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Methodology to calculate radiological impact for NPP Krško life time extension environmental impact assessment

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ABSTRACT

Initially NPP Krško (NEK) was licensed for 40 years of operation (until 2023). To obtain lifetime extension, an Environmental Impact Assessment (EIA) should be performed to evaluate the impact of NEK prolonged operation on the environment. The gaseous radioactivity release from reactor core during possible accidents has the largest potential for environmental impact. It is enveloping any other radioactivity accident and related releases. According to plant's SAR, a limiting plant accident, from point of view of radiological release, is the Large Break LOCA. The radiological release in case of any possible severe accident (DEC-B or beyond design basis accident (BDBA)) was analysed using Station Black Out (SBO) without mitigation in the first 24 hours and release through passive containment system vent system (PCFVS) as a reference case. It is selected, due to an expected complete core melt, and the fastest and the most conservative radioactivity release within a containment.

The methodology used to assess the dose rates and the consequences to the environment at selected distances from NEK in case of DBA LOCA and BDBA SBO scenario was described. It includes calculation of plant specific fuel source term, RADTRAD model calculating isotopic release to the environment and X/Q relative concentrations determined using ARIA Industry Lagrangian particle atmospheric dispersion model and WRF meteorology for distances up to 100 km from release point. For distances up to 200 km RODOS model using simplified spatial and weather data and release source term calculated by RADTRAD can be applied. Although the calculation models are different, the calculated doses at a distance of 100 km from the NPP agree well.

The results of performed analyses show that no significant transboundary impact from the Krško NPP, in case of DBA or DEC-B accident, is expected, except possibly at parts of Croatian border.

1 INTRODUCTION

As one of conditions to obtain lifetime extension, an Environmental Impact Assessment (EIA) should be performed to evaluate the impact of NPP Krško (NEK) prolonged operation on the environment. As a part of that, an assessment of the radiological consequences of NPP operation was performed. Small releases of radioactive material during normal operation or possible releases during accidents are the most important influences NPP can have on the environment.

The releases of gaseous and liquid effluents during normal NPP operation are under strict administrative control. In case of NPP Krško all radioactive emissions in past period were well within allowable regulatory limits. That is verified by properly developed radiological monitoring program, performed by the plant and independent organizations. There is no reason to expect any change in normal operation releases in case of extended operation.

Any release of radioactivity other than normal release is result of some kind of radiological or nuclear accident. Largest amounts of radioactive materials are present in the spent fuel in a reactor core and in a spent fuel pool (after start of IFSI operation part of the spent fuel will be in SFDS casks). The primary fluid and auxiliary waste processing systems and related tanks have limited content of radioactive materials that are consequences of NPP regular operation. The same is true for temporary storage of Low and Intermediate Radioactive Waste (LIRW) at the site.

The amount of radioactive material in primary fluid is limited according to technical specifications, its release is possible only during a reactor accident and then it is, depending of the type of an accident, a small fraction of the activity that can be released by the gap release.

The amount of radioactive material found in the spent fuel stored in the plant’s SFP is large. Its source term depends on a spent fuel burnup and cooling time. Any radioactive release that can be a consequence of spent fuel assemblies manipulation accidents in FHB is, according to plant’s SAR, enveloped by other SAR DBA releases (like LBLOCA).

The number of spent fuel assemblies is increasing in case of NEK extended operation, but due to limited capacity of the pool, part of the fuel will be relocated in a new plant’s dry storage before the start of the plant’s extended operation period. That way, the amount of the spent fuel present at any time in the pool will be lower than the current one.

Except by spent fuel manipulation accidents, the radioactive material can be released from an SFP due to prolonged loss of cooling or due to loss of coolant inventory accidents. The SFP has a large thermal inertia, and the situation is additionally improved by introduction of an alternative cooling system (that can be supported by flex equipment), an SFP spray and by a decrease of spent fuel content in the pool. The relevant (for release of radioactivity) loss of coolant inventory can be caused by large seismic event or air plane crash. It was shown by the plant’s specific PSA analyses that a frequency of such releases is of the order of 1.e-9 per year. Taking into account the annual frequency and available means for mitigation, the SFP fuel uncovery (due to loss of cooling and loss of coolant accidents) and consequential release from the SFP is very unlikely.

With the introduction of Spent Fuel Dry Storage (SFDS) at the plant’s location, most of the spent fuel will be relocated to a Dry Storage Building (DSB) where SFDS casks will be stored. SFDS casks are a way of reliable storage and their leak tightness is guaranteed in normal operation and for all design basis and beyond design basis events. The limiting analysed event for this type of storage is an air plane crash with subsequent jet fuel fire. According to performed structural and thermal analyses, the SFDS casks will maintain their leak tightness (including limited number of casks that are directly affected by impact of plane’s heavy components). Still, in order to estimate the type of unexpected release influence, an arbitrary damage of one cask was assumed, showing that radiological impact to the environment would be within plant's design basis accident radiological consequences.

The reactor core related accident radiological releases are analysed in two steps. In the first one, radiological release covered by the plant design basis was evaluated. According to plant's SAR, a limiting plant accident, from point of view of radiological release, is the Large Break LOCA (it is called Design Basis LOCA (DBLOCA) also). There is no other design basis accident releasing more radioactivity to the environment. That included containment bypass class of accidents, as represented by SGTR also. The plant design basis takes into account one damaged U-tube. The activity of primary coolant allowed according to technical specifications and measures performed according to plant's AOP and EOP procedures minimizes radiological consequences of that event.

In the second step radiological release in case of a representative severe accident (DEC-B or beyond design basis accident (BDBA)) was analysed. Station Black Out (SBO) without mitigation in the first 24 hours and release through passive containment system vent system (PCFVS) was selected. That sequence has initial probability of the order 4.e-7 per year and when combined with assumed delayed mitigation, additional two orders of magnitude lower. It was selected, due to the expected complete core melt, and the fastest and the most conservative radioactivity release within containment. NEK has installed PCFV system to protect integrity of the containment in case of a pressure increase during severe accident. It is a system fully designed according to DEC requirements (including seismic) and its existence can be credited for radioactivity release after severe accident. Its performance should not be compromised by any credible seismic or other event.

The release, dispersion and dose rates that are consequences of gaseous radioactive materials are analysed in this paper. The release of larger quantities of radioactive liquid effluents is less probable and their dispersion in the environment is much slower. The necessary analyses were performed to assess the dose rates and the consequences to the environment and population at selected distances from NEK in case of DBA LOCA and BDBA SBO scenario. LOCA accident is described in NEK USAR Chapter 15 [1]. Assumptions on thermal hydraulic conditions in the reactor and containment were taken from the SAR and used in radiological calculations. SBO sequence is analysed using the MELCOR [2] and MAAP [3] codes. The radioactivity release from the design containment leakage in case of LOCA accident and from design containment leakage and discharge from Passive Containment Filtered Vent (PCFV) system in case of SBO accident were considered.

2 METHODOLOGY AND MODELS USED IN CALCULATION

The calculation of radiation doses was performed using different approaches. Firstly, the dose rates arising from released radioactive material during postulated accident scenarios at distances between 5 km and 100 km are calculated using the RADTRAD code. The averaged X/Q coefficients (relative concentrations or atmospheric dilution factors) are calculated by detailed and realistic Lagrangian particle model of the region starting at the plant's location and extending up to 100 km from it. Secondly, dose rates beyond 100 km are calculated, for the same radioactivity release rates, organized in release rate intervals, using RODOS and regional meteorology data for number of weather sequences from the year 2016 and 2020.

The primary source term or fuel source term is an isotopic activity inventory of a reactor core and it is a starting point of any radioactivity release calculation. In NEK case it is calculated using ORIGEN 2.2 code [4], real fuel assembly data and real operating history of the fuel. The depletion is performed on a fuel assembly basis (one node per fuel assembly), using the plant's cycle data and 3D cycle depletion as implemented in the PARCS code. The activities for the 60 representative radioactive isotopes are used in DBA and BDBA release calculations in the

RADTRAD code. The selected isotopes are very similar to the isotopes used for the same purpose in the MELCOR and MAAP code. The activities are given at the time of the shutdown, what is usually time zero in release calculation. The radioactive decay from that point is handled by the codes used to calculate radioactivity release (in this case RADTRAD or RODOS). The core inventory is calculated for nominal core power of 1994 MWth. In the RADTRAD calculation an additional linear upscaling is used to take into account possible core power calorimetric error of 2%. The source term calculations were performed for the past 6 fuel cycles (current cycle is cycle number 32). The difference between the cycles is small. For present calculation Cycle 26 source term is used as reference source term because it is very close to the average value of the total activity for all six cycles. It has the total activity for about 0.8% lower than Cycle 28, having the maximum total activity, and the difference is well within added 2% increase due to nominal power uncertainty.

In order to determine the amount of each isotope release from the fuel to containment atmosphere, codes like MELCOR and MAAP are used for selected accident sequences. In this paper, in order to speed-up the process and make it more transparent, the release fractions are based on approach used in NUREG-1465 [5] for calculation of Accident Source Term (AST, sometimes called Alternative source term, being alternative to the old TID-14844 source term). Separate release fractions are used for DBA LOCA release calculation and separate release fractions are used for severe accident release calculation (represented by the SBO).

Design Basis LOCA accident was analysed using most of the assumptions from the NEK USAR Chapter 15. Two release phases were assumed according to RG-1.183 [6]. In the first phase, gap release starts almost immediately after the break and lasts 0.5 hours, and in the second phase, early in vessel release follows immediately after gap release and lasts 1.3 hours. Iodine is released with the following chemical composition: 95% aerosol, 4.85% elemental and 0.15% organic. More isotopes, compared to the SAR calculation, were released in early in-vessel phase. Time calculation zero is the time of the reactor shutdown. Radioactive decay of released material (including daughters) is done internally in the RADTRAD code [7].

The release from the containment to the environment is analysed using the RADTRAD model with the containment divided into two volumes; part of the containment volume which is sprayed (1) and part of the containment volume which is unsprayed (2). The model, Figure 1, includes direct containment leakage, annulus leakage, annulus filtration and filtered release form the annulus. The release path 12 is representing PCFV duct in case of an SBO calculation.

All important processes, for time dependent behaviour of radioactive material, are taken into account. Radioactive material is released in sprayed and unsprayed volumes, with a split fraction based on volume fractions of nodes, 0.752/0.248. Paths 1 and 4 are used to model their mixing. Paths 3 and 6 are the containment direct leakage paths. Paths 2 and 5 are containment leakage paths to annulus (3) (when underpressure is established). The annulus is equipped with a recirculation filter. The filtered exhaust path (7) is integral part of that filter. Path 11 is the annulus leakage path to the environment. Main control room is volume number 5. It is connected to the environment through unfiltered inleakage flow path 9 and filtered inlet flow path 8. The filtered path 8 is integral path of MCR recirculation filter. Path 10 is MCR exhaust (flow equal to sum of path 8 and 9 flows). RADTRAD is used in calculation of doses in MCR, Exclusion Area Boundary (EAB), Low Population Zone (LPZ) and in additional points in the environment at different distances from the release point.

Based on preliminary MAAP calculations, SBO accident sequence without any mitigation in the first 24 hours was selected, as a sequence leading to severe core damage, to be representative as DEC-B/BDBA radiological source. The size of the initial break at the time of SBO is ranging from zero (limited to letdown leak and RCP seals leak development), breaks categorized as small breaks, up to large double ended breaks (that is enveloping seismic breaks also).

The assumptions related to the size of the initial break can influence pressure and temperature dynamics of the containment and to some extent the time of the first PCFV actuation, but they have small influence on the release of radioactive effluents within the containment. For this calculation the sequence without the initial break was selected due to the potential for the reactor vessel damage at a high pressure.

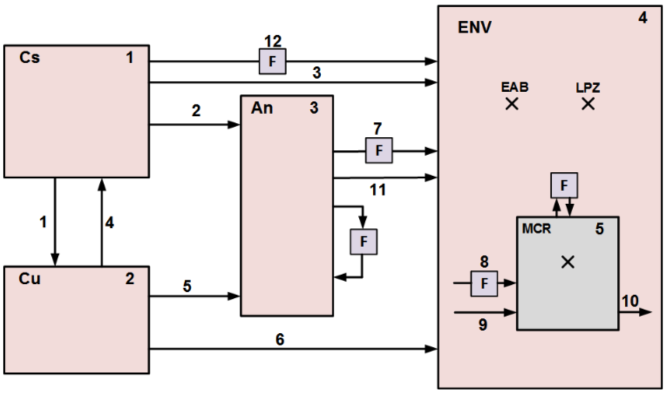


Figure 1: RADTRAD nodalization for NEK LOCA and SBO PCFV releases

Thermal hydraulics transient of the primary system and containment was calculated using earlier developed and verified NEK MELCOR input with explicit PCFV model [8], but release fractions and timing of radioactivity release to the containment were based on the NUREG-1465 Table 3.13. The first two release phases (gap release and early in vessel release) are the same as for DBA accidents and extended release is provided during ex vessel and late in vessel phases. The release from the containment to the environment is part of the RADTRAD model. It is almost the same as for DBLOCA case and includes direct containment leakage, annulus leakage, and PCFV filtered release shown as flow path 12. The annulus recirculation filter and annulus exhaust filtered release are shown, but not used due to the assumed no action of active systems for the first 24 hours. Its use after the start of a mitigation is not assumed because that system is not a DEC system. The containment spray starts after 24 hours. It is switched off after two hours for radiological calculation (after that spray is not effective in radioactive material removal from containment atmosphere), but in reality it is on in a recirculation mode for thermal hydraulics calculation.

The leakage between the containment and annulus is described with flow paths 2 and 5. The flow is determined using the MELCOR run from t=0 hr till t=28.56 hr (end of MELCOR calculation). The flow is based on design leakage openings and real containment pressure difference. After that till the end of the RADTRAD calculation, the rate of 0.1%/day is assumed (% means percent of a containment free volume). The direct leakage from the containment to the environment is described with flow paths 3 and 6. Again, from the beginning till the end of the MELCOR calculation, the flow is based on MELCOR results (design leakage opening on pressure higher than the design containment pressure), after that leak rate of 0.01%/day is conservatively assumed. It is important to calculate the influence of containment and annulus leak before and after the PCFV actuation. Pathway 11 is used to describe the annulus leak rate. Flow rates are based on the MELCOR calculation. After containment spray actuation as part of a mitigation after 24 h, the annulus pressure is decreased (due to reverse heat transfer) and the same is true for annulus leak to the environment. Long term annulus behaviour is described conservatively as 1%/day leak to the environment till the end of the calculation. Flow path 12 is used to describe the PCFV influence. Due to large system decontamination factors (DF is 137000 for aerosols, 100000 for elemental and 15 for organic Iodine), a pipe with the prescribed decontamination factors is used. The actuation time (one opening), duration and flow rate are based on the MELCOR calculation (PCFV is open from 19.8 to 22.8 hours).

2.1 Atmospheric dispersion models

For the wider surroundings of NEK, the sources of emissions from NEK into the atmosphere are regarded as point sources. Lagrangian particle models are the most suitable for a realistic examination of dispersion from point sources, combined with a 3D spatial simulation of the meteorological condition of the atmosphere [9]. Lagrangian particle models are capable of correctly simulating plume rise and atmospheric turbulence in a 3D space at the appropriate temporal resolution.

The dispersion capacity of the atmosphere was presented with relative concentrations, also called dilution coefficients X/Q, which use a constant emission for the selected emission period and are used within RADTRAD for dose calculation.

The modelling system was built for the 200 km x 200 km area with NEK at the centre using the WRF and ARIA Industry models [10]. The ARIA Industry model consists of the meteorological preprocessor SURFPro, the wind model Minerve, and the Lagrangian particle dispersion model Spray.

We used the WRF version 4.2.1 model with GFS input data. The setting up of a weather forecasting model began for a slightly wider area, Figure 2. Larger domain has 89 cells x 89 cells horizontally, each cell is a square with a side of 12 km. Smaller domain has 85 cells x 85 cells horizontally, each cell is a square with a side of 4 km. Yellow circle labelled with 2 indicates the centre of the internal (smaller, second) domain.

The weather data, which are the result of simulations using the weather model, are then used as input data in a detailed weather preprocessor, which provides 3D spatial calculations at a slightly higher resolution. We used the SURFPro preprocessor. The output fields of the weather variables data are available for all the key variables that affect the atmosphere's dispersion/dilution capacities (temperature, global solar radiation, turbulence parameters, etc.). We simulate the wind field and all other meteorological variables at a fine resolution in a 3D space. The most important variable is the wind field, which we simulate using the mass-consistent wind model Minerve. Minerve receives the input data from WRF at a resolution that is lower than the final one. Minerve then interpolates the input data over complex orography at the final resolution, which is used to calculate dispersion. Through iterations it makes sure that the final field is mass consistent.

We used validated Lagrangian particle model Spray to calculate dispersion. The 3D spatial description of weather variables and the physical description of the characteristics of the source that emits radionuclides from NEK function as input data for the model used for calculating atmospheric radionuclide dispersion. The used input data and the settings of the Minerve and Spray models are as follows:

- domain of 200 km x 200 km with a resolution of 2 km and NEK at the centre, 100 x 100 cells horizontally;
- digital relief model from 2012 (source resolution 25 m, converted into the model's resolution of 2 km)
- land use (CORINE Land Cover) from 2018 (source resolution 100 m, converted into the model's resolution of 2 km)
- Extrapolated data for different seasons from the land-use database: “surface roughness length”, “Bowen ratio”, “albedo” and “soil heat flux”;
- Spatial division into cells, horizontally: 2 km, vertically: terrain-following layers; the first layer close to the ground is 10 m thick, followed by the terrain-following sigma coordinate system to the altitude of 3000 m;
- Temporal resolution of 30 minutes, average values;
- The elaborated months: February, May, August and November 2020.

Figure 2: Larger and smaller domain of the selected WRF model configuration

The simulations and statistical processing needed for X/Q calculation were performed for the month of May 2020. The 30-minute relative concentration or dilution coefficient (X/Q) is the basic result. The temporal statistical processing for each ground-layer cell (for 10,000 cells organized in the form of a 2D matrix), independently of the other cells, was carried out. The results are the temporal moving averages for 2, 8, 16, 72 and 624 hours in each spatial cell.

Afterwards, we found the temporal 95th percentile in each spatial cell separately. That way, we gained a statistical assessment of how much the atmosphere's dispersion/dilution capacities vary in each spatial cell (the weather impact in connection with the physical properties of the source).

The X/Q for each spatial cell anywhere within the domain of 200 km x 200 km represents the benchmark of the dose rate an inhabitant living in the selected spatial cell would receive from a passing cloud in the event of an accidental release from NEK.

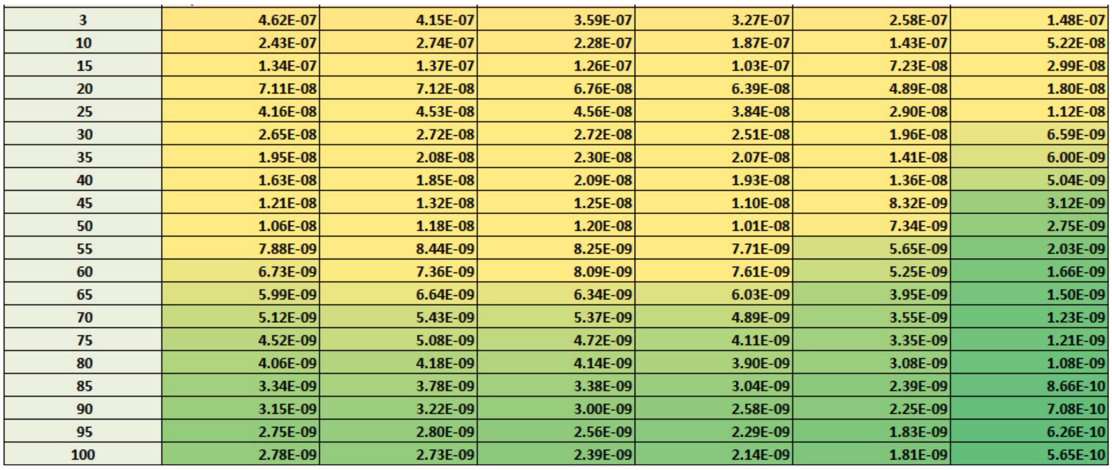
Then, we found all the temporal 95th percentile values on the rings for selected classes of distances from NEK for the entire 2D spatial area among all the cells for the selected month. A single class contains all the locations at a specific distance from NEK, regardless of direction. Then, we statistically processed all the temporal 95th percentiles of X/Q for each distance class separately. For the further calculation of doses, we selected the spatial 95th percentiles of the temporal 95th percentiles in the selected distance class and displayed them in a table.

Statistical analysis was performed for the plant ventilation, ground-level release and PCFVS. The 95th percentiles for plant vent and PCFV release are given in Table 1 and Table 2, respectively. These final calculations for the spatial 95th percentile are the input data for the calculation of doses in RADTRAD code.

As already said, additional calculation based on the RODOS model (DIPCOT and LASAT dispersion modules) was used for estimation of doses beyond distance of 100 km and for comparison with RADTRAD + SPRAY results from 50 to 100 km.

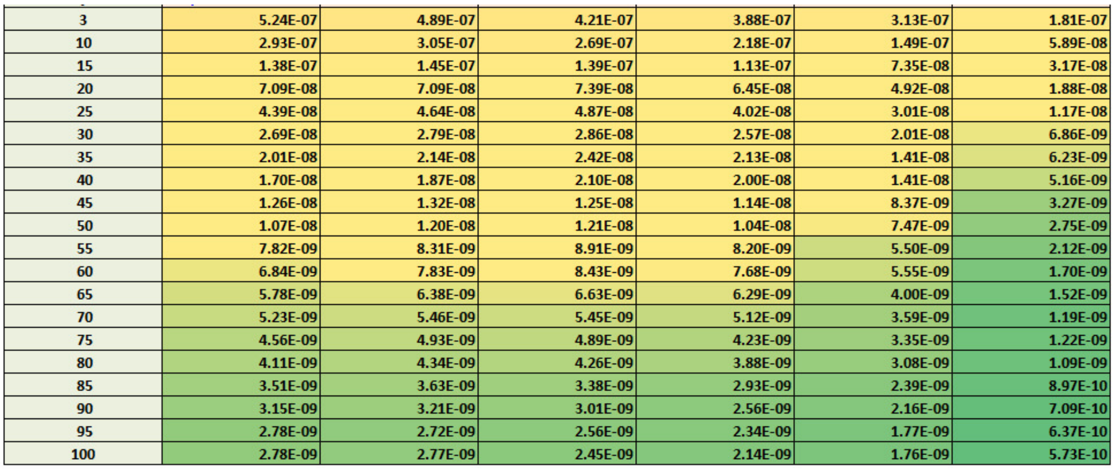
RODOS [11] calculation cells are set in the grid with five density levels, ranging from 1x1 km to 16x16 km, Figure 3. The total number of grid cells is 8056. RODOS topographical information is averaged over 1x1 km grid. Required meteorological data were prepared by Croatian Meteorological and Hydrological Service (CHMS) for two years (2016 and 2020) and two different spatial resolutions. For 2016 CHMS provided meteorological data every 12 hours. Each data set consists of 55 hourly files (1 hour of measurement and prognosis for 54 hours). The total area covered by the prognosis is a rectangle centred on the NPP Krško location, 36 grid squares wide (east – west) and 26 grid squares high (north – south) – 288x208 km. The data for 2020 are given in 4x4 km grid, with additional 13 vertical levels and coverage of larger area (144 grid squares east – west and 104 grid squares north – south, 576x416 km). Data sets are available each 6 hours (each one covers one hour measurements and 54-hour prognosis).

Table 1: Plant ventilation release – spatial 95th percentiles values of the temporal 95th percentile of X/Q [s/m^3] for the selected distance (km) and the selected (0.5, 2, 8, 16, 72 and 624 hours) temporal moving averages



3	4.62E-07	4.15E-07	3.59E-07	3.27E-07	2.58E-07	1.48E-07
10	2.43E-07	2.74E-07	2.28E-07	1.87E-07	1.43E-07	5.22E-08
15	1.34E-07	1.37E-07	1.26E-07	1.03E-07	7.23E-08	2.99E-08
20	7.11E-08	7.12E-08	6.76E-08	6.39E-08	4.89E-08	1.80E-08
25	4.16E-08	4.53E-08	4.56E-08	3.84E-08	2.90E-08	1.12E-08
30	2.65E-08	2.72E-08	2.72E-08	2.51E-08	1.96E-08	6.59E-09
35	1.95E-08	2.08E-08	2.30E-08	2.07E-08	1.41E-08	6.00E-09
40	1.63E-08	1.85E-08	2.09E-08	1.93E-08	1.36E-08	5.04E-09
45	1.21E-08	1.32E-08	1.25E-08	1.10E-08	8.32E-09	3.12E-09
50	1.06E-08	1.18E-08	1.20E-08	1.01E-08	7.34E-09	2.75E-09
55	7.88E-09	8.44E-09	8.25E-09	7.71E-09	5.65E-09	2.03E-09
60	6.73E-09	7.36E-09	8.09E-09	7.61E-09	5.25E-09	1.66E-09
65	5.99E-09	6.64E-09	6.34E-09	6.03E-09	3.95E-09	1.50E-09
70	5.12E-09	5.43E-09	5.37E-09	4.89E-09	3.55E-09	1.23E-09
75	4.52E-09	5.08E-09	4.72E-09	4.11E-09	3.35E-09	1.21E-09
80	4.06E-09	4.18E-09	4.14E-09	3.90E-09	3.08E-09	1.08E-09
85	3.34E-09	3.78E-09	3.38E-09	3.04E-09	2.39E-09	8.66E-10
90	3.15E-09	3.22E-09	3.00E-09	2.58E-09	2.25E-09	7.08E-10
95	2.75E-09	2.80E-09	2.56E-09	2.29E-09	1.83E-09	6.26E-10
100	2.78E-09	2.73E-09	2.39E-09	2.14E-09	1.81E-09	5.65E-10

Table 2: PCFVS release – spatial 95th percentiles values of the temporal 95th percentile of X/Q [s/m^3] for the selected distance (km) and the selected (0.5, 2, 8, 16, 72 and 624 hours) temporal moving averages



3	5.24E-07	4.89E-07	4.21E-07	3.88E-07	3.13E-07	1.81E-07
10	2.93E-07	3.05E-07	2.69E-07	2.18E-07	1.49E-07	5.89E-08
15	1.38E-07	1.45E-07	1.39E-07	1.13E-07	7.35E-08	3.17E-08
20	7.09E-08	7.09E-08	7.39E-08	6.45E-08	4.92E-08	1.88E-08
25	4.39E-08	4.64E-08	4.87E-08	4.02E-08	3.01E-08	1.17E-08
30	2.69E-08	2.79E-08	2.86E-08	2.57E-08	2.01E-08	6.86E-09
35	2.01E-08	2.14E-08	2.42E-08	2.13E-08	1.41E-08	6.23E-09
40	1.70E-08	1.87E-08	2.10E-08	2.00E-08	1.41E-08	5.16E-09
45	1.26E-08	1.32E-08	1.25E-08	1.14E-08	8.37E-09	3.27E-09
50	1.07E-08	1.20E-08	1.21E-08	1.04E-08	7.47E-09	2.75E-09
55	7.82E-09	8.31E-09	8.91E-09	8.20E-09	5.50E-09	2.12E-09
60	6.84E-09	7.83E-09	8.43E-09	7.68E-09	5.55E-09	1.70E-09
65	5.78E-09	6.38E-09	6.63E-09	6.29E-09	4.00E-09	1.52E-09
70	5.23E-09	5.46E-09	5.45E-09	5.12E-09	3.59E-09	1.19E-09
75	4.56E-09	4.93E-09	4.89E-09	4.23E-09	3.35E-09	1.22E-09
80	4.11E-09	4.34E-09	4.26E-09	3.88E-09	3.08E-09	1.09E-09
85	3.51E-09	3.63E-09	3.38E-09	2.93E-09	2.39E-09	8.97E-10
90	3.15E-09	3.21E-09	3.01E-09	2.56E-09	2.16E-09	7.09E-10
95	2.78E-09	2.72E-09	2.56E-09	2.34E-09	1.77E-09	6.37E-10
100	2.78E-09	2.77E-09	2.45E-09	2.14E-09	1.76E-09	5.73E-10

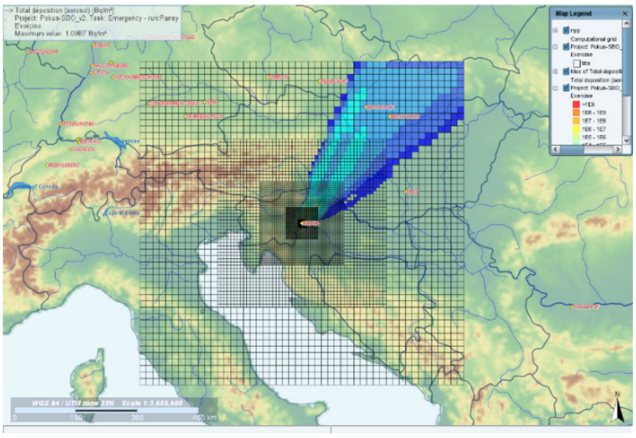


Figure 3: Overlay of RODOS calculation grid centered at NEK and map of the region

3 DOSES IN THE ENVIRONMENT

The doses in the environment are determined first for design basis LOCA release and then for severe accident SBO sequence. For each release the doses are first calculated using X/Q relative concentrations determined by detailed SPRAY atmospheric dispersion model for representative meteorology for the year 2020 and for distances up to 100 km. Additional RODOS calculations using real meteorology for the years 2016 and 2020 are performed for distances up to 200 km from the release point.

In the RADTRAD calculation continuous isotopic release rates (Bq/s) to the environment are multiplied by externally calculated X/Q (s/m^3) relative concentrations (dilution factors) for each location distance to get isotopic concentrations (Bq/m^3). RADTRAD uses dose conversion factors based on FGR 11 [12] and FGR 12 [13] to calculate organ dose rates and total effective dose equivalent (TEDE). Dose rates are integrated over the release interval to get corresponding doses. Deposition is not taken into account in X/Q calculation to maximize airborne activity. All exposure pathways except ingestion are taken into account in dose rates calculation.

The releases from all release paths (leakage from the containment to the environment, leakage from the annulus to the environment and from the plant vent filtered exhaust) are in RADTRAD treated as the total released activity to the environment. To maximize dose at larger distances, plant ventilation spatial 95th percentiles X/Q factors from Table 1 are used. In all cases breathing rates are used according to the SAR accident analysis values. Occupancy factor is one. There are no protective measures of any kind.

In order to assess radiological influence of NEK design basis LOCA accident sequence to the environment at distances greater than 100 km from NPP Krsko site, RODOS (JRodos) calculations are performed as well. The same release source term was used as in the RADTRAD calculation. The released activities (Bq) for important isotopes, organized in three time intervals (the first day, from the first to the third day and from the third day to the 30th day) are shown in Table 3.

Table 3: Characteristic isotopes released activities during NEK DBLOCA

0.0 - 24.0 h	24.0 - 72.0 h	72.0 - 720. H	Total
Kr-85 1.7749E+13	Kr-85 4.4774E+13	Kr-85 5.2844E+14	Kr-85 5.9096E+14
Kr-85m 7.1662E+13	Kr-85m 5.3687E+12		Kr-85m 7.7031E+13
Kr-87 1.0941E+13			Kr-87 1.0941E+13
Kr-88 8.6110E+13	Kr-88 1.1840E+12		Kr-88 8.7294E+13
I-131 1.4780E+13	I-131 8.9780E+12	I-131 2.6292E+13	I-131 5.0050E+13
I-132 3.5760E+12	I-132 9.6204E+08		I-132 3.5770E+12
I-133 2.2692E+13	I-133 5.1112E+12	I-133 1.1104E+12	I-133 2.8914E+13
I-134 2.3094E+12			I-134 2.3094E+12
I-135 1.1870E+13	I-135 3.6149E+11		I-135 1.2231E+13
Xe-133 3.2447E+15	Xe-133 6.9147E+15	Xe-133 1.9532E+16	Xe-133 2.9691E+16
Xe-135 3.2902E+14	Xe-135 1.1702E+14		Xe-135 4.4604E+14
Cs-134 1.7926E+12	Cs-134 1.1960E+12	Cs-134 7.3445E+12	Cs-134 1.0333E+13
Cs-136 5.5574E+11	Cs-136 3.4288E+11	Cs-136 1.2735E+12	Cs-136 2.1721E+12
Cs-137 1.1723E+12	Cs-137 7.8310E+11	Cs-137 4.8545E+12	Cs-137 6.8099E+12

Eight intervals were used to define the RODOS release source term. Release paths are described earlier. A continuous RADTRAD isotopic release (60 isotopes) is organized in intervals of constant activity release so that the amount of discharged radioactive material is preserved. The first interval was assumed to be direct containment release at low temperature and ground elevation. All other intervals were assumed to be releases from the plant vent, with medium temperature and appropriate initial velocity. That was done to promote transport to larger distances. Total duration of release/calculation is 72 hours. Design calculation assumes the leakage continued up to 30 days. In order to keep the RODOS calculation time reasonable, the radioactivity released in last interval (from 48 to 72 h) was increased to correspond to the activity released in whole 30 days. In order to check the influence of that assumption additional calculation was done (DIPCOT atmospheric dispersion module with increased time interval between release of particle puffs from 10 to 30 seconds). The usage of full 30 days release interval calculation usually decreases closer doses and increases farther ones. Taking into account low TEDE values beyond 100 km, that does not pose a problem. The total effective dose was calculated without any protective measures. All mechanisms responsible for radioactive dose calculation were taken into account except ingestion. The starting times of accident sequences are selected randomly within the day, one sequence per each day in year 2016. That was the year with the most complete time dependent meteorological data to drive the calculation. Once selected, starting times of the release (source term is always the same) are kept for all subsequent calculations. That way radiological consequences of DBA and severe accident can be compared. The available meteorological data for the year 2020 were then used to check if there is a significant difference in weather data from year to year at NPP Krsko location. It was demonstrated that the predicted 95% values determined on a yearly basis are similar. The effective dose versus distance curves of 95th spatial percentile values are shown in Figure 4 for distances representative for transboundary influence. For the year 2016 DIPCOT dispersion model is used first, and then LASAT model (approximately two times slower) was used to verify the influence of the dispersion model on calculated doses. LASAT model usually predicts lower doses close to the release point and larger doses at distances beyond 100 km. The difference is not so important due to low 95% values predicted by both models. LASAT model was not used with 2020 data due to longer calculation time (larger amount of weather data) and generally low TEDE values at larger distances. The influence that meteorological data taken at the same time in two different years (2016 and 2020) can have on calculated DBLOCA TEDE values was demonstrated using only DIPCOT results. As can be seen the obtained doses are similar and the difference is smaller than the difference obtained for the same year with different atmospheric dispersion models. In case of larger SBO release LASAT calculation is performed for both years showing smaller year-to-year difference than for DIPCOT dispersion model. The effective dose values obtained with two RODOS modules are higher than the values obtained with RADTRAD calculation with SPRAY X/Q factors. The difference is expected taking into account different spatial resolution of models (both terrain and meteorological data) and different approach to calculation (intervals with averaged release and time dependent dispersion in RODOS, and time dependent release and moving time average X/Q factors in RADTRAD). Due to a limited range of spatial meteorology data in 2016 the results are shown only till distance of 100 km. The meteorology data available for RODOS calculation in the year 2020 are usable up to distance of 200 km from the release point. All calculated TEDE values below 0.1 mSv are within regulatory limit for 30 days exposure (based on the annual limit for general population). DBLOCA 30-day thyroid 95th spatial percentile doses are given in Figure 5. In order to illustrate the type of the difference obtained between the RADTRAD and RODOS calculation only DIPCOT module results for 2020 year are shown. This time RADTRAD doses are slightly higher due to different assumed breathing rate in two calculations (RODOS is using normal breathing rate all the time).

In RODOS case TEDE versus distance curves are calculated from 2D distribution of corresponding doses, Figure 6. 2D distributions show for each calculation cell 95% values of number of release times (weather sequences). Shown results were obtained with RODOS DIPCOT air dispersion module. The 95% values are calculated for one weather sequence each day in year 2020 (the same release is started at different times and corresponding weather conditions are responsible for atmospheric dispersion). That means that any 2D cell have a dose that can be exceeded only in 5% of calculated weather sequences. The circles shown in figures are drawn at distances 100 km and 200 km from the NPP Krsko. In order to obtain dose versus distance curves at distances up to 200 km from the plant, spatial 95% value is calculated from all doses in 2D distribution having specified distance from the release point. That again means that only 5% of doses at selected distance can have a dose larger than the one shown in graph.

In order to assess radiological influence of low probable NEK severe accident sequence the same type of calculation as for DBLOCA was performed. The selected accident sequence is SBO without any action in the first 24 hours (the core is damaged and relocated to the containment cavity) and then mitigation using available alternative safety systems is applied. Most of the radioactivity is released during actuation of the PCFV system, but leakage release before and after that was calculated as well. The released activities (Bq), for important isotopes, organized in three time intervals (the first day, from the first to the third day and from the third day to the 30th day) are shown in Table 4.

Table 4: Characteristic isotopes released activities during NEK SBO accident with PCFV actuation

0.0 - 24.0 h		24.0 - 72.0 h		72.0 - 720. H		Total	
Kr-85	8.2517E+15	Kr-85	5.9200E+12	Kr-85	9.5090E+13	Kr-85	8.3527E+15
Kr-85m	1.0247E+16	Kr-85m	7.4000E+11			Kr-85m	1.0248E+16
Kr-87	1.2790E+13					Kr-87	1.2790E+13
Kr-88	4.5806E+15					Kr-88	4.5806E+15
I-131	3.1798E+14	I-131	6.2008E+13	I-131	1.2321E+14	I-131	5.0320E+14
I-132	2.2709E+13	I-132	8.8796E+09			I-132	2.2718E+13
I-133	4.1803E+14	I-133	4.4918E+13	I-133	8.8800E+11	I-133	4.6384E+14
I-134	4.3778E+12					I-134	4.3778E+12
I-135	1.5476E+14	I-135	3.9368E+12			I-135	1.5870E+14
Xe-133	1.4637E+18	Xe-133	8.8800E+14	Xe-133	2.8490E+15	Xe-133	1.4674E+18
Xe-135	9.3407E+16	Xe-135	1.4800E+13			Xe-135	9.3422E+16
Cs-134	4.0356E+13	Cs-134	1.0578E+13	Cs-134	6.6593E+13	Cs-134	1.1753E+14
Cs-136	1.2399E+13	Cs-136	3.1002E+12	Cs-136	9.1986E+12	Cs-136	2.4698E+13
Cs-137	2.6396E+13	Cs-137	6.9223E+12	Cs-137	4.4182E+13	Cs-137	7.7500E+13

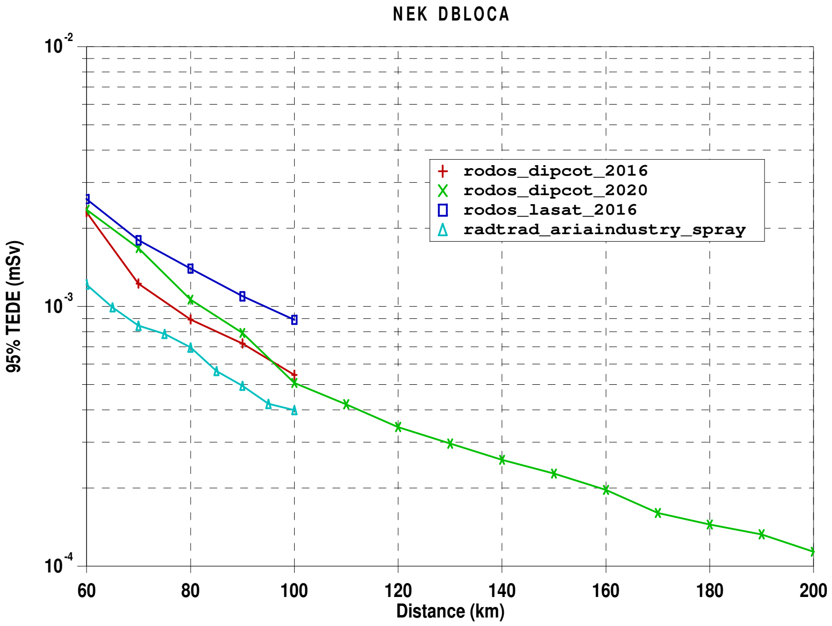


Figure 4: Total effective dose (95th percentile spatial values) for NEK DBLOCA

Ten intervals were used to define the RODOS release source term (based on release rates available for 60 isotopes in RADTRAD). The total duration of release/calculation is 72 hours. During that time around 99% of radioactivity available for release in the first 30 days, after selected accident, was released. The first time interval takes into account containment leakage in time interval 0 to 0.5 hours. The material is released as ground release (10 m) of low thermal content and low mass flux gas. The isotopic content of the release is in accordance with the isotopic composition of containment atmosphere at that time. Next five time intervals, between 0.5 and 2 hours, between 2 and 4 hours, between 4 and 8 hours, between 8 and 12 hours, and between 12 and 19.3 hours, have similar release characteristics (design containment leakage release) taking into account a change in containment pressure and isotopic composition of containment atmosphere. The seventh release interval is used to describe actuation of the PCFV system. Its duration is between 19.3 and 22.3 hours and most of the radioactivity is released to the environment during this interval.

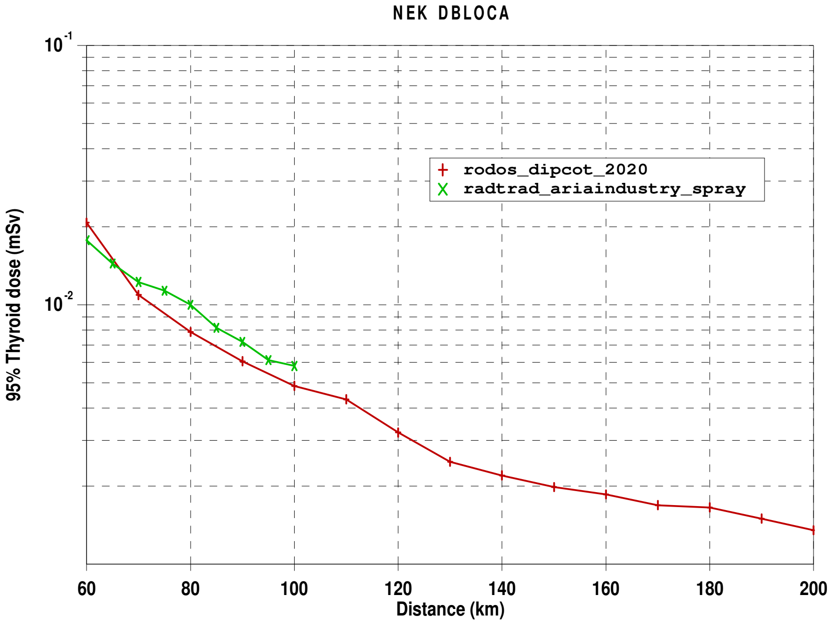


Figure 5: Thyroid 30-day dose (95th percentile spatial values) for NEK DBLOCA

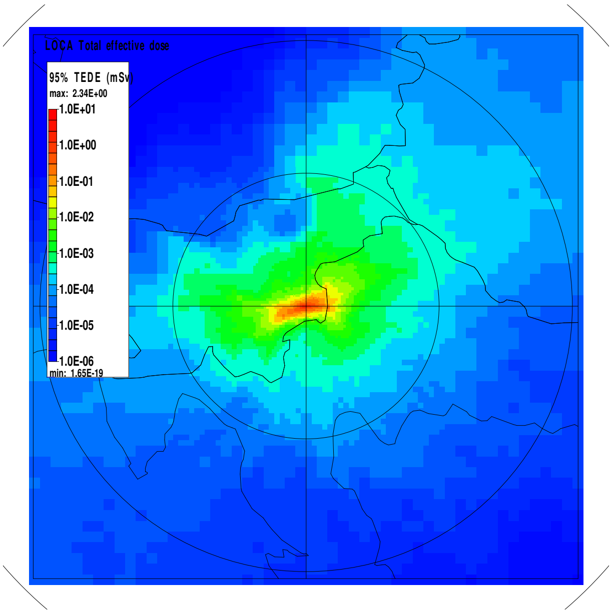


Figure 6: 95% LOCA TEDE values for distances up to 200 km, DIPCOT year 2020

Due to high efficiency aerosol and iodine filters most of the material released through the PCFV duct belongs to noble gases category, but still some other volatile radioactive products were present. The release height is at the top of the PCFV duct, and thermal content and exit velocity of gas discharge were taken into account. The remaining three release intervals, between 22.3 and 24 hours, between 24 and 48 hours, and between 48 and 72 hours, are again intervals when only containment leakage is taken into account and ground release is assumed with low thermal content. The total effective dose equivalent was again calculated without any protective measures. All mechanisms responsible for radioactive dose calculation were taken into account except ingestion. The starting times of accident sequences are the same as in the case of DBLOCA. That way radiological consequences of DBA and severe accident can be compared.

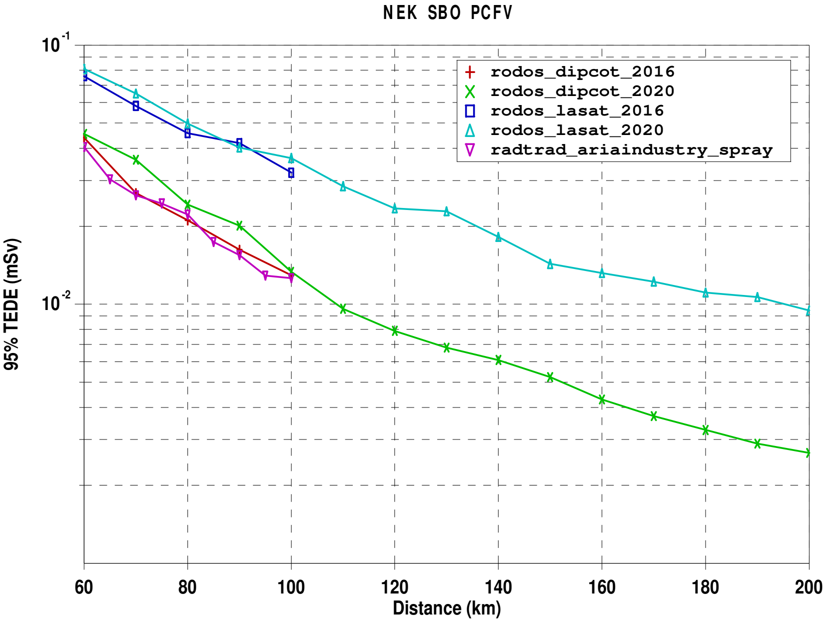


Figure 7: Total effective dose (95th percentile spatial values) for NEK SBO PCFV

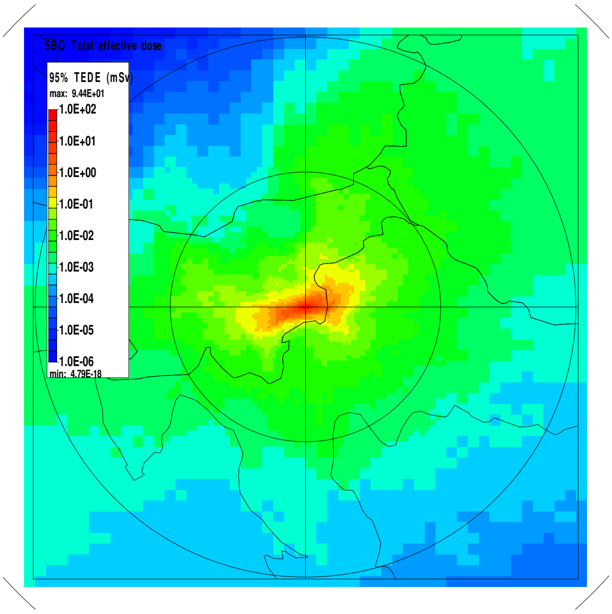


Figure 8: 95% SBO TEDE values for distances up to 200 km, DIPCOT year 2020

The 95% spatial TEDE values are shown in Figure 7. The doses calculated for two different years are very similar. LASAT calculated doses are higher than DIPCOT doses, but both dose predictions are giving low TEDE values. The dose values calculated by RADTRAD with SPRAY X/Q factors and DIPCOT are similar. The same as in LOCA calculation, the RODOS results obtained with 2016 meteorology are shown only up to distance of 100 km due to spatial limitation of available meteorology data. The SBO doses are for more than order of magnitude higher than in the case of DBLOCA, but still lower than the dose acquired in the same time interval according to regulatory limit (based on the annual limit for normal population). The same as before, 95% spatial values are obtained from 2D distribution of 95% temporal values. The values calculated by DIPCOT module for the year 2020 are shown in Figure 8.

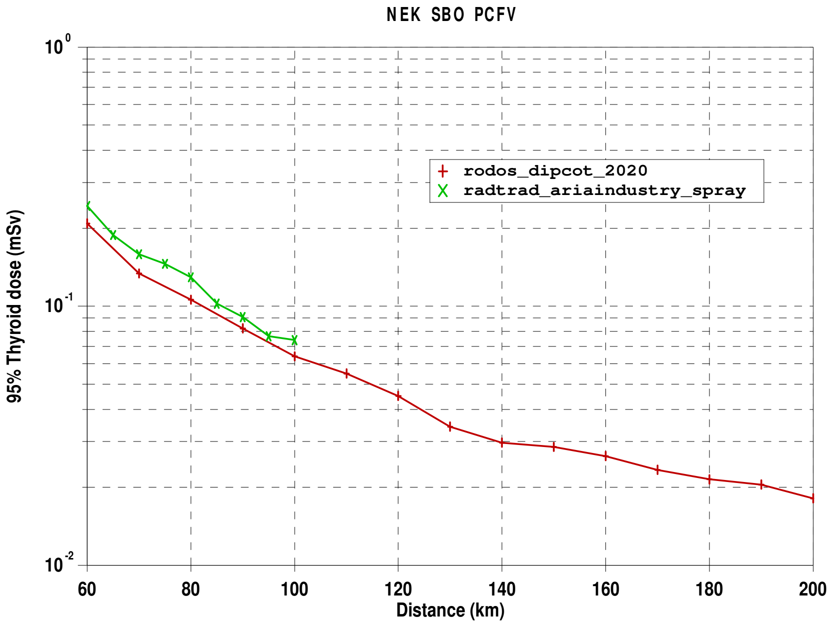


Figure 9: Thyroid 30-day dose (95th percentile spatial values) for NEK SBO PCFV

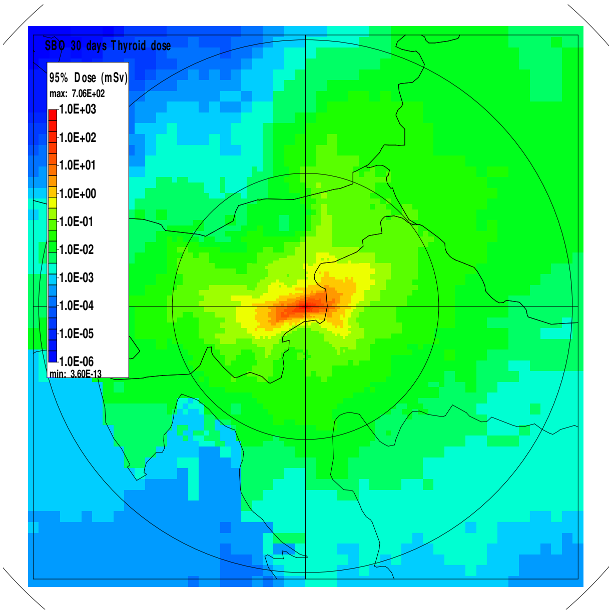


Figure 10: 95% SBO Thyroid doses for distances up to 200 km, DIPCOT year 2020

The corresponding 95th spatial percentile 30-day thyroid doses are shown in Figure 9. The thyroid doses calculated up to 100 km (RADTRAD + SPRAY X/Q) and beyond 100 km (DIPCOT calculation) are very similar. DIPCOT thyroid doses are again lower due to lower assumed breathing rates at larger distances. 2D distribution of 95th temporal percentile dose values is shown in Figure 10. As expected, the shapes of isodose boundaries are similar as for 2D TEDE distribution.

4 CONCLUSION

The radiological impact of NPP Krško life time extension should be quantified as part of the environmental impact assessment. The methodology used to perform necessary analyses to assess the dose rates and the consequences to the environment at selected distances from NEK in case of a DBA LOCA and BDBA SBO scenario were described.

The doses for distances up to 100 km (local and temporal 95th percentile values) are calculated using the RADTRAD code in combination with detailed and validated realistic model Spray (explicit release rates and moving time average X/Q factors). Additionally, the doses for distances up to 200 km are calculated with the RODOS code (time averaged release rates and explicit atmospheric dispersion). That approach uses simplified representation of the terrain around the NPP Krško and has a different approach in the use of meteorological data and calculation of doses.

Although the calculation models are different, the calculated doses at a distance of 100 km from the NPP agree well. Used two dose calculation approaches, different atmospheric dispersion models and meteorology for two different years quantified the expected differences in dose predictions. Even if we apply that differences in conservative direction the calculated doses for shown distances are acceptably low.

The results of performed analyses show that no significant transboundary impact from the Krsko NPP, in case of DBA or DEC-B accident, is expected, except possibly at parts of Croatian border. The effective 30-day dose at the borders with other neighbouring countries for the worst-case accident is usually lower than the corresponding influence from the background radiation. The way how the plant can radiologically influence environment in the period of extended operation is not different than the way of influence predicted during current operation (year 2021).

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