swedish and German ones ([3], [4]). The most significant difference, from radiological point of view, is around 3 times higher iodine release than Swedish case, relative to NPP power.

4 RODOS

RODOS (Real-time On-line DecisiOn. Support) system is system designed for off-site nuclear emergency management. In case of nuclear emergency in Europe, RODOS provides consistent and comprehensive information on the present and future radiological situation, the extent and the benefits and drawbacks of emergency actions and countermeasures, and methodological support for taking decisions on emergency response strategies. The RODOS system is the result of a close collaboration between almost 40 institutes from about 20 countries within the European Union, Eastern Europe and the former Soviet Union. The RODOS project was funded by the German Ministry of Environment, the European Commission and the participating institutes [5].

RODOS system has many features, functions and capabilities. Only some are presented in this article.

4.1 Selected RODOS features

RODOS system has two main operation modes, automatic and continuous mode:

- Automatic mode enables automatic calculation whenever real-time meteorological and radiological data is present. This mode can use user-defined source term, and between calculations with real data it can run calculations with prognostic data, but it cannot be set up without access to real-time meteorological data.
- In continuous mode RODOS automatically starts calculation for defined source term in defined intervals (default is 1 hour), changing start of the release to match time of the start of the calculation. User has to ensure that new meteorological data is regularly fed into RODOS. This mode enables the user to see at any time possible spread and consequences of sudden release of radioactive material.

RODOS has internal data for core inventories for various burnups for select NPPs, including generic inventories for LWR. User can add plant specific core inventories. RODOS is capable to calculate decay from the time designated as reactor shutdown and includes progeny in the analysis.

EMERSIM model is used for simulating urgent protective actions and calculating doses with and without those actions. The code calculates deposition of radioactive materials, and can calculate effects and costs of different clean-up measures. The food contamination and received dose from eating it, are calculated for variety of food and feedstuff.

New version of RODOS, JRodos, works with GIS database and results can be exported as .shp files.

RODOS includes three models for atmospheric dispersion of radioactive material. One of them RIMPUFF, is puff model, while the other two, DIPCOT and LASAT, are particle models.

4.2 DIPCOT

DIPCOT model was created during the development of RODOS system. DIPCOT is a dispersion model, which simulates the motion of air pollutants over complex terrain, based on a 3-D Lagrangian particle scheme. In order to build up a picture of the concentration distribution the total mass of the pollutant is assigned to a certain number of computational particles. Each particle is "moved" with a velocity which takes account of two basic components: the transport due to the mean wind velocity, provided by meteorological pre-processors, and the random turbulent fluctuations are estimated by the Langevin equation. The knowledge of the spatial and temporal distribution of the particles allow the calculation of the mean ensemble concentration of the pollutants. DIPCOT utilizes topographical and meteorological information given at a 3-D grid and is capable of simulating dispersion from multiple point sources, at all atmospheric conditions. In the case of buoyant point sources, the model performs plume rise calculations. [6].

DIPCOT is of particular interest because, depending on the direction, plume from the NPP Krško is expected to start over hilly areas, continuing either over mountains or over low-lends. DIPCOT should handle such a terrain better then puff model.

DIPCOT has been validated against experimental data [6], [7].

4.3 Calculation spatial mesh

RODOS uses mesh of square cells. Calculations were done for the distance up to 400 km from the NPP, to allow for extreme cases. That means that calculation mesh was square with side length of 800 km and NPP Krško in the centre.

RODOS uses five different sizes of squares in calculation area, depending on the proximity to the NPP. Up to 10 km from the NPP, cell size is 1 km. From 10 to 40 km, it is 2 km. From 40 to 104 km from the NPP, cell size is 4 km, from 104 to 208 km it is 8 km and from 208 km to the end of the calculation area (400 km) it is 16 km.

5 RESULTS

From each calculation the furthest point from the NPP where action was implemented in the calculation was selected (tip of the cell that is furthest from the NPP). Tip of the cell, as opposed to the centre, was selected because it is easier to select on the graphical display of the results. Coordinates of that point were taken and distance was calculated, using "haversine" formula:

$$a = \sin^2(\Delta\varphi/2) + \cos\varphi_1 \cdot \cos\varphi_2 \cdot \sin^2(\Delta\lambda/2) \quad (1)$$

$$c = 2 \cdot \arctan(\sqrt{a}/\sqrt{(1-a)}) \quad (2)$$

$$d = R \cdot c \quad (3)$$

, where:
φ is latitude,
λ is longitude,
R is earth radius (calculated with mean radius of 6371 km).

For each calculation the procedure was repeated four times, once for each urgent protective action considered.

For each urgent protective action one other parameter was determined – does the area where protective action is implemented in RODOS cover any part of Croatia (is the centre of any cell on Croatian territory).

5.1 Actions on Croatian territory

The parameter whether measure needed to be implemented on Croatian territory is interesting, but not really important for decision-making. This parameter just states if measure was implemented on any area in Croatia, not the size of the area, so there are plenty of calculations where measure is implemented just between Kumrovec and Hum na Sutli in Croatia, but is implemented up to 100 km in Slovenia and Austria. Also, there were instances where measure is implemented just up to Croatian border. Since border in RODOS is smoothed actual border, this may mean that measure was actually implemented on Croatian territory, but the program does not show it. The other way around is also valid, that is, measures where cell is just over the border may actually be implemented fully in Slovenia, but because of smoothing of the border are presented in RODOS as if they are in Croatia.

Number of calculations when measure needed to be implemented in Croatia is shown in Table 2.

Table 2: Is measure implemented in Croatia

Measure	Yes (number of calculations)	No (number of calculations)
Evacuation	159	182
Sheltering	132	209
ITB, adults	236	105
ITB, children	248	93

Calculations where ITB for children is not implemented in Croatia indicate that radioactive plume is going away from Croatia or that plume is going towards Gorski Kotar or Istria and is well dispersed. Calculations where ITB for children is implemented, but one or more of other measures is not indicate that plume is going towards Croatia, but meteorological conditions are such that it is dispersed well enough that high doses are not reached in Croatia.

5.2 Distance of implemented actions

In Table 3 selected calculated distances are given for each measure. Distances in table are minimum, mean, median and maximum.

Table 3: Distances where measures are implemented (in km)

Distance	Evacuation	Sheltering	ITB, adults	ITB, children
Minimum	8.5	7.0	19.6	22.7
Median	25.0	19.9	62.1	93.4
Mean	30.5	23.5	71.5	104.3
Maximum	107.9	94.7	303.6	351.8

In most cases maximum distances are relatively close together, but in small number of cases maximum distances are extremely far. This can be seen in Figures Figure 1 toFigure 8, and Table 4. Difference between 90th and 100th percentile for all measures is larger than absolute distance for 90th percentile. In such circumstances expecting protective actions to be fully prepared and planned for the whole area of 100% of cases would be very expensive and counterproductive. Such an extension of protective zones would increase their area enormously. At the same time, people living so far from the NPP need first to be awoken to the fact that they need to plan some actions. In such circumstances, most of resources would need to be spent in the areas furthest from the NPP, potentially hurting the ability to protect the people closest to the NPP, those who may be in danger in non-extreme cases.

Also, implementation zones for extreme distances are not continuous – for extreme cases, implementation zones are usually up to the median continuously distributed and several distant cells are located where meteorological conditions stop the plume for a few hours over one location.

All the results of the calculations are shown in Figure 1 (evacuation), Figure 2 (sheltering), Figure 3 (ITB), and Figure 4 (ITB for children).

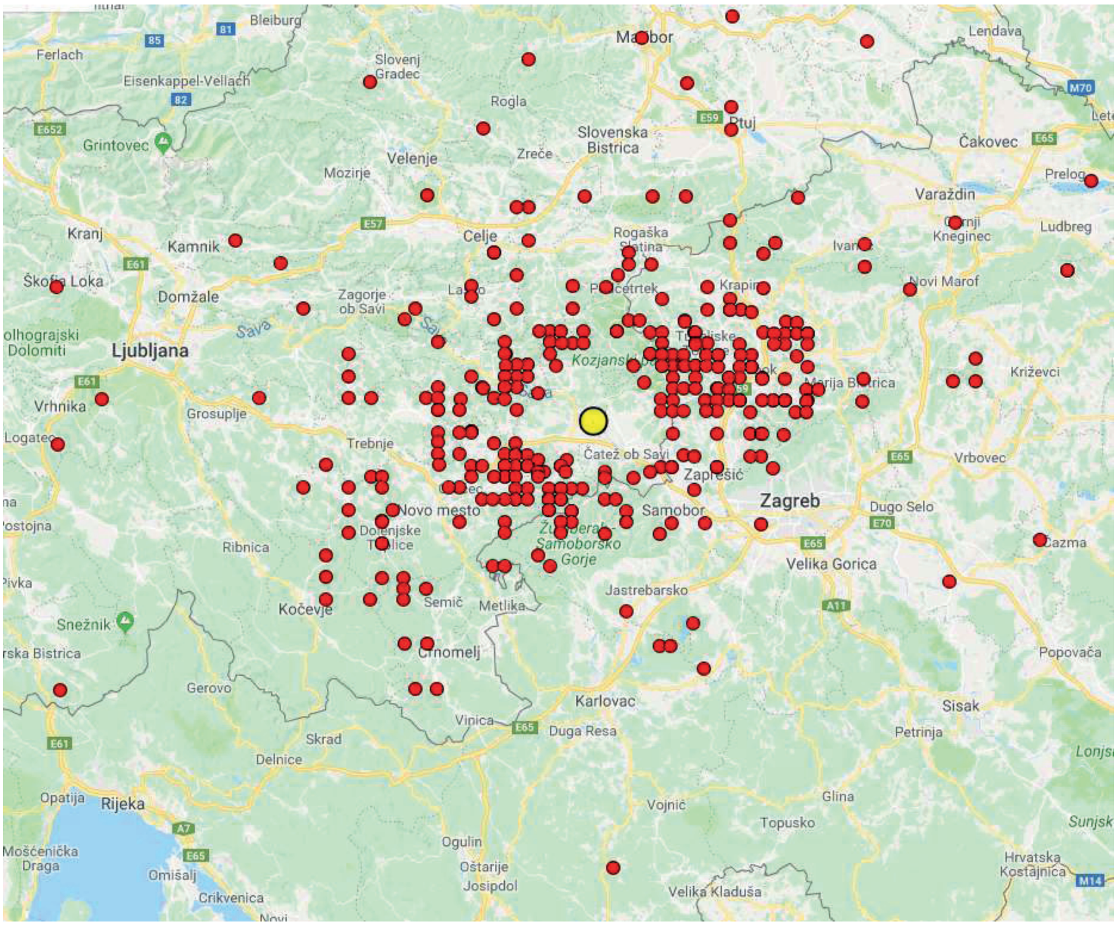

Figure 1: maximum distances for evacuation, all calculations

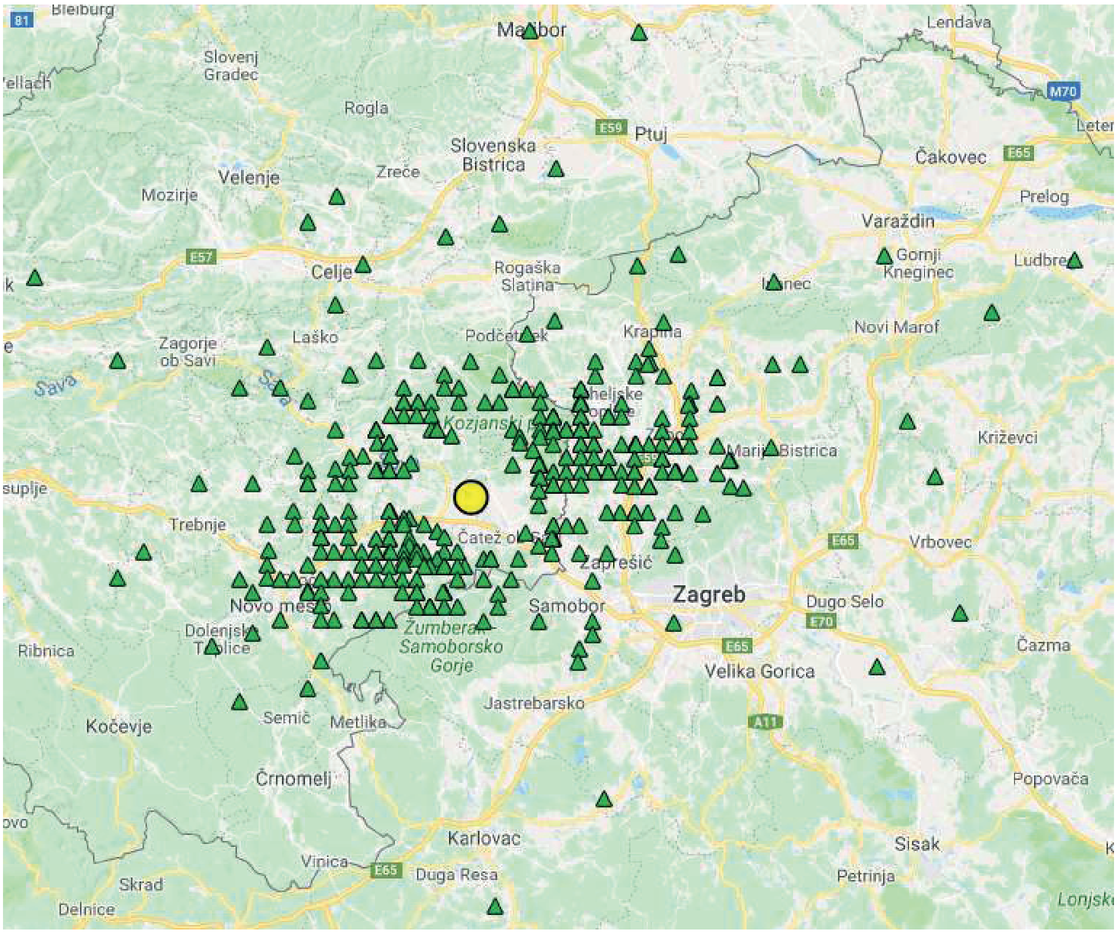

Figure 2: maximum distances for sheltering, all calculations

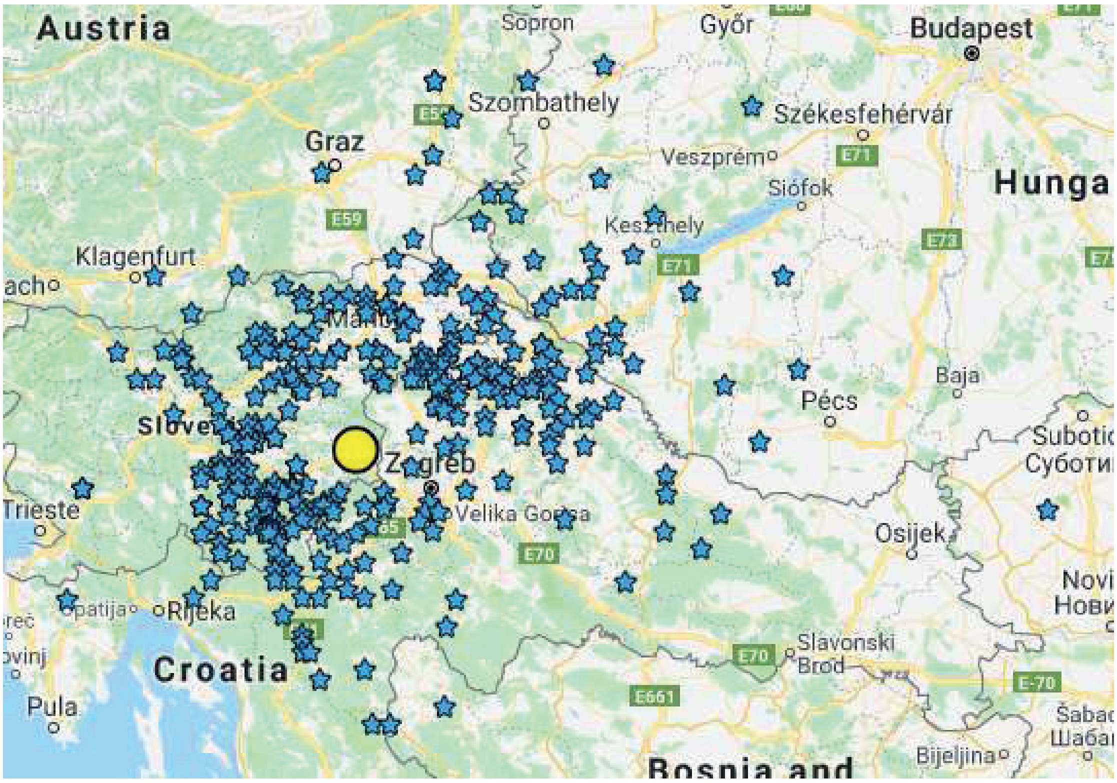

Figure 3: maximum distances for ITB, all calculations

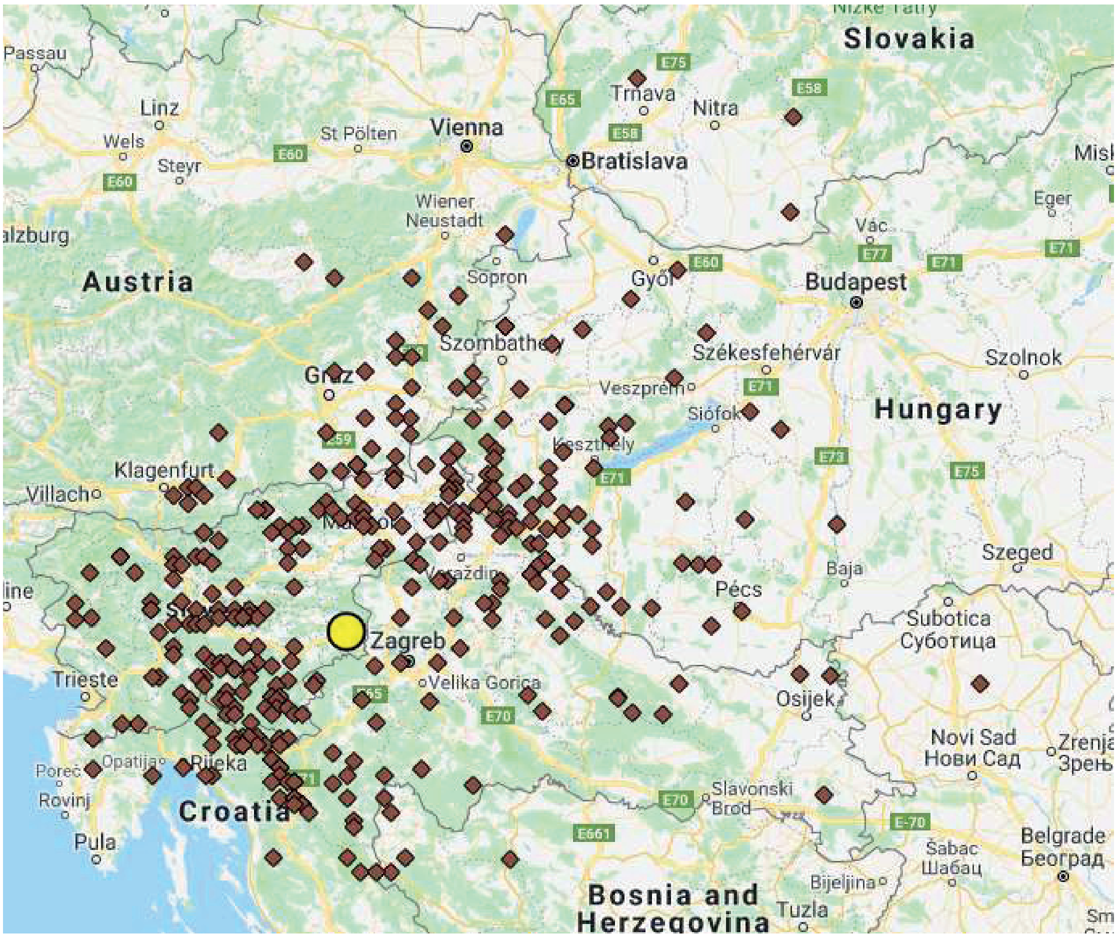

Figure 4: maximum distances for ITB for children, all calculations

While protection zones should not cover every case, question is how many cases they should cover. It is important to remember that Germany and Sweden selected for their calculations most extreme release for the NPPs they consider possible. German experts decided that 80% of analysed cases is enough, while Swedish experts displayed results for 70^{th}, 80^{th} and 90^{th} percentile, with 70^{th} being considered good enough. Protection zones that cover 70% or 80% of possible outcomes for largest predicted release would cover well over 90% of possible outcomes for other large release scenarios and 100% possible outcomes for any accident that does not result in large release.

Source term selected in this paper is even more extreme than source terms selected in German and Swedish calculations, because the whole released inventory is released in the first five hours. Therefore, it should be expected that protection zones of similar dimension like in Germany and Sweden should cover less possible outcomes.

Distances for percentiles are given in Table 4.

Table 4: Distance percentiles (in km)

Percentile (%)	Evacuation	Sheltering	ITB, adults	ITB, children
10	14,4	11,2	36,6	52,4
20	16,5	13,4	44,6	64,5
30	18,8	15,9	49,6	76,3
40	22,0	17,1	55,7	83,5
50	24,9	19,9	62,1	92,8
60	29,6	22,7	68,3	103,5
70	34,5	26,0	80,5	114,2
80	41,0	30,9	91,9	131,0
90	53,5	38,0	120,6	167,1
100	107,0	94,7	303,6	351,8

Distances and percentiles are shown in Figure 5 (evacuation), Figure 6 (sheltering), Figure 7 (ITB), and Figure 8 (ITB for children).

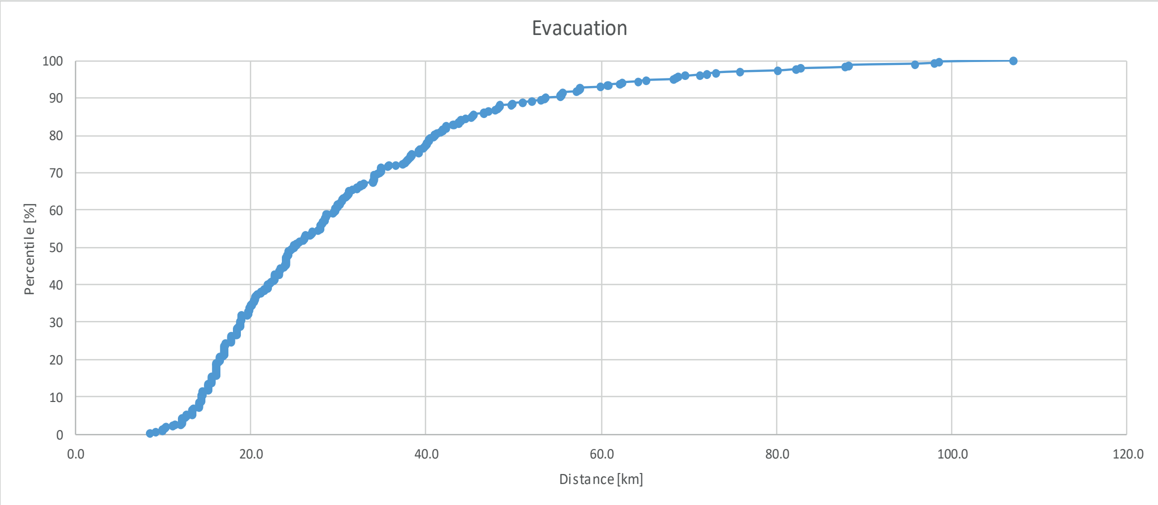

Figure 5: Percentiles for evacuation.

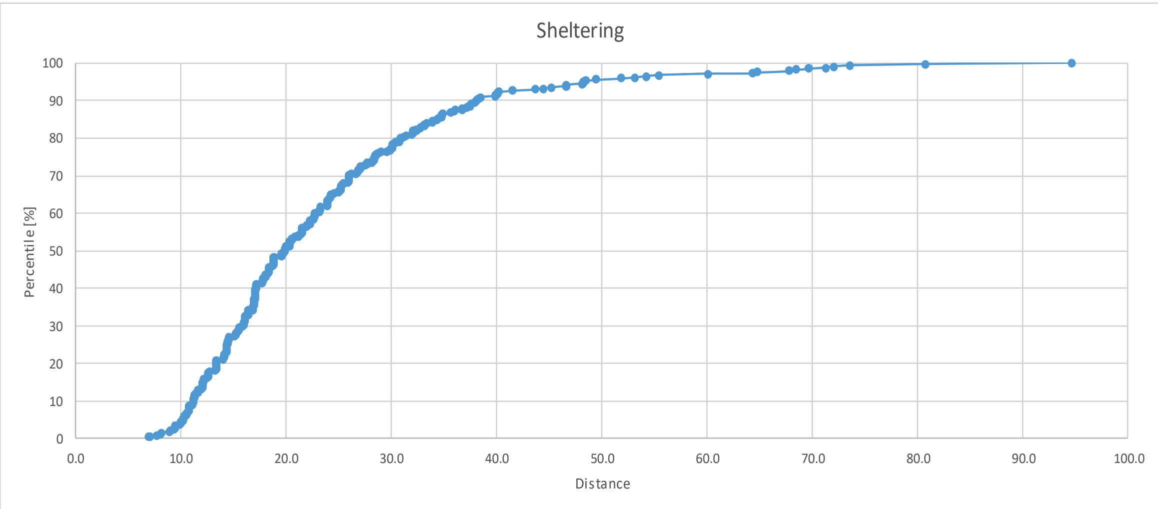

Figure 6: Percentiles for sheltering

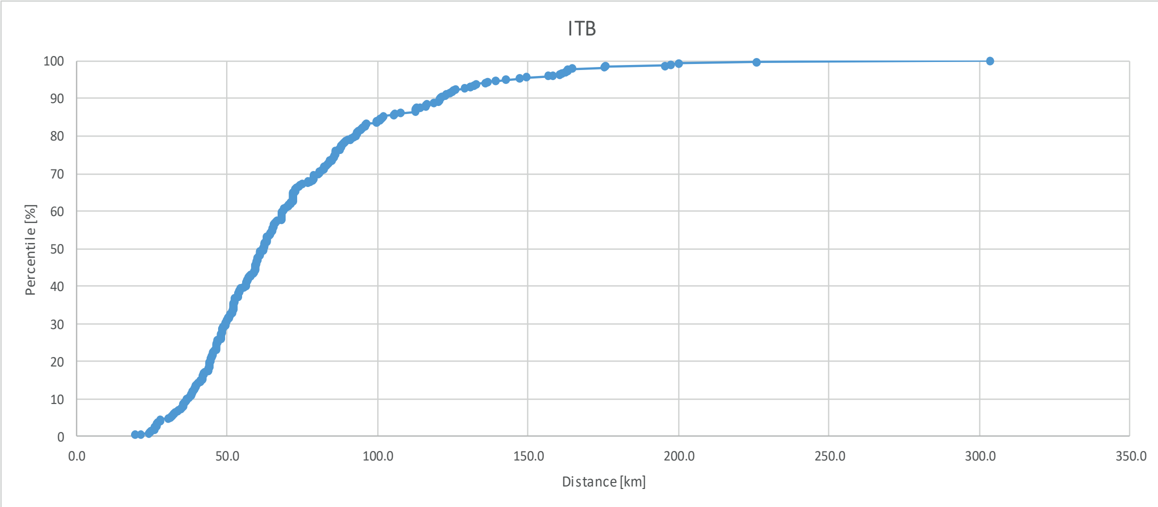

Figure 7: Percentiles for ITB

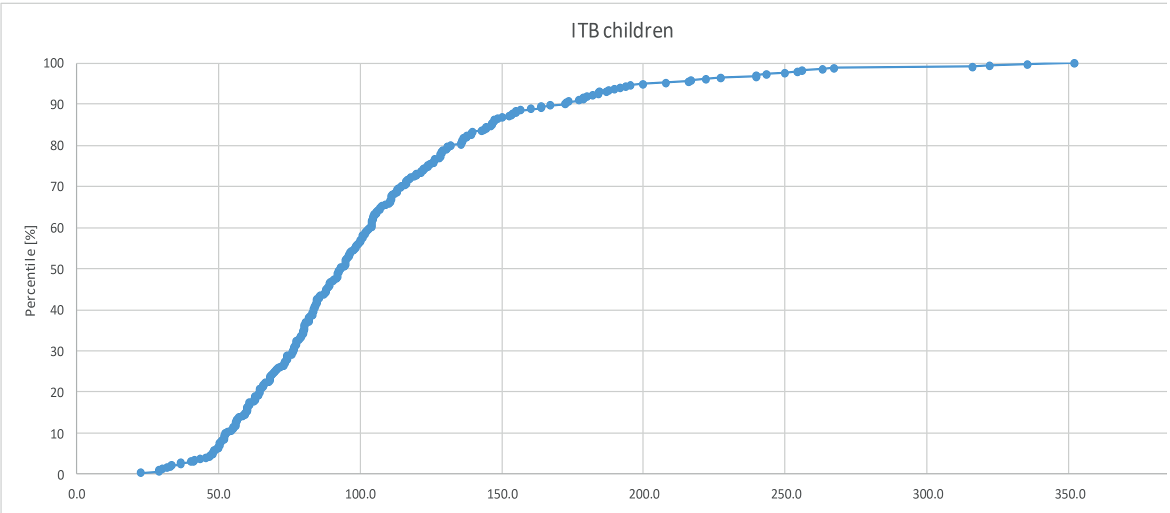

Figure 8: Percentiles for ITB for children

5.3 Comparison with current Croatian zones

Current Urgent Protective Zone (UPZ) covers over 30% of cases where evacuation is needed and over 50% of cases where sheltering is needed. These results are immediately interesting: area where sheltering is considered useful (it will reduce effective dose received by at least 10 mSv) is in all calculations smaller than the area where evacuation is considered useful (reducing effective dose received by at least 100 mSv over seven days). Sheltering protects from cloudshine and from inhalation during the passage of radioactive cloud. Evacuation, if implemented before the arrival of the cloud (for this set of calculations both sheltering and evacuation are expected to be fully implemented at the time of the release), protects from cloudshine, from inhalation during the passage of radioactive cloud and from groundshine. RODOS assesses need for each protective action individually. Area where evacuation is needed, but not sheltering, means that avoided dose from groundshine and inhalation is less than 10 mSv, but total dose from cloudshine, inhalation and groundshine is at least 100 mSv over 7 days. There are three possible explanations for such a situation: radioactive plume does not pass during first 24 hours, reduction coefficients for sheltering are very low, or deposition is very high.

There are some cases where meteorological situation is such that radioactive cloud circles over one area. However, such conditions are anomaly, not standard and cannot explain why all calculations show that evacuation area is larger than sheltering area.

Croatia is just outside of the Central European area that is fully characterized in RODOS. Most of the population living between 20 and 50 km from the NPP Krško live in cities and sheltering factors should be fairly high. If population density and cities are not properly entered in RODOS for area in question, RODOS may use lower sheltering factors. If that is the case, it should be obvious soon. Announced update expected in July should bring the whole Europe to the level of detail of Central Europe in current version.

Groundshine in calculations is very high. It can be explained by source term. Since no specific source terms were available, source term was taken from InterRAS (very large release) and released during 5 hours without additional decay calculated (see 3.3). Around 80% of groundshine comes from I-132, I-133 and I-135, isotopes with half-life of 2.3 hr, 20.8 hr and 6.6 hr respectively. Plant-specific source term, including realistic release intervals, should be used to check realistic groundshine.

Current Extended Planning Distance (EPD) covers over 80% of cases where ITB for adults is needed and over 50% of cases where ITB for children is needed. Considering number of cases and area covered, it is not advisable or even useful to extend EPD nor to plan pre-distribution of iodine tablets outside of EPD. Instead, it would be advisable to create several (2-4) regional storages from which iodine tablets can be quickly distributed to selected points (schools, kindergartens, hospitals) in areas where they may be needed outside of EPD. Because of time constraints, it is advisable to plan pre-distribution if not for the whole EPD, then at least for UPZ.

5.4 Comparison with other works

As has been previously said, Sweden and Germany did similar calculations as input for regulatory purposes. Both have used scenarios and source terms specific to their NPPs.

Swedish analysis in [3] shows that evacuation of up to 20 km is enough to prevent population receiving more than 100 mSv in 70% of cases. Because of different criteria for other protective actions, they cannot be directly compared.

German analysis in [4] shows that evacuation up to 26 km is enough to prevent population receiving more than 100 mSv in 80% of cases for all analysed NPPs, and only NPP Phillipsburg (1400 MWe PWR) needs evacuation of more than 20 km to cover more than 80% of the cases. As with Swedish analysis, criteria for other protective actions is sufficiently different that they cannot be directly compared.

Both previous analyses performed with similar tools (Germany used RODOS, Sweden ARGOS) show much smaller evacuation zones needed than the calculation in this paper, even though power plants analysed have higher power. There are several possible reasons for such discrepancy.

Source term selected for this paper released maximum inventory in five hours. Plant-specific source terms release radionuclides over a period of days. Longer release time in most cases ensures larger dispersion. Also, it means significant reduction in the activity of short-lived radionuclides. Both factors should reduce doses in areas with highest doses.

Sweden used ten years of data for calculations, Germany five. This paper only uses one year. Less data means more possibility for extremes.

5.5 Further work

These calculations need to be repeated when better local data is available in RODOS. It would be advisable to extend the calculations to larger time period (not just 2017, but also previous years) and to start release at different time of day (if possible, doing several calculations for each day). It would be especially useful if specific source terms for specific large release scenarios (like station blackout or steam generator tube rupture) were available.

6 CONCLUSION

This paper presents calculations made with large release source term and real weather data in order to assess current emergency preparedness zones in Croatia. Calculations show that EPD covers over 80% of cases that need ITB for adults and over 50% of cases that need ITB for children. At the same time, current UPZ covers only 34% of cases analysed that need evacuation, lower percentage than for sheltering (50%). This is not in line with other internationally performed calculations, which showed that UPZ of similar size completely covers of 70% of cases that need evacuation. The main difference in the setup of this calculation compared the other international calculations is that other calculations used plant-specific source terms, with both release and calculation lasting up to days, depending on the scenario.

In other internationally performed calculations distance where sheltering should be initiated is between 2 and 7 times larger than distance where evacuation should be initiated (this paper uses same criteria for evacuation and sheltering as Germany and Sweden). If supposition that too high source term is responsible for such large evacuation areas is correct, and we use the lowest factor from other calculations (sheltering distance is two times higher than evacuation distance), Croatian UPZ would cover over 90% of cases that need evacuation. This number is also in line with expectations based on the results of German and Swedish calculations, taking into account power of their NPPs compared to the power of NPP Krško.

This paper should be expanded using weather data from multiple years, modelling release at different times of day and using plant-specific source terms for large release scenarios.

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