



A novel method to improve dose assessment due to severe NPP accidents based on field measurements and particle swarm optimization



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ABSTRACT

Severe nuclear power plant (NPP) accidents are those which involve significant core degradation and lead the plant to conditions more severe than a design basis accident. Under such conditions the accident progression might become unpredictable and the source term estimation, imprecise by orders of magnitude. The consequence is a dose assessment very far from the reality and a deficient decision making support. This work presents a novel approach to improve accuracy of dose estimation, based on field measurements and particle swarm optimization (PSO) algorithm. The main idea is to determine a correction matrix, which once applied to the originally estimated (incorrect) dose distribution map, generates a corrected one, which better fits to the field measurements. The proposed correction matrix is the result of a concatenation of geometric transformations and an amplification/attenuation factor, aimed to fit the shape of the original map and radiation intensities in order to match the field measurements. Finding the optimum transformations (correction matrix) is, however a complex nonlinear optimization problem, which has been successfully solved by using a PSO algorithm. Results demonstrate that PSO was able to find good correction transformations, which can be used to better project future dose distributions and, consequently, improve decision making support.

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1. Introduction

According to the International Atomic Energy Agency (IAEA) classification, the “beyond design basis accidents” are those which comprises conditions more severe than a “design basis accident”, and may or may not involve core degradation (IAEA, 2007). When the “beyond design basis accident” involves significant core degradation, it is classified as a “severe accident” (SA).

Due to the very nature of SA, the source term (release material and its characteristics) estimation under such circumstances becomes a very difficult task. The nuclear power plant (NPP) is beyond design conditions; instrumentation might be affected becoming unreliable; quick and unexpected changes in the plant statuses may occur, making the accident progression unpredictable (McKenna and Giitter, 1988). Therefore, great imprecision is expected in source term estimation and instrumentation readings, leading to a poor dose assessment. The projection of doses received by the people in the area affected by the atmospheric dispersion of

the radioactive material will be, probably, very far from reflecting the reality and decision making would be compromised.

In order to improve accuracy of dose predictions, several approaches that use field measurements to better estimate (or correct) the source term have been investigated. Some of them are very simple, such as considering a linear correlation between field measurements and the source term (Athey et al., 2013). In this case a proportionality factor is applied. The problem of this method is that, in real situations, the correlation is often very non-linear.

Others more complex and time consuming approaches propose solving the inverse problem aimed to characterize the actual source term based on field measurements. Most of them are applied to air pollution models in general (Chow et al., 2008; Zheng and Chen, 2010).

Chow et al. (2008) proposed to solve an inverse problem to estimate plume dispersion in urban environments using downwind concentration measurements and Building-Resolving Simulations. The method is very time consuming and needs hours to be executed in a computer cluster.

Zheng and Chen (2010) proposed a method also based on downwind measurements. They formulate an optimization problem to be solved by a pattern search method in order to predict strength

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and location of hazardous materials releases. The computations indicate that this method can achieve optimal solutions in a relatively shorter time.

Due to the complexity of a nuclear source term estimation (great number of radionuclide and release characteristics), these kind of approaches have been used in post-accident phase and, generally, in continental scale, which allows greater time window for calculations (Delle Monache et al., 2008). Delle Monache et al. (2008) talked about many hours in a computer cluster to run the proposed inverse problem. As example, some recent works have been motivated by the Fukushima Daiichi Nuclear Power Plant accident (Chino et al., 2011; Katata et al., 2015).

This work presents a novel approach, which is not aimed to estimate a more realistic source term. Instead, it proposes to make corrections directly on the Atmospheric Dispersion System (ADS) output – the dose distribution map – which is the basis for decision making under severe situations with nuclear material releases. Doing this, it is possible to overcome many possible uncertainties, not only due to the source term estimation, but also due to any process or physical model comprised by the ADS.

To accomplish that, a non-linear transformation matrix should be obtained, which applied to the original (incorrect) predicted dose distribution generates a corrected one (optimally fitted to the field measurements). The proposed correction matrix is the result of a concatenation of geometric transformations and an amplification/attenuation factor, aimed to fit the shape of the original map and radiation intensities in order to match the field measurements. Finding the optimum transformations (correction matrix) is, however a complex and nonlinear optimization problem, which has been successfully carried out using particle swarm optimization (PSO) algorithm (Kennedy and Eberhart, 1995), a powerful global scope optimization technique.

Obtained results demonstrate that the PSO algorithm was able to find optimized transformations (correction matrixes), which could be used to better fit the estimated dose distribution map to the field measurements. The use of the correction matrix was also able to improve future projections of spatial dose distribution, enhancing considerably the decision making support.

The remaining of this paper is subdivide as follow. Section 2 gives an overview on atmospheric dispersion of radionuclide and dose distribution calculation. Section 3 presents the proposed method. tion 4 describes method application and results, and finally, concluding remarks are provided in Section 5.

2. Prediction of atmospheric dispersion of radionuclide

The source term, the atmospheric dispersion of radionuclide and doses are estimated by means of dedicated NPP systems, here referred to as Atmospheric Dispersion Systems (ADS), comprised by computer implementations of physical models, which considers specific NPP information.

In this work, simulations have been done by the ADS used in Central Nuclear Almirante Álvaro Alberto (CNAAN) NPP, a Brazilian NPP sited in Angra dos Reis, Rio de Janeiro. The ADS (SCA-MOD, 1987) is basically comprised by 4 modules: i) Source Term prediction module; ii) Wind Field module; iii) Plume Dispersion (including dose calculations) and iv) Plume Projection (also including dose calculations) module. Fig. 1 shows a simplified schematic diagram of such ADS.

The Source Term module estimates the amount and rate of nuclear material released (source term). The Wind Field module uses topographical and meteorological information to produce a divergent-free wind field. Then, the Plume Dispersion module uses the outputs of Source Term and Wind Field modules to simulate the plume dispersion and calculate doses and doses rates. The

Plume Projection module makes projections of the plume dispersion in future time steps.

3. Proposed approach

As already mentioned, predictions made under severe NPP accidents are highly imprecise, that means: the magnitude and spatial distribution of radiation dose estimated by the ADS might be very different from reality.

In order to improve the accuracy of dose estimations, several methods based on field radiation measurements have been proposed. Some of them consider a proportional correction of the source term considering radiation measurements taken downwind (Athey et al., 2013). These methods are quite simple and may be subjected to great errors due to the possible associated non-linearity. Other approaches are more refined and complex, proposing the solution of inverse problems to characterize the source term starting from the field measurements (Chow et al., 2008; Zheng and Chen, 2010; Delle Monache et al., 2008). Due to the complexity involved, these approaches may not be efficient to model realistic nuclear problems, involving great number of possible radionuclide and many possible release characteristics.

In this work, a simpler alternative approach, highly focused in the decision making support, is proposed. The idea is to directly correct the dose distribution map (dose map), without needing to estimate or correct the source term. To accomplish that, it is proposed to find a transformation matrix, which applied to a given (possibly erroneous) estimation, changes its shape and dose intensities in order to better fit to the field measurements.

3.1. Transformation matrix

Here, the three basic geometric transformation (scale, translation and rotation), as well as a proportionality factor (to correct dose intensities) are considered. Eq. (1) describes such transformations.

$$P' = P \cdot S \cdot R \cdot T \cdot I \quad (1)$$

where P is a given point (x, y) in the original map, P' is the transformed (corrected) point (x', y') , S is the scale matrix, R is the rotation matrix and T is the translation matrix. Here, the rotating and scaling center considered in S and R are defined at the release position (the NPP location). I is a scalar that provides a proportionality factor to be applied in order to attenuate or amplify dose intensity. Eqs. (2), (3) and (4), describe the 2D geometric transformation matrices using homogeneous coordinates.

$$T = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ T_x & T_y & 1 \end{bmatrix} \quad (2)$$

$$S = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ -X_0 & -Y_0 & 1 \end{bmatrix} \cdot \begin{bmatrix} S_x & 0 & 0 \\ 0 & S_y & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ X_0 & Y_0 & 1 \end{bmatrix} \quad (3)$$

$$R = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ -X_0 & -Y_0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \cos \theta & -\sin \theta & 0 \\ \sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ X_0 & Y_0 & 1 \end{bmatrix} \quad (4)$$

where T_x and T_y are translations and S_x and S_y are the scales referred to X and Y axis respectively. The rotation angle is θ and (X_0, Y_0) is the release position – the reference point to proceed scale and rotation transformation.

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