Uncertainties in Modelling Atmospheric Dispersion of Radioactive Contaminants

PhD Thesis booklet

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2024

INTRODUCTION

In order to assess the safety of nuclear facilities which is a critical issue since the emergence of the peaceful use of nuclear power, the impact of the radioactive releases to the environment has to be evaluated with the primary aim of minimizing the population dose as reasonably achievable. From the different types of nuclear facilities, nuclear power plants pose the greatest risk in terms of the scale of potential radioactive releases. The transport of radioactive material through the atmosphere, surface and ground waters and food chain can be modelled, from which the radiation exposure conditions in the environment and the population doses can be estimated. Atmospheric dispersion models have been widely used to analyze the consequences of radioactive release providing information about processes and quantities that are not possible or only very imprecisely to measure in case of an emergency, and enabling analysis of hypothetical scenarios used for assessing the safety of an installation. In a model, which is a generalized description of a phenomenon, due to the omissions of mechanisms that are less relevant, there are different types of uncertainties, which can affect the accuracy of the modelled quantities. My work focuses on the epistemic uncertainties including model uncertainty (arising from simplifications, numerical approximations or incomplete treatment of the modelled phenomena) and parameter uncertainty (resulting from the uncertainties of the model parameters and input data). These types of uncertainties are present in atmospheric dispersion model calculations and can significantly influence the modelled dispersion, the calculated radioactivity concentrations and the resulting doses. Quantifying these uncertainties is particularly important considering that modelling the atmospheric dispersion modelling of radioactive material is performed to assess off-site consequences of releases with various goals in the field of nuclear safety and radiation protection, including safety analysis calculations such as deterministic and probabilistic safety analyses, and emergency preparedness and response calculations.

Safety analysis calculations are conducted to verify that the spread of radioactivity and the resulting exposure consequences for all reasonably possible occurrences remains below a pre-defined regulatory limit (e.g. dose or risk criterion) to ensure that the facility is safe in case of a wide range of events. These assessments need to be transparent and well documented to enable comparison and independent evaluation of the safety of different installations. There are different approaches and models utilized in deterministic safety assessments of releases from a nuclear facility around the world, as there are no harmonized requirements for the specific details of application of the concept. Even though there are international guidance and various national regulations aimed at avoiding accidents that could lead to large or early radioactive environmental release, e.g. the Council Directive 2014/87/Euratom, these do not oblige the countries to adopt identical methodologies. To support this harmonization effort, a simplified and easy-to-use computational methodology has been developed in the last decade in the Centre for Energy Research so that compliance with atmospheric release criteria for nuclear facilities can be confirmed. I joined this work and participated in the implementation of these methods into the CARC (Calculating Atmospheric Release Criteria) software. In order to be able to conduct assessments with the software, the validation of the models and the verification of their applicability was also needed.

Atmospheric dispersion modeling for deterministic safety assessments is usually carried out for single scenarios which are characterized by conservative input parameters (e.g. release characteristics, meteorological conditions, exposure duration and habits of the population. To ensure conservativism in the calculations using meteorological input parameters that describe the worst case scenario is complicated, because the worst meteorological characteristics differ depending on the distances and endpoints being considered. Another approach is to perform calculations with an extended, years-long meteorological database and select a percentile of the results (e.g. the upper limit of the 99.5%-or 95% of the cases). As the meteorological data used in the atmospheric dispersion model can highly influence the activity concentrations and thus the doses, the usage of different meteorological data and different percentiles has to be investigated to evaluate the level of variation of the chosen endpoint to ensure that the final result of the safety assessments is robust and not depend significantly on the variation of the weather conditions.

Atmospheric dispersion models are also used for emergency preparedness and response in decision support systems providing estimations in the event of a real or a hypothetical accident based on which recommendations can be made regarding countermeasures aiming to reduce the received dose to ensure the protection of the public. Given that the decisions are based on these estimations, the computed results (i.e. environmental contamination and resulting effect on the population) need to be reliable and robust. Thus it is crucial to evaluate the level of influence of the model and parameter uncertainties in the atmospheric dispersion model of decision support systems.

Such a decision support tool, the SINAC (Simulator Software for Interactive Modelling of Environmental Consequences of Nuclear Accidents) has been used in the Hungarian Atomic Energy Authority's Centre for Emergency Response, Training and Analysis. The SINAC has been developed by researchers working at the Centre for Energy Research in the last decades. The dose estimation calculations made for emergency preparedness and response need to be as precise as possible with limited time available for the simulations. To optimize the atmospheric dispersion calculations of the SINAC, various new methods have been implemented to compute the propagation of the radioactive material released to the atmosphere from a nuclear power plant. These need to be investigated and the optimal approach needs to be identified as the various methods and parametrizations can highly affect the dose results and the time of the simulations.

In addition to the various models, the uncertainty of meteorological data required in decision support systems can also influence results of the calculations. Usually the source of the meteorological data is a numerical weather prediction model (providing data for a large spatial domain and with appropriate temporal resolution) due to the limited availability of real meteorological measurements and observation. The most common approach to assessing the effect of meteorological uncertainties is sensitivity analysis perturbing the meteorological parameters one by one and evaluating their influence separately. A different and relatively new method is to use ensemble meteorological data (produced by running the numerical weather prediction model several times with slightly different initial conditions or parametrizations) which is advantageous because the ensembles inherently incorporate the meteorological uncertainties with their influence directly appearing in the results of the atmospheric dispersion calculations. In an international project from 2017 to 2020 with the goal of identifying and reducing uncertainties in nuclear emergencies titled CONFIDENCE (COping with uNcertainties For Improved modelling and DEcision making in Nuclear emergenCiEs), the influence of the input uncertainties of atmospheric dispersion and dose calculation models was investigated with the usage of ensembles. As part of the project, a new module was integrated into the SINAC software to consider meteorological ensembles used in the CONFIDENCE project in addition to the ensemble data that is produced by the Hungarian Meteorological Service. It is important to acknowledge that there is a disadvantage associated with using such meteorological data as well, namely the increased computational burden of running the simulations multiple times which is not optimal in an emergency situation. In order to be able to apply the ensemble method in operation, the calculations need to be optimized. There are different ways of optimizing the simulation e.g. reducing the number of ensembles or reducing the run time of a single ensemble member. These approaches need to be investigated, the most suitable ones should be identified and introduced in practice.

OBJECTIVES

My work focused on the assessment of model and parameter uncertainties that are present in atmospheric dispersion and dose calculations conducted for deterministic safety assessments and nuclear emergency preparedness and response.

The new methodology and the related CARC software for confirming compliance with atmospheric release criteria for nuclear facilities has been developed in the last decade, but the validation of the used models and the verification of the applicability was required. The aim of my assessment was to perform the validation of the methodology by comparing the internal results of the models with the corresponding values computed with widely used commercially available programs, as well as to show the applicability of the methodology through a case study, comparing the results of the calculations with actual regulatory requirements. In addition, regarding the atmospheric dispersion model of the CARC software, my objective was to assess how the variation in the meteorological data affect the results of deterministic safety analysis, and how the different percentiles of the results respond to the variations. For the dose calculations, I wanted to identify which parameters characterizing the habits of the population have the largest influence on the computed final results, the effective doses.

Atmospheric dispersion calculations are also used in decision support systems such as SINAC, to simulate the atmospheric dispersion of contaminants and provide recommendation about protective measures to be introduced in case of an accident. Regarding the model uncertainties, I aimed to evaluate the new methods implemented in the SINAC software to compute the propagation of the radioactive material in the atmosphere. My goal was to identify which method produces the most precise result but with the additional consideration of limited computation time to optimize this type of simulation. In case of the parameter uncertainties, my objective was to evaluate the influence of each meteorological parameter (wind speed, wind direction, atmospheric stability, precipitation) separately through a sensitivity study and determine which has the largest influence on the air activity concentration calculated by the atmospheric dispersion model of SINAC. Furthermore, I aimed to verify the applicability of the ensemble method of the software through a case study with the consideration meteorological data provided for the Paks Nuclear Power Plant. As part of the CONFIDENCE project, I evaluated the uncertainties of the atmospheric dispersion model of SINAC software by using ensemble input data in the Radiological Ensemble Modelling case studies. To optimize the ensemble simulations in order to enable operational usage, I aimed to investigate various methods for reducing the run time for single ensembles (decreasing the modelling area, reducing the time resolution of the emission and the computation of the endpoints), to quantify the time reduction and the change in the computed results and their uncertainty.

NEW SCIENTIFIC RESULTS

1. Thesis Statement:

I improved analytical models with regard to the transparency and simplicity of the calculation process and integrated them into the CARC (Calculations for Release Criteria) software for verifying compliance with release criteria for nuclear facilities. I showed that the internal results of calculations obtained with the improved models show differences between 50%-150%, and agree adequately according to such comparisons with the results obtained with other conventional programs used in international practice

- in the environmental activity concentrations there were more significant differences of up to 60-90% in some cases,
- the difference in the external and inhalation dose was less than 13%,
- the difference in the ingestion dose was maximum 26% for the nuclides that typically contribute to the public dose.

I pointed out that most of the differences are caused by the discrepancies between the individual methods of the compared models and model parameters used. I showed that the value of the effective dose determined for deterministic safety analyzes is significantly influenced by some parameters that describe the habits of the population (i.e. breathing rate, time spent outdoors, shielding and food consumption). Of these, changing the breathing rate (between 0.7 m^3/h and 3 m^3/h), the degree of shielding (between 0.01 and 0.4) and the time spent outdoors (between 1 h and 6 h) do not significantly affect the 1-year effective dose (causing a maximum of 24% difference). The consumption of certain contaminated foodstuffs (i.e. leafy vegetables and milk) increased the 1-year effective dose considerably: the difference compared to no consumption ranged between 124%-251% depending on the used meteorological data. I verified the practical applicability of the models and the CARC program through a case study confirming the verification of compliance with a criteria applied in nuclear deterministic safety analyses for a hypothetical release scenario. [P1][P2]

2. Thesis Statement:

I showed that during deterministic safety analyses, the use of an at least 5-years-long database based on real meteorological measurements and a well-chosen dose percentile gives a more robust result than using fixed meteorological parameters associated with the estimate worst case used in general practice. Using a real annual meteorological dataset, I verified that in the case of random omission of points from the meteorological database, the difference of the 95^{th} percentile of the 7-day dose the 95th percentile compared to the result determined with the full dataset is adequate, less than 5%. I confirmed the adequacy of the method and the advantage of using a well-chosen percentile by finding that, compared to the estimated worst case appointed based on expert judgement (not considering site specific real measurement data), the largest deviation between the maximum doses determined for different years can be nearly 5000% depending on the percentile, while for the 95^{th} percentile of using real meteorological data a maximum of 50% was obtained. [P3]

3. Thesis Statement:

I proved that from the various puff propagating models available in the atmospheric dispersion model of the SINAC (Simulator Software for Interactive Modeling of Environmental Consequences of Nuclear Accidents) emergency response decision support system, the closest to the result regarded to be precise but generated with the longest runtime obtained with the method using the smallest fixed time step was given by the quicker autoscaling procedure that considers the increment of the σ_z vertical dispersion parameter (using a step multiplication factor of M_0 =1.001 and 1.004). Obtaining a difference of less than 1% for the specific release scenario, at 1 km, 3 km and 30 km distance and considering fix meteorological parameters (1 m/s wind speed, D Pasquill stability class and 0 mm/h rain intensity). I showed that in the case of emergency preparedness calculations, in order to minimize the running time, it is optimal to use the model in which the step of the puff depends on the value of the σ_r horizontal dispersion parameter. I proved that in this case by choosing the right parameter (e.g. step multiplication factor m_0=0.5), the running time is significantly shorter (a half or a quarter) compared to other methods, while the time-integrated activity concentration for the plume passage differs by only 3-5% compared to the case that is considered precise. [P4]

4. Thesis Statement:

I pointed out that the uncertainty of meteorological data can have significant effect on the results of atmospheric dispersion calculation model used for emergency preparedness, I identified the parameters that dominantly influence the calculation of environmental activity concentrations and I quantified the extent of their influence. I proved that a change in the wind speed from 1 m/s to 10 m/s close to the emission point (1-5 km) and in the wind direction from 0° to 10° further away (5-30 km) can cause a difference of 3 orders of magnitude in the activity concentration. I developed a new module for the SINAC emergency preparedness decision support system, with which, using ensemble meteorological data, the uncertainty of the atmospheric dispersion calculation derived from meteorological data can be directly determined and displayed without a labor-intensive sensitivity or uncertainty assessment. I verified the applicability of the ensemble method of the SINAC program with calculations carried out in the framework of an international project. [P5][P6][P7][P8][P9][P10]

5. Thesis Statement:

With the series of calculations performed with the SINAC decision support system, I identified the possibilities of optimizing the run time which is critical from the point of view of emergency decision-making. I showed that reducing the original modelling area to 4/9 and 1/9 and reducing the time resolution of the results to two and four times, while keeping the values of the examined results unchanged, reduced the running time for the simulation of 10 ensemble members from 76 min to 28 min, 9 min, 59 min and 57 min, respectively. I proved that reducing the time step of the release, i.e. the number of puffs emitted in a given time, by a quarter (from 64 to 16 then to 4) while beneficially reduced the run time of the 10 ensemble calculation (from 179 min to 76 min then to 47 min), caused a variation of 25% in the expected value of Cs-137 deposition, one of the most important results in terms of radiation protection and increased its standard deviation by more than six times. [P11][P12]

LIST OF PUBLICATIONS

Publications related to the thesis statements

[P1] **Cs. Rudas**, T. Pázmándi, P. Zagyvai, "Evaluation of an Improved Method and Software Tool for Confirming Compliance with Release Criteria for Nuclear Facilities", *Annals of Nuclear Energy*, Vol. 159, 2021, https://doi.org/10.1016/j.anucene.2021.108332

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[P3] **Cs. Rudas**, T. Pázmándi, "Consequences of Selecting Different Subsets of Meteorological Data to Utilize in Deterministic Safety Analysis", *Journal of Environmental Radioactivity*, Vol. 225, 2020, https://doi.org/10.1016/j.jenvrad.2020.106428

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[P11] P. Bedwell, I. Korsakissok, S. Leadbetter, R. Périllat, **Cs. Rudas**, J. Tomas and J. Wellings, "Operationalising an ensemble approach in the description of uncertainty in atmospheric dispersion modelling and an emergency response", *Radioprotection*, Vol. 55, pp. S75 – S79, 2020. https://doi.org/10.1051/radiopro/2020015

[P12] **Cs. Rudas**, P. Szántó, T. Pázmándi, P. Zagyvai, "Efficiency savings in model setup for an ensemble approach used to describe atmospheric dispersion model uncertainty", *CONFIDENCE Dissemination workshop*, Bratislava, Slovak Republic, 5-9 December 2019. https://eu-neris.net/library/archives/concert/confidence/confidence-dissemination-workshop-2-5-december-2019/posters.html

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