AIR POLLUTION PREDICTION AND DOSES CALCULATION IN CASE OF NUCLEARY EMERGENCY AT KRŠKO NPP

Primož Mlakar[1], Marija Zlata Božnar[1] and Borut Breznik[2]

[1] MEIS d.o.o., Mali Vrh pri Šmarju 78, SI-1293 Šmarje - Sap, Slovenia
[2] Krško Nuclear Power Plant, Vrbina 12, SI-8270 Krško, Slovenia

Abstract: In the paper it is described how air pollution resulting from eventual emission of radioactive material from Krško NPP, Slovenia is elaborated using on-line automatic modelling system. Krško NPP lies in complex terrain in Slovenia very close to Croatia border. A dedicated SW is available for detail estimation of possible radioactive emission (source term). This part of the procedure is used by trained NPP operators and then automatically coupled with dilution coefficients to obtain radionuclide air pollution concentrations. As radioactive material causes dose also with distant cloud shine not only by direct touch or inhalation, special procedure is implemented for dose estimation. We will present in detail our algorithm for distant cloud shine estimation based on dilution coefficients calculation. The paper conclude with stressing the importance of correct air pollution prediction with best possible modelling techniques where achieving time and space accurate modelling is required for proper population protection.

Key words: *cloud gamma, dose, air pollution, prediction, dose calculation and estimation, nuclear emergency, radioactive emission, source term, radionuclide concentration, population protection, Lagrangian particle dispersion model*

INTRODUCTION

Fukushima nuclear accident has shown that air pollution prediction is an important task in the frame of reducing the impact of a nuclear emergency situation to the local inhabitants. Countermeasures such as temporary sheltering, iodine prophylaxis and evacuation should be based on accurate radioactive air pollution prediction to be effective for protection of population. Several ground level meteorological stations as well as high tower and SODAR measurements are available for diagnosis of meteorological situation in local area around the plant that would be firstly subject to the countermeasures in an early phase of the emergency situation. A dedicated SW (Breznik, B. et al., 2004, Božnar, M. Z. et al., 2012) is available for detail estimation of possible radioactive emission (source term). This part of the procedure is used by trained NPP operators and then automatically coupled with dilution coefficients to obtain radionuclide air pollution concentrations. This is done for almost 50 radionuclides that may be exhausted into the atmosphere. As radioactive material causes dose also with distant cloud shine not only by direct touch or inhalation, several complex procedures are implemented for dose estimation. We will present in detail our algorithm for distant cloud shine estimation as this is one of the most interesting tasks. Population doses estimation in 2D over map of the area is then used by NPP experts and Civil defence for inhabitant's protection.

THE HISTORY OF DISPERSION MODELLING FOR THE NEEDS OF THE KRŠKO NUCLEAR POWER PLANT (NPP) AND METEOROLOGICAL MEASUREMENT REQUIREMENTS

The authors of the study do not have exact information on when the 10- and 70-metre measurement towers in the direct vicinity of the Krško NPP were built and when the automatic measuring station (Stolp AMS) first came into use. However, in June 1977, the Hydro-meteorological Institute (now known as the Slovenian Environment Agency - SEA) began to collect data. The station was constructed at the Jožef Stefan Institute in Ljubljana (JSI) using analogue and digital CAMAC modules as used in nuclear medicine.

Requirements for the latest upgrade to the Stolp AMS in 1985

The development of science in the field of air pollution dispersion and transport in the 1970s also brought progress in the field of legislation, in which the main role was played by the United States Atomic Energy Commission, which issued "Regulatory Guides" (RG). The Krško NPP also had to follow these guidelines (the Krško NPP had been built by the US company Westinghouse). Two RGs were of particular importance for the upgrading of the Stolp AMS: RG 1.111 Methods for Estimating Atmospheric Transport and Dispersion of Gaseous Effluents in Routine Releases from Light-Water-Cooled Reactors (U.S. Nuclear Regulatory Commission, 1977) and RG 1.145 Atmospheric Dispersion Models for Potential Accident Consequence Assessments at the Nuclear Power Plant (U.S. Nuclear Regulatory Commission, 1982), which established the requirements in the field of the modelling of releases into the planetary boundary layer and the estimation of the transport and dispersion of radioactive substances through wind and atmospheric stability measurements.

In 1985, the Milan Vidmar Institute prepared "Project Designs" (Paradiž, B., 1985), which defined in detail the requirements for measurements at the Stolp AMS, additional measurements in Krško, Brežice, Cerklje and Libna, and a dispersion model according to RG 1.145. The "Project Designs" were also prepared in accordance with the “On-Site Meteorological Instrumentation Requirements to Characterize Diffusion from Point Sources” EPA guidelines (Strimaitis, D. et al , 1981).

The question arose of whether it was really necessary to measure so many parameters at so many altitudes and at different locations. The answer to this question is still very relevant. It is, however, very different from the answer from 25 years ago. Even 25 years ago, they knew that the surroundings of the Krško NPP are very complex (a plain surrounded by hills, temperature inversions, and weak winds). The “Project Designs” therefore included additional ground-based meteorological measurements. The problem was that the regulatory models (also in accordance with RG 1.145 (U.S. Nuclear Regulatory Commission, 1982)) used at the time could not use this data. Even worse, wind, temperature and humidity measurements at different altitudes and precipitation and global solar radiation measurements from the Stolp AMS could not be used with the chosen model. Only the wind speed and direction at 10m and the temperature difference between 70m and 10m could be used with the RG 1.145 model (U.S. Nuclear Regulatory Commission, 1982).

The development of the air pollution dispersion models showed that basic meteorological data (wind, temperature, global solar radiation) for different locations in a given space produce results of much higher quality than special stability measurements (temperature fluctuations or differences) from a single 70m tower.

The SNSA (Slovenian Nuclear Safety Administration), in cooperation with the SEA and the Krško NPP, was also aware of these issues. To resolve them, the Krško NPP environmental system was upgraded with a SODAR system around 15 years ago, and a Lagrangian particle model with a 3D meteorological preprocessor for the assessment of the dispersion of radioactive substances which has been running since 2002.

THE “DOZE” SOFTWARE PACKAGE FOR RAPID RADIATION DOSE PREDICTION IN THE EVENT OF RELEASES INTO THE ENVIRONMENT

The “DOZE” software package was developed in the 1990s for the rapid radiation dose prediction in the event of accidental releases into the environment (Breznik, B. et al., 2004, Božnar, M. Z. et al., 2012). The software package is regularly updated. The “DOZE” software package includes different procedures which can be used to relatively accurately determine reactor damage, release activities, the route of the release, reduction of activity released into the atmosphere using different procedures, dispersion and estimated population doses. The software package is linked to the environmental information system of the Krško NPP, which collects measurement data on the operation of the Krško NPP and the conditions in the area through meteorological stations and external radiation monitors.

The “DOZE” software package calculates the activities of all the main isotopes produced in the reactor in real time. The current activities of the isotopes in the reactor are determined by the software on the basis of time-series measurements of the electrical output of the power plant, the mass of the uranium and the average burnout. The software also determines the time of shutdown and start-up and records the data in a special database. In the event of an emergency, the software determines activities in the containment atmosphere. Multiple parallel procedures are run to determine the potential shares of the total amount of activity which can be released from the core in the containment. The quickest procedure is run on the basis of radiation measurements and thermocouple indications in the containment. The software package enables the selection of different routes of the release and the associated procedures for reduction of released activities. The effectiveness of the reduction depends on the individual isotopes. Finally, the software produces an inventory of the isotopes which are to be released.

To determine the radiation doses to the local population, the software also requires a prediction of the dispersion during the discharge. This is done using two-dimensional relative concentration fields (X/Q), which were calculated using the RG 1.145 model before 2002, but are now calculated using a Lagrangian particle model - LPM (Tinarelli, G. et al., 2000, Desiato, F. et al., 1998). Both models are of a diagnostic nature, meaning that they predict dispersion using current meteorological measurements. Because the LPM requires complex calculations, the calculations are performed automatically in the background of the software package. The results of the LPM relative concentrations (X/Q) delay meteorological measurements by a maximum of 15 minutes.

The software package determines the radiation dose to the local population on the basis of each nuclide which is to be released, relative concentrations (X/Q) and the dose conversion coefficient. The relative concentration (X/Q) method is suitable to determine the internal dose and the thyroid dose, which results from isotope inhalation, but the method is not suitable to determine the external gamma radiation dose. The dose conversion coefficients are defined for a homogeneous half of a spherical cloud irradiating the body under observation. This is in no way realistic, but RG 1.145 does not provide a better method for estimating the dose to the entire body if the bulk of the cloud is moving over the body under observation.

A SIMPLE CLOUD DOSE CALCULATION ALGORITHM USING RELATIVE CONCENTRATION

RG 1.145 uses a simplified formula which uses homogeneous radionuclide concentrations for half of a spherical cloud. We implemented an algorithm for the existing Lagrangian model which uses the actual activity values of individual atmospheric cells for all vertical layers. The software thus calculates the dose at ground level if the radioactive cloud is anywhere above the area under observation. The algorithm is integrated into the software package, which stores the results of the model in a special internal database for the DOZE program. The calculation is carried out whenever new model calculations are available. The calculation has been numerically optimized.

At the "HARMO13 – 1–4 June 2010, Paris, France – 13th Conference on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes," authors *Peter Bedwell*[1], *Joseph Wellings*[1], *Stephanie M. Haywood*[1] *and Matthew C. Hort*[2] *from the* [1]Health Protection Agency (HPA), Chilton, UK, and the [2]Met Office (MO), Exeter, UK, presented an article entitled: "CLOUD GAMMA MODELLING IN THE UK MET OFFICE'S NAME III MODEL" (Bedwell, P. et al., 2010). The article describes how they upgraded a Lagrangian particle model with a dose estimation routine based on the calculation of the contribution of individual particles throughout a given space during a given period.

This method requires modifications to the Lagrangian model itself, as the dose must be calculated at every step when new particle positions are determined (every 10s at the Krško NPP). The Lagrangian model Spray used by the Krško NPP cannot be easily upgraded in this manner. It is only possible to use its results, which are given as half-hourly average activity density values (Bq/m³) for individual cells in a three-dimensional space measuring 25km × 25km × 3km.

The 25km × 25km × 3km model domain at the Krško NPP is divided into 100 × 100 horizontal cells and 20 vertical cells. Each cell measures 250m × 250m, while the height depends on the location of the cell. A ground-level cell is 10m high, the cell above it is 12m high and the third cell is already 19m high. The highest cells are 385m high. The accuracy of the data closer to the ground, e.g. the first 500m, is more important for the model, whereas the layer between 2,500 and 3,000m is not as important. Instead of a Cartesian coordinate system, models therefore usually use a terrain-following sigma coordinate system as presented on Figure 1 (Tinarelli, G. et al., 2000).

As described above, each cell has a certain activity density. Until now, the dose at ground level has been calculated using the dose conversion factor multiplied by the activity density. The dose conversion factor is defined for half of a spherical cloud:

$$D_i = dcf \cdot ActivityDensity_i \tag{1}$$

where "D_i" is the dose rate in the "i" cell, "dcf" is the dose conversion factor, and "$ActivityDensity_i$" is the activity density in the "i" cell calculated with the model. We propose modifying the formula as follows:

$$D_i = K \cdot dcf \cdot (ActivityDensity_i + \sum_{x,y,z} k \cdot \frac{ActivityDensity_{x,y,z}}{r^2}) \tag{2}$$

where "D_i" is the dose rate in the "i" cell, "K" is the compensation factor, "dcf" is the dose conversion factor, "$ActivityDensity_i$" is the activity density in the "i" cell, $\Sigma_{x,y,z}$ is the sum of all cells, "$ActivityDensity_{x,y,z}$" is the activity density in the cell with the coordinates x, y and z, r^2 is the square of the average distance between the "i" cell and cell (x,y,z), and k is the unit coefficient required to maintain the physical units. The compensation factor K can be determined when the activity density is uniform throughout the domain and according to formulas (1) and (2) the dose rates are thus equal:

$$K = \frac{1}{(1 + \sum_{x,y,z} (\frac{k}{r^2}))} \tag{3}$$

In formula (2), the activity density can be replaced with the product of the relative concentration (X/Q) and the emission (Q):

$$D_i = K \cdot dcf \cdot (X/Q_i \cdot Q + \sum_{x,y,z} (k \cdot X/Q_{x,y,z} \cdot \frac{Q}{r^2})) \tag{4}$$

The same can be done with formula (1). If we compare the modified formula (1) with the formula (4), we get a new “relative cloud concentration” (C/Q_i in the “*i*” cell at ground level:

$$C/Q_i = K \cdot (X/Q_i + \sum_{x,y,z} (k \cdot \frac{X/Q_{x,y,z}}{r^2})) \tag{5}$$

This was our intention. Using the relative concentration across the entire space, we have obtained the weighted relative cloud concentration (*C/Q*), which is used to estimate the cloud dose in a given cell.

In comparison with the method described in the article (Bedwell, P. et al., 2010), our method is less accurate because:
– instead of integrating partial contributions, we simply added together entire cells,
– we assumed that the average distance in the “i” cell is 1 m,
– we assumed that the cells were homogeneous,
– we did not take into account that if we are located at the edge of a cell, adjacent cells have a greater influence.

The accuracy also depends on our location in the cloud. If we are located in the centre of the cloud, the method is more accurate than at the edge. Regardless of the simplifications, the method is very time consuming if we wish to integrate it across the domain. We therefore tested different radii around the cell under observation and obtained results presented in Table 1.

Table 1. Results of testing different radii around the cell under observation

no. of points	radius	1/K	value of K
12	3,000m	1.006656E+00	0.993
30	7,500m	1.008266E+00	0.992
50	12,500m	1.009143E+00	0.991
51	12,750m	1.009195E+00	0.991
100	entire	1.009195E+00	0.991

The differences in the values of K are very small. We chose a radius of 7,500m, or 30 points, around the point under observation, as even with this radius, the calculation for all points requires around 15 seconds using an Intel i7 processor.

ESTIMATION OF THE DIFFERENCE BETWEEN THE RELATIVE CONCENTRATION (X/Q) AND THE “RELATIVE CLOUD CONCENTRATION” (C/Q)

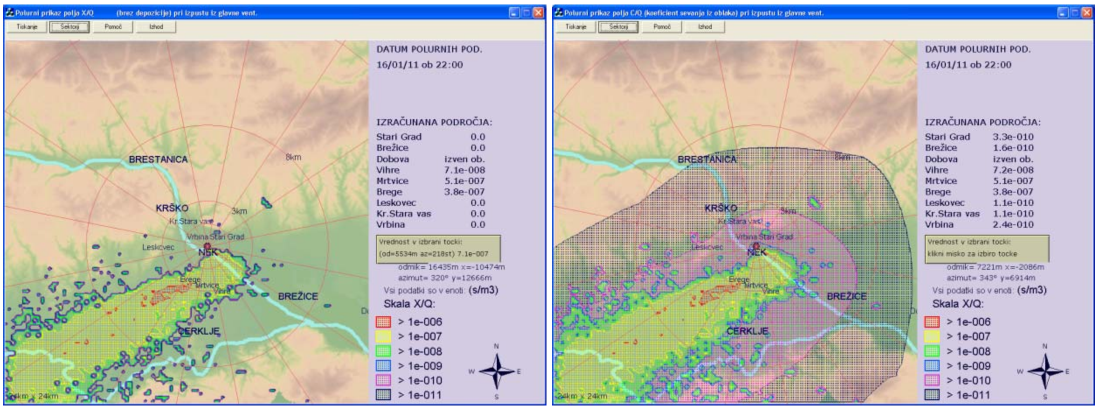

Figure 1. A comparison for a release from the main ventilation. In the example X/Q is shown on the left and C/Q on the right. The greatest difference is at the edges of the cloud, where most of the cloud is at a higher altitude.

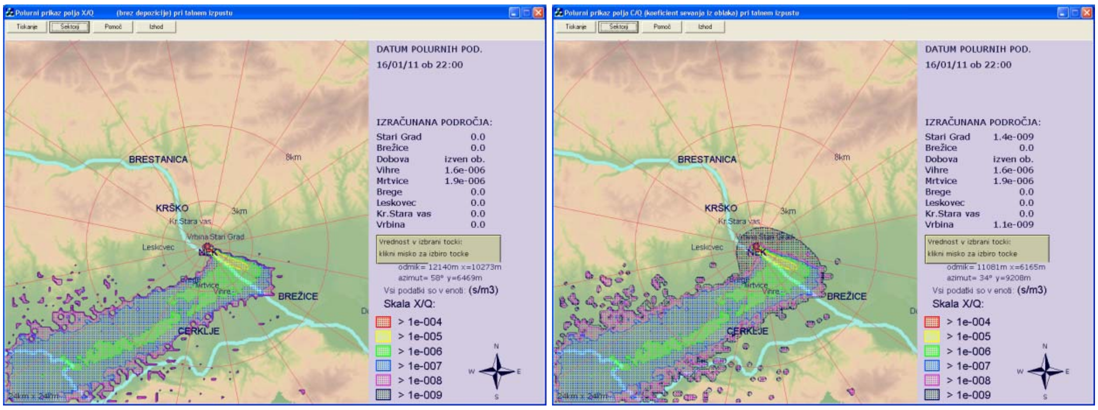

Figure 2. A comparison for a ground-level release. X/Q is shown on the left and C/Q on the right. The greatest difference is on the windward side, where X/Q = 0. There is no difference at the edges, because the cloud stays close to the ground.

The difference between the "regular" relative concentration (X/Q) and the relative cloud concentration (C/Q) is the greatest if the release is at a high altitude and the cloud does not reach the ground at all. Conversely, if the cloud is near the ground (ground-level release), the difference is minimal. This fact is also confirmed by the figures 1 and 2.

CONCLUSIONS

It is very important that correct air pollution predictions with best possible modelling techniques are available for proper population protection.

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REFERENCES

Bedwell, P., J. Wellings, S. M. Haywood and M. C. Hort, 2010: Cloud gamma modelling in the UK Met Office's NAME III model. Harmo13 : proceedings of the *13th International Conference on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes*, 1-4 June 2010, Paris, France.

Božnar, M. Z., P. Mlakar and B. Breznik, 2012: Dose projection in case of a nuclear emergency. V: ŽAGAR, Tomaž (ur.), FÜRST, Samo (ur.). 21st International Conference Nuclear Energy for New Europe, Ljubljana 2012, September 5-7. Proceedings. Ljubljana: Nuclear Society of Slovenia, 2012, 7 pages.

Breznik, B., M. Z. Božnar, P. Mlakar and G. Tinarelli, 2004: Dose projection using dispersion models. *International Journal of Environment and Pollution*, vol. **20**, pp. 278-285.

Desiato, F., S. Finardi, G. Brusasca and M.G. Morselli, 1998: TRANSALP 1989 Experimental Campaign - Part I: Simulation of 3-D Flow with Diagnostic Wind Field Models. At*mospheric Environment*, Vol. **32**, 7, pp.1141-1156.

Paradiž, B., 1985: Projektne zasnove (in Slovene). Elektroinstitut Milan Vidmar, Februar 1985.

Strimaitis, D., G. F. Hoffnagle and A. Bass, 1981: On-site Meteorological Instrumentation Requirements to Characterize Diffusion from Point Sources: Workshop Report. EPA-600/9-81-020, April 1981. National Technical Information Service, Office of research and development, U. S. Environmental Protection Agency, Environmental Research & Technology, Inc, 112 pages.

Tinarelli, G., D. Anfossi, M. Bider, E. Ferrero and S. T. Castelli, 2000: A New High Performance Version of the Lagrangian Particle Dispersion Model SPRAY, Some Case Studies. *NATO challenges of modern society* Vol. **23A**, 499-508.

U.S. Nuclear Regulatory Commission, 1977: Methods for Estimating Atmospheric Transport and Dispersion of Gaseous Effluents in Routine Releases from Light-Water-Cooled Reactors: Regulatory Guide (RG) 1.111, Revision 1, July 1977.

U.S. Nuclear Regulatory Commission, 1982: Atmospheric Dispersion Models for Potential Accident Consequence Assessments at Nuclear Power Plants: Regulatory Guide (RG) 1.145, Revision 1, November 1982.