Calculation of Radiological Consequences of Design Basis Accidents for Licensing Purposes

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ABSTRACT

The calculation of radiological consequences of Design Basis Accidents (DBA) is used for licensing purposes including siting and SAR Chapter 15 applications. In this paper NPP Krško LOCA was used as a reference DBA accident. The released radiological effluents were calculated using Regulatory Guide RG 1.183 assumptions and RADTRAD computer code. Plant specific fuel source term is obtained using ORIGEN code for real plant's operation history data. The dispersion X/Q factors needed to perform calculation of doses in the environment (Exclusion Area Boundary EAB and Low Population Zone LPZ locations, and 1D/2D spatial dependence around the plant) were determined using two different approaches. The first is a classical one based on RG 1.145 as implemented in the PAVAN code with close range additions from RG 1.249 as implemented in ARCON96 code. The second is a X/Q calculation based on the Lagrange particle methodology developed by MEIS d.o.o. Both approaches use similar sets of meteorological data measured at NPP Krško location. Additional independent radiological consequences calculation was performed using MACCS2 code for the same release source term and meteorological data. The last methodology proposed to calculate TEDE doses around the plant was based on number of JRODOS calculations for selected past sequences of meteorological data, and statistical post processing of obtained spatial dose rate data. Three different approaches of radiological consequences calculation are compared from the point of view of accuracy, type of provided results, calculation time and user requirements. The methodologies were applied to existing Gen II NPP, but are mentioned to be applied to SMR plants with more focus on the radiological impact close to the plant too.

Keywords: *radiological consequences, DBA accident, LOCA, atmospheric dispersion*

1 INTRODUCTION

Nuclear power plant risk analysis requires a comprehensive analysis of the consequences of potential nuclear accidents during the plant's operation [1]. Given the complexity of the process, it is necessary to divide the entire chain of events into several packages, and consider each of them separately. In general, in theory there are two approaches to solving this problem: a conservative approach using simple models that are a combination of physical and engineering solutions, and a mechanistic approach with application of best estimate dedicated realistic computer codes.

There are many codes for individual stages of a nuclear accident. To begin with, it is necessary to determine the isotopic composition of the reactor core. With known data on fuel burnup and composition, this can be done relatively easily. However, problems arise already when one wants to quantify the release of radioisotopes from damaged fuel. Mathematical modelling based on the physical description of the process is not enough, but experimental confirmation is needed, which does not exist today for most severe accident scenarios. After that, the uncertainties only grow as the nature of the process becomes increasingly stochastic. Core damage and melting, release and chemical form of radionuclides, transport and retention within the reactor building, time and location of release, are just some examples of phenomena whose quantification is necessary when determining the source term.

The goal of the analysis is to determine the doses in the vicinity of the power plant, which requires a detailed calculation of the dispersion of the nuclear cloud caused by atmospheric effects. It is evident that the methodology requires the application of multiple numerical tools and a multidisciplinary approach to solving the problem of determining the consequences of a reactor accident.

2 BACKGROUND

Calculations are guided by international and national regulations, such as 10CFR100, 10CFR52, IAEA standards (SRS 19, GS-G-2.1), and Slovenian decree on areas of limited use of space due to a nuclear facility and the conditions of facility construction in these areas (UV3). The analysis is performed for a postulated design basis large break LOCA scenario in the NPP Krško. Specific regulatory guides (RG) are implemented (RG 1.183 for source term [2], RG 1.145, RG 1.249 and RG 1.194 for atmospheric dispersion models).

Dose limits, given in mSv, for the exclusion area boundary (EAB) and low population zone (LPZ) are specified by 10CFR100 [3] and UV3 criteria [4], separately for the thyroid and for the whole body (TEDE - total effective dose equivalent), Table 1.

Table 1: Dose limits for EAB and LPZ

Limits	10CFR100	UV3
EAB Thyr (mSv)	3000	3000
EAB TEDE (mSv)	250	250
LPZ Thyr (mSv)	3000	3000
LPZ TEDE (mSv)	250	100

3 METHODOLOGY

Radionuclide core inventory is calculated by the ORIGEN2 code [5] using real power history (scaled to 1994 MWt × 1.02). PARCS 2D/3D code power/burnup distribution was used for fuel assembly depletion calculation. The RADTRAD 3.03 code [6] is used for dose calculation and, before that, for release source term preparation for which it uses simplified containment nodalization, Figure 1, and takes into account radionuclide physical and chemical behaviour within the plant systems, before the release in the environment.

The containment is divided into sprayed (1) and unsprayed volume (2). Radioactive material is released in sprayed and unsprayed volumes according to prescribed release and split fractions. Paths 1 and 4 are used to model mixing between the containment volumes. Paths 3 and 6 are containment direct leakage paths. Paths 2 and 5 are containment leakage paths to annulus (3) when underpressure is established. The annulus is equipped with 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).

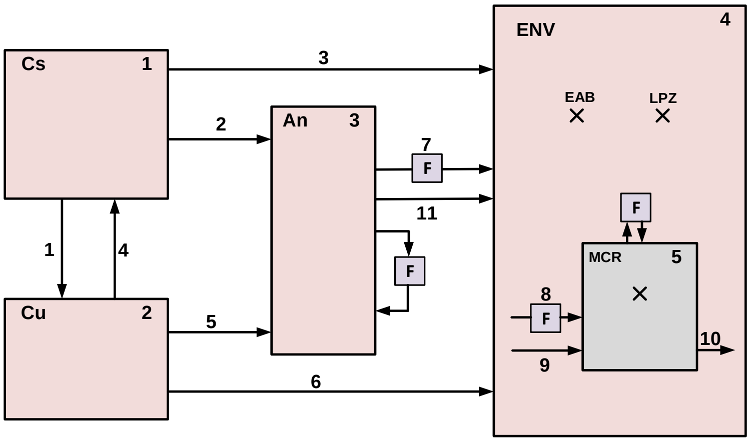

Figure 1: RADTRAD model for NEK DBLOCA calculation

RADTRAD uses dose conversion factors based on FGR 11 [7] and FGR 12 [8] to calculate organ dose rates and total effective dose equivalent. The code does not have models for atmospheric dispersion, instead a set of so-called X/Q (s/m^3) factors should be prepared beforehand which describe environmental isotopic concentrations. A mechanistic Lagrangian particle model SPRAY [9] is used to calculate X/Q factors, MEIS d.o.o. [10]. The RADTRAD thus enables integral dose calculations by modelling the power plant containment, but it needs relative concentration factors which are independently calculated for a general meteorology and prescribed particle sizes. It is also required to specify fuel source term from the primary system as a boundary condition.

Another approach is to use the JRODOS code [11], a dedicated atmospheric dispersion code for radionuclides. Its shortcoming is that it needs the plant source term in Bq/s, which can be obtained by any severe accident code that involves containment modelling, eg. MELCOR, MAAP, ASTEC, etc. RADTRAD thus needs the source term at the primary and/or secondary system boundary, and JRODOS at the containment boundary. The RADTRAD and JRODOS both calculate the thyroid dose and TEDE. JRODOS uses Langrangian particle model for best-estimate radionuclide dispersion calculation. Coupling of MELCOR/ASTEC and JRODOS provides the most realistic doses estimates following a DBA or a severe accident [12].

The weather data needed for the Lagrangian model include wind speed, wind direction, precipitation and weather stability conditions. In order to estimate the dozes, detailed dataset for the vegetation and urbanization are also required.

Lagrangian particle models are based on the Langevin equation that describes the temporal evolution of the velocity of pollutant particles in a turbulent field. The original equation in principle describes Brownian motion, a fluctuating motion of a particle in a fluid. Brownian motion is described by the Wiener process, a continuous-time stochastic process.

The Langevin equations [13] for the particle turbulent velocity and its position are given as:

$$du_i(t) = a_i(\vec{x},\vec{u},t)dt + b_{i,j}(\vec{x},\vec{u},t)dW_j \,, \tag{1}$$

$$dx_i(t) = u_i(t)dt \,, \tag{2}$$

where a and b are function of velocity and position, and W is the incremental Wiener process. The total velocity is the sum of the mean and fluctuating velocity terms.

4 CALCULATIONS AND DISCUSSION

Primary source term or fuel source term is isotopic activity inventory of reactor core and it is starting point of any radioactivity release calculation. In the case of the NPP Krško it is calculated using ORIGEN 2.2 code, real fuel assembly data and real operating history of the fuel. The depletion is performed on fuel assembly basis (one node per fuel assembly), using plant's cycle data and 3D cycle depletion as implemented in PARCS code. The core inventory is calculated for nominal core power of 1994 MWth with additional linear upscaling used to take into account possible core power calorimetric error of 2%. The total core activity and contribution to power is represented by 60 isotopes. The dependence of power on time for different radionuclides and the fuel cycle is shown in the figures 2 and 3, respectively. The largest short-term contribution to the total thermal power is made by caesium and iodine, while in the long term caesium is the most important radionuclide. The impact of the fuel cycle is negligible.

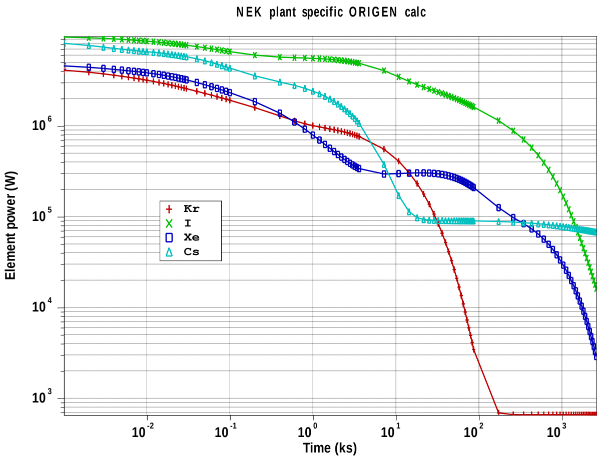

Figure 2: Element power for Kr, I, Xe and Cs

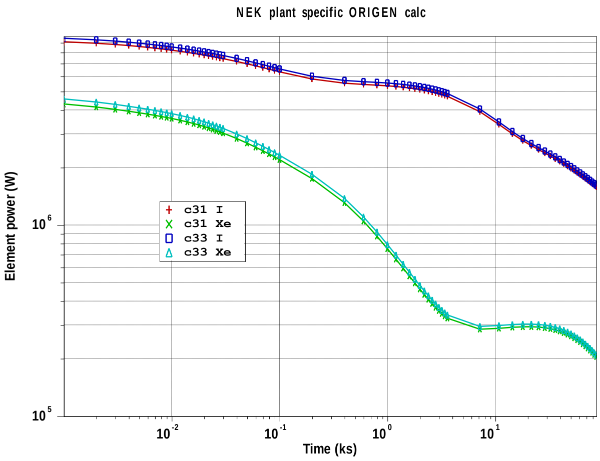

Figure 3: Element power for I and Xe for different fuel cycles

Containment dynamics is simulated by the RADTRAD code. The analytical method of assessing release into the environment accounts for removal or reduction of fission products due to safety systems (containment sprays, passive containment filtered vent) as well as due to natural processes such as aerosol deposition. Gas mixing is enabled by the operation of fan coolers. It is assumed that mixing flow is the sum of their flow and natural circulation flow between volumes. Removal of radioactive material from containment atmosphere due to spray actuation in sprayed volume is modelled using first order spray removal coefficients for aerosol and elemental iodine. It is assumed that for the first 1200 s (time to establish under pressure in annulus) containment release rate into the environment is 0.2 vol.%/day. The release rate between 1200 s and 1 day is 0.02 vol.%/day, and after that 0,01 vol.%/day. Ground release is assumed and breathing rates are in accordance with the U.S. NRC regulations [2]. Filter efficiency is modelled according to plant design data [14], [15].

Specific containment atmosphere activity (GBq/m^3) of iodine and caesium are shown in figures 4 and 5 respectively. The release to the containment is done in two steps (duration 0.5 h and 1.3 h) and it has finished 1.8 hours after accident initiation (at 0 h). The spray is present up to time t= 2 h and it is able to reduce activity in upper and lower part of the containment. The natural deposition in unsprayed compartment has small impact on containment activity in the late phase of the simulation. The presence of radioactive decay is important mechanism for activity reduction in all phases of calculation. The design leakage has limited influence on containment activity reduction and the influence is clearly increasing with time. It is typically less effective than assumed wall deposition in unsprayed compartment. Most effective short term reduction is due to spray and long term reduction due to decay.

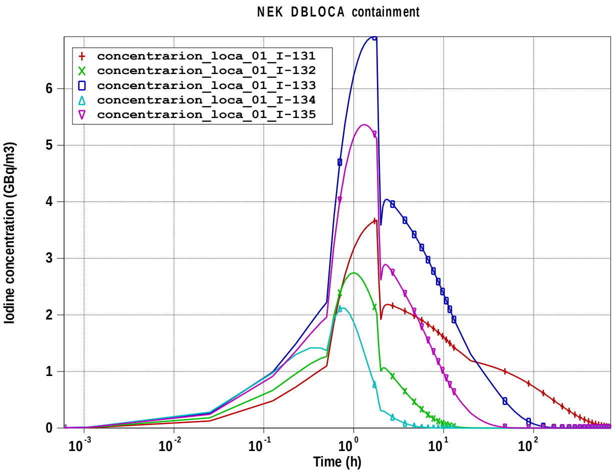

Figure 4: Iodine specific activity in the containment

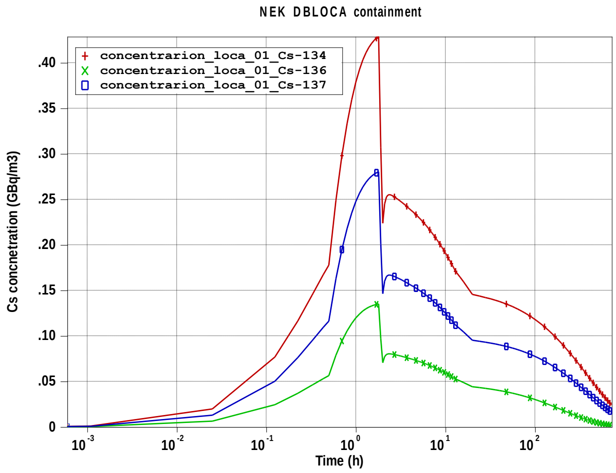

Figure 5: Caesium specific activity in the containment

There are 16 release intervals, from the containment to the environment, with nine of them being in the first 24 hours, Figure 6. Total activity released is 829.5 kCi. In figures 7 and 8 released activities for iodine and caesium are shown (label _01). The curves with label _02 are activity of the isotope present in the environment at that time.

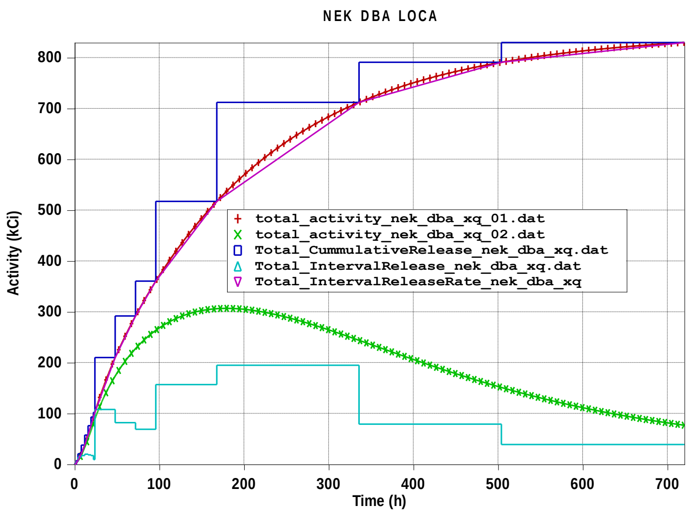

Figure 6: DB LOCA release source

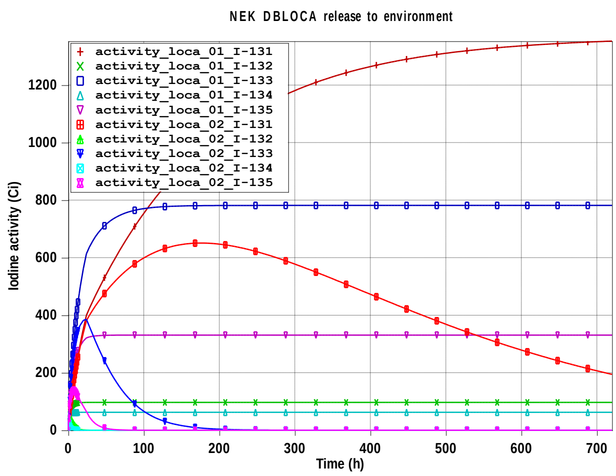

Figure 7: Iodine activity released to the environment and present in the environment

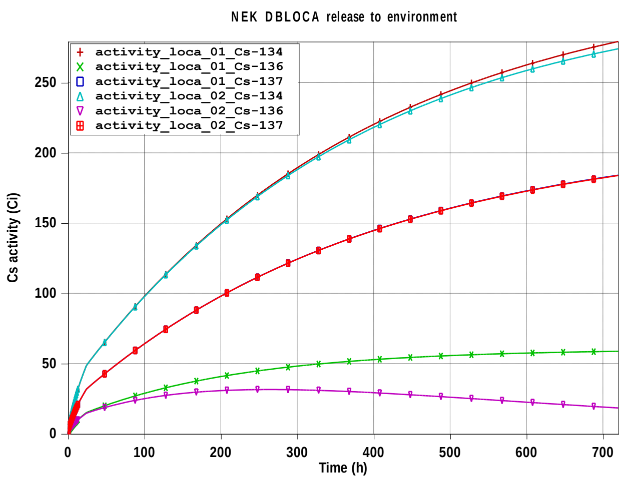

Figure 8: Caesium activity released to the environment and present in the environment

As mentioned before, RADTRAD needs pre-calculated X/Q factors that represent ratio between the effective radioisotope concentration and the source strength. They were determined by MEIS, using the following methodology:

- Long-term meteorological measurements (at least 10 years of measurement data),
- WRF weather prognosis (3D domain, time resolution 0.5 h),
- Lagrangian particle model SPRAY (ARIANET s.r.l. Milano) used to calculate dispersion in the atmosphere based on conservative MINERVE/SWIFT flow model over realistic ground (SURFPRO),
- Typical spatial raster 5 km×5 km near NPP Krško, and then 25 km×25 km; reanalysis based on WRF calculation: 200 km×200 km, 400 km×400 km (Figure 9),
- Height and parameters of the release depend on the sequence,
- 2D X/Q data using temporal resolution of 0.5 h,
- Moving average for: 2, 8, 16, 72 and 624 hour intervals (Figure 10),
- 95 percentile values in time for each calculation cell,
- X/Q data reduced to 1D using selected distances using 95 percentile spatial filter.

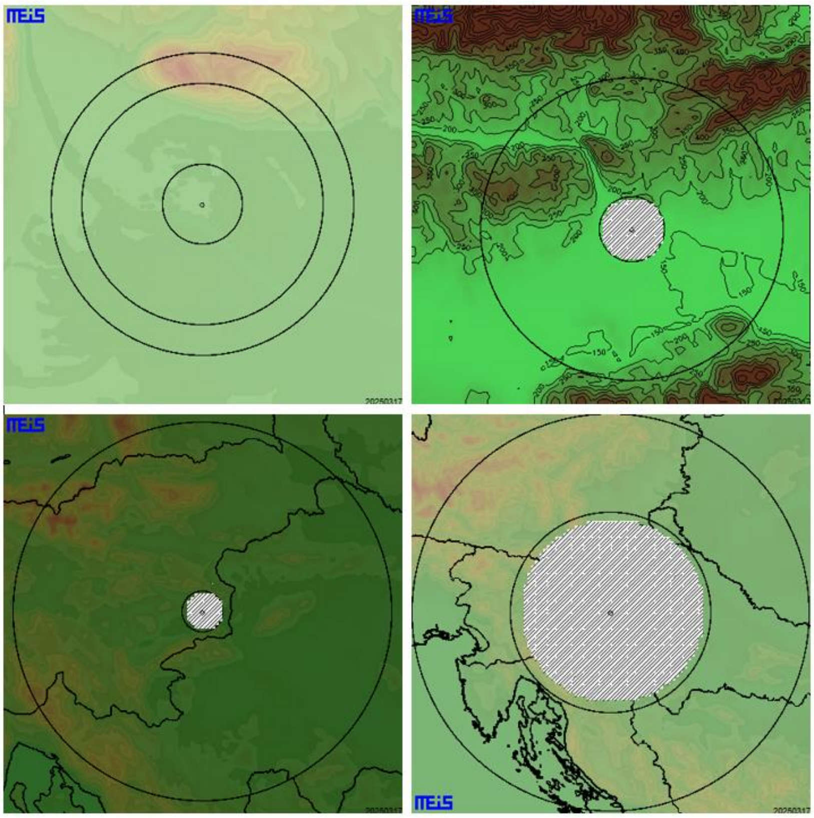

Figure 9: Spatial domain for X/Q, C/Q, D/Q calculation

In accordance with the X/Q factor values, the 30-day total effective dose and 30-day thyroid dose (95th percentile spatial values), at ground level are given in Figure 11. Two most important weather properties for atmospheric dispersion that influence dose rates are wind speed and wind direction, Figure 12. These plant measurements are indication of initial radioactive effluent dispersion direction, however in most calculated dose rate patterns the initial wind direction influence is clearly present. For comparison, X/Q factors were calculated for short distances using the PAVAN code [16], Table 2.

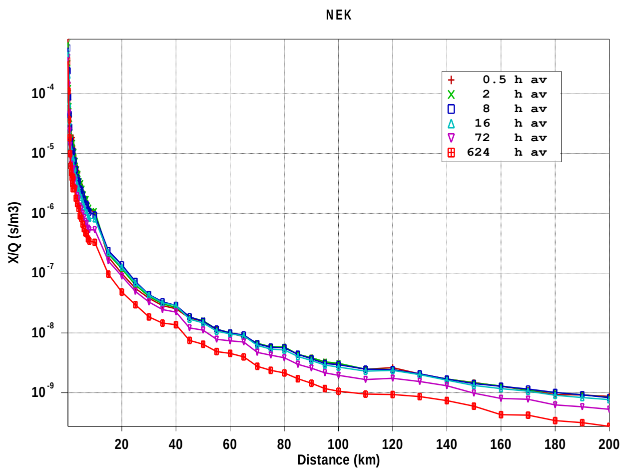

Figure 10: Time averaged X/Q factors

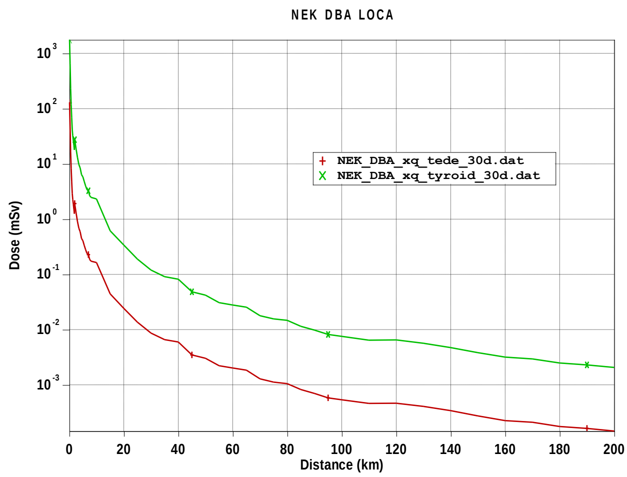

Figure 11: 30-day doses at different distances from the power plant

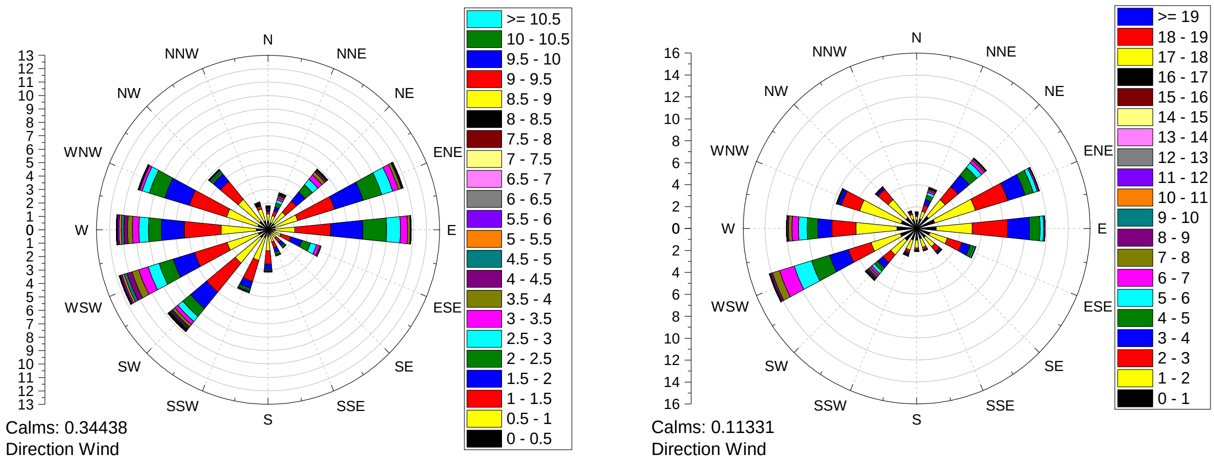

Figure 12: Wind roses based on NPP Krško measurements at 10 m and 100 m

Dose rates were additionally calculated by mechanistic code JRODOS. The code is widely used for applications in nuclear power consequence analyses, for example for quantifying doses after the accident in Fukushima NPP [17].

The specific features of the JRODOS model applied in the calculation are as follows:

- Realistic meteorology and terrain morphology,
- Release source term obtained from RADTRAD calculation,
- LOCA leakage release at 10 m elevation,
- Long-range dose rate estimation covers distance of more than 200 km,
- Iodine chemical forms: elemental 0.3, organic 0.45, aerosol 0.25,
- Influence of deposition is taken into account,
- Required meteorological data were prepared by Croatian Meteorological and Hydrological Service for two years (2016 and 2020) for the spatial domain 400 km×400 km,
- Usage of nested calculation grid (0.5 km×0.5 km to 8 km×8 km) shown in Figure 13.

Table 2: NPP Krško PAVAN X/Q factors (500 m/1500 m) for ground level release

PROGRAM: PAVAN, 10/76, 8/79 REVISION, IMPLEMENTATION OF REGULATORY GUIDE 1.145

RELATIVE CONCENTRATION (X/Q) VALUES (SEC/CUBICMETER) VERSUS AVERAGING TIME

DOWNWIND SECTOR	DISTANCE (METERS)	0-2 HOURS	0-8 HOURS	8-24 HOURS	1-4 DAYS	4-30 DAYS	ANNUAL AVERAGE	HOURS PER YEAR MAX 0-2 HR X/Q IS EXCEEDED IN SECTOR	DOWNWIND SECTOR
S	500.	5.10E-05	3.48E-05	2.87E-05	1.90E-05	1.04E-05	5.03E-06	0.6	S
SSW	500.	9.38E-04	5.45E-04	4.15E-04	2.30E-04	9.86E-05	3.50E-05	9.7	SSW
SW	500.	1.04E-03	6.66E-04	5.33E-04	3.30E-04	1.65E-04	7.11E-05	1.9	SW
WSW	500.	9.58E-04	6.36E-04	5.18E-04	3.32E-04	1.75E-04	8.03E-05	1.0	WSW
W	500.	6.17E-04	3.90E-04	3.10E-04	1.88E-04	9.18E-05	3.82E-05	0.9	W
WNW	500.	9.44E-04	5.50E-04	4.19E-04	2.33E-04	1.00E-04	3.59E-05	8.6	WNW
NW	500.	1.67E-03	9.34E-04	6.99E-04	3.72E-04	1.50E-04	4.96E-05	17.6	NW
NNW	500.	2.96E-03	1.62E-03	1.20E-03	6.27E-04	2.46E-04	7.82E-05	27.9	NNW
N	500.	3.04E-03	1.66E-03	1.23E-03	6.42E-04	2.51E-04	8.00E-05	28.8	N
NNE	500.	1.61E-03	9.81E-04	7.67E-04	4.49E-04	2.08E-04	8.13E-05	8.7	NNE
NE	500.	1.24E-03	8.36E-04	6.85E-04	4.45E-04	2.39E-04	1.12E-04	1.6	NE
ENE	500.	1.63E-03	1.12E-03	9.33E-04	6.23E-04	3.50E-04	1.72E-04	2.9	ENE
E	500.	1.99E-03	1.35E-03	1.11E-03	7.27E-04	3.96E-04	1.88E-04	5.8	E
ESE	500.	2.95E-03	1.81E-03	1.42E-03	8.33E-04	3.89E-04	1.53E-04	20.4	ESE
SE	500.	4.90E-03	2.36E-03	1.64E-03	7.43E-04	2.39E-04	5.94E-05	43.7	SE
SSE	500.	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.53E-06	0.0	SSE
MAX X/Q		4.90E-03				TOTAL HOURS AROUND SITE:		180.2	

RELATIVE CONCENTRATION (X/Q) VALUES <SEC/CUBICMETER) VERSUS AVERAGING TIME

DOWNWIND SECTOR	DISTANCE (METERS)	0-2 HOURS	0-8 HOURS	8-24 HOURS	1-4 DAYS	4-30 DAYS	ANNUAL AVERAGE	HOURS PER YEAR MAX 0-2 HR X/Q IS EXCEEDED IN SECTOR	DOWNWIND SECTOR
S	1500.	9.22E-06	5.88E-06	4.70E-06	2.89E-06	1.43E-06	6.09E-07	0.5	S
SSW	1500.	2.28E-04	1.18E-04	8.46E-05	4.14E-05	1.48E-05	4.21E-06	8.7	SSW
SW	1500.	2.55E-04	1.45E-04	1.10E-04	5.98E-05	2.50E-05	8.59E-06	1.9	SW
WSW	1500.	2.35E-04	1.39E-04	1.06E-04	5.99E-05	2.63E-05	9.60E-06	1.0	WSW
W	1500.	1.50E-04	8.38E-05	6.25E-05	3.31E-05	1.33E-05	4.36E-06	1.0	W
WNW	1500.	2.34E-04	1.20E-04	8.60E-05	4.16E-05	1.47E-05	4.10E-06	9.5	WNW
NW	1500.	4.27E-04	2.09E-04	1.46E-04	6.76E-05	2.23E-05	5.72E-06	19.0	NW
NNW	1500.	7.78E-04	3.73E-04	2.58E-04	1.16E-04	3.69E-05	9.09E-06	30.2	NNW
N	1500.	7.98E-04	3.82E-04	2.64E-04	1.19E-04	3.77E-05	9.25E-06	31.1	N
NNE	1500.	4.22E-04	2.26E-04	1.65E-04	8.36E-05	3.15E-05	9.55E-06	11.0	NNE
NE	1500.	3.24E-04	1.92E-04	1.47E-04	8.32E-05	3.66E-05	1.34E-05	2.8	NE
ENE	1500.	4.00E-04	2.44E-04	1.91E-04	1.12E-04	5.22E-05	2.05E-05	2.9	ENE
E	1500.	4.89E-04	2.93E-04	2.27E-04	1.31E-04	5.90E-05	2.23E-05	5.8	E
ESE	1500.	7.23E-04	3.93E-04	2.89E-04	1.49E-04	5.76E-05	1.80E-05	20.4	ESE
SE	1500.	1.20E-03	5.13E-04	3.35E-04	1.33E-04	3.53E-05	6.98E-06	43.7	SE
SSE	1500.	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.70E-07	0.0	SSE
MAX X/Q		1.20E-03				TOTAL HOURS AROUND SITE:		189.8	

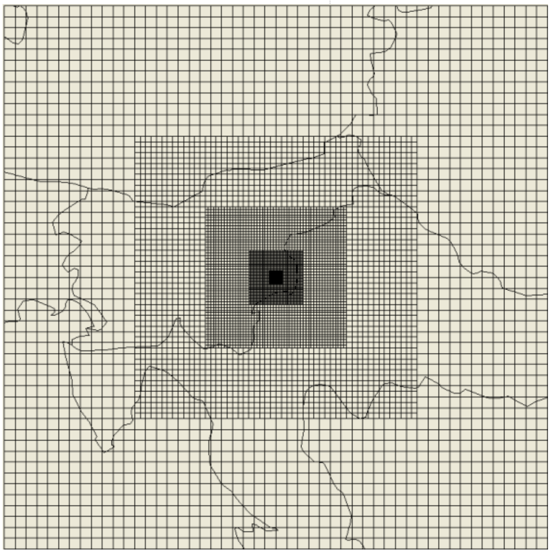

Figure 13: JRODOS grid used in calculation

In JRODOS case TEDE and thyroid dose (95th percentile spatial values) versus distance curves are calculated from 2D distribution of corresponding doses, figures 14 and 15. 2D distributions show for each calculation cell 95th percentile values obtained from calculations of the same release with the different release starting times. The different release times mean that different weather sequences will determine atmospheric dispersion of radioactive effluents. The 95% values are calculated using one weather sequence per day for 311 days in year 2020 (the same release is started at different times and corresponding weather conditions are responsible for atmospheric dispersion).

The results were obtained with JRODOS DIPCOT air dispersion module, which simulates the motion of air pollutants over complex terrain, based on a 3-D Lagrangian particle scheme. 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.

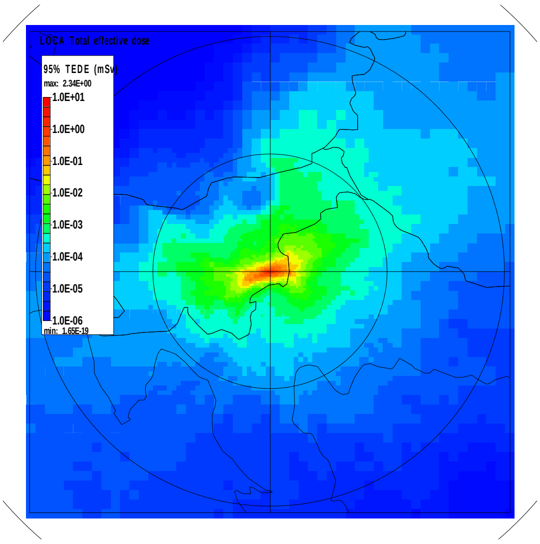

Figure 14: 95% LOCA TEDE values for distances up to 200 km, DIPCOT for year 2020

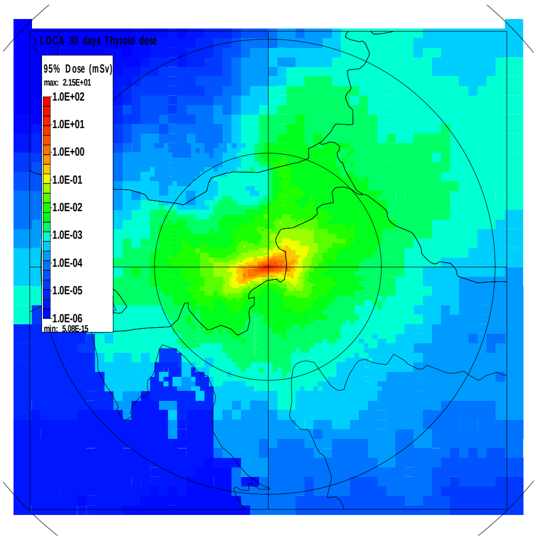

Figure 15: 95% LOCA thyroid doses for distances up to 200 km, DIPCOT for year 2020

Total effective 30-day dose and corresponding 30-day 95% thyroid doses are given in Figure 16 and Figure 17, respectively. Total doses decrease with distance, and different codes, regardless of the models used and the uncertainties of the boundary conditions, give similar values. In addition to the DIPCOT model, the JRODOS model LASAT was also used. LASAT includes weather pre-processor to process 2-D meteorological data, but it will use 3-D meteorological data when and if available. In JRODOS the same meteorological pre-processor prepares the data for both LASAT and DIPCOT. The difference is that DIPCOT uses JRODOS default layer heights (the ones directly available in the meteorological data prepared for JRODOS) and adjusts to the size of the JRODOS dispersion grid during the calculation. The LASAT JRODOS pre-processor adjusts the data for different layer heights and the calculation grid.

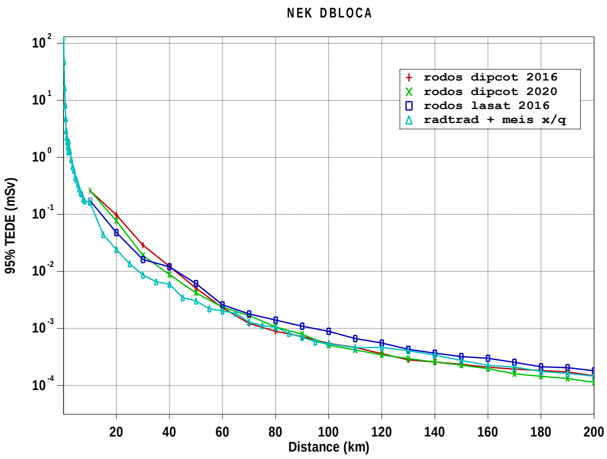

Figure 16: 95% TEDE calculated by different codes and models

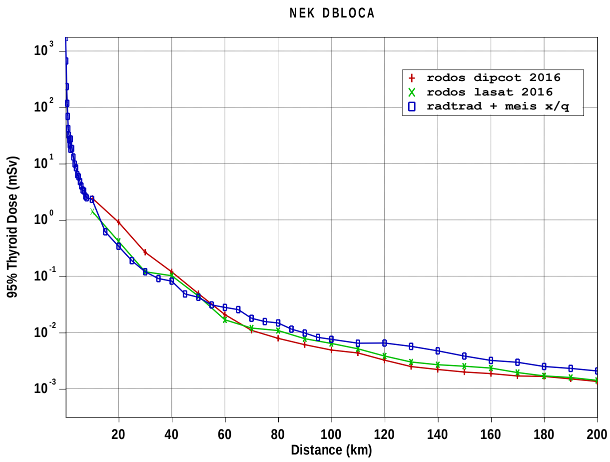

Figure 17: 95% thyroid dose calculated by different codes and models

The additional insight in environmental consequences of radioactivity release can be obtained using integrated isotopic activity concentrations (Bq-s/m^3) for selected isotopes, Cs-134 and I-131, shown in Figure 18 and Figure 19, respectively. The integrated concentrations are time integral values of concentrations without radioactivity decay. The person being outside during whole release is exposed to time dependent concentrations after effluent arrival to that location at the end of each calculation interval. The integral of the concentrations is related to the dose acquired at that location.

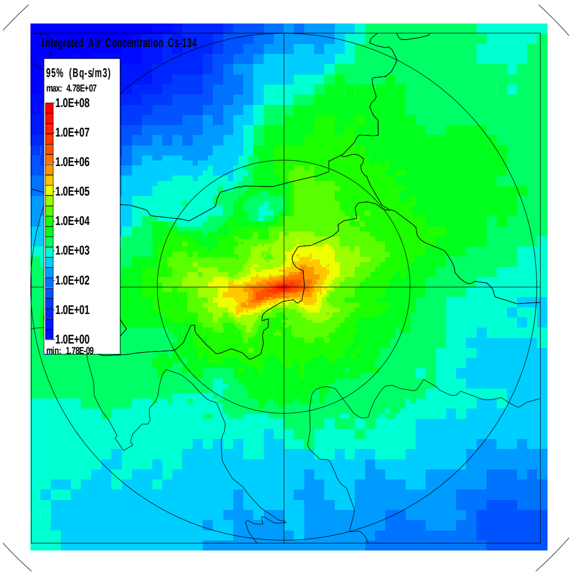

Figure 18: Integrated air concentration of Cs-134

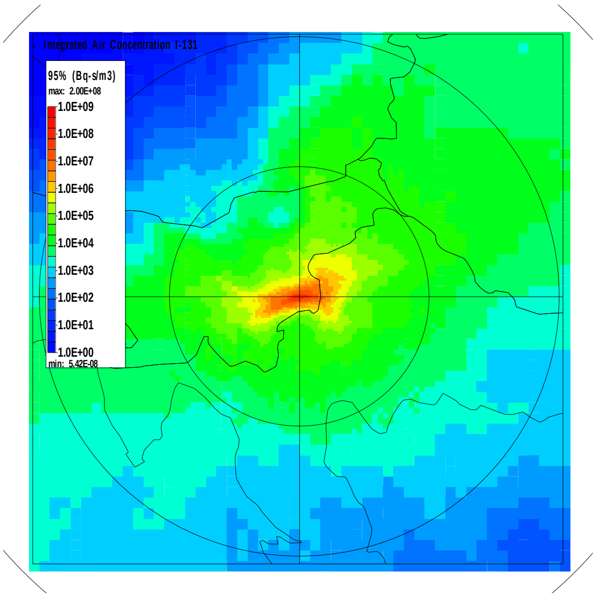

Figure 19: Integrated air concentration of I-131

5 CONCLUSION

A comprehensive analysis of radiological consequences with different numerical tools and models enables a realistic insight into the consequences of possible accidents in nuclear power plants. A methodology for calculating radiological consequences for licensing purposes (location, SAR, ER) is presented. Different approaches to atmospheric dispersion were adopted:

- RADTRAD code + externally supplied X/Q factors,
- JRODOS code for number of weather sequences,
- possible application within and outside of the low population zone.

Analyses indicate the necessity of using explicit time dependent isotopic source with statistically time interval averaged dispersion factors and explicit time dependent meteorology with averaged interval isotopic releases and doses postprocessing. Calculations confirm total doses decrease with distance, and that different codes, regardless of the models used, as long as they are representative of the weather conditions and terrain profile, and the uncertainties of the boundary conditions, give similar values.

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