



## Predicting and Controlling Nuclear Accident Hazards: Issues and Challenges

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### ABSTRACT

Global nuclear security is threatened by nuclear accidents and the purposeful use of nuclear weapons. Accordingly, atmospheric pollution prediction and control for nuclear accidents, including identifying sources in nuclear or radiological incidents, predicting hazards to persons and environments, and optimally controlling accident hazards, are current areas of nuclear security research. Source inversion, hazard prediction, and optimal control are three interrelated key issues for nuclear accident emergencies. Although progress has been made in hazard prediction for nuclear accidents since the 1970s and some source inversion methods were presented after the Fukushima nuclear accident, optimal control methods are rarely reported, source inversion methods are less practical, and prediction accuracy remains unsatisfactory. Thus, novel theories are required for optimal control and source inversion for nuclear accidents, and to develop methods for simulating the influences of radioactive plume dispersion and deposition under complex meteorological and terrain conditions. This work reviews the current progress, uncertainties, and research needs in nuclear security. In addition, a rapid source inversion method based on the Lagrangian model is developed and implemented in a test case. To address future challenges, an innovative architecture for Atmospheric Pollution Prediction and Optimal Control System for nuclear accidents (APPOCS) is proposed, and the perspectives are generalized to promote future research on nuclear accident hazard prediction and optimal control. At this time, forward-looking ideas and revolutionary perspectives are required to foster nuclear security research in the academic community.

**Keywords:** Nuclear accident; Hazard prediction; Optimal control; Atmospheric dispersion; Source inversion.

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### INTRODUCTION

With the rapid development of the nuclear industry and the continuous aging and life extensions of already operating Nuclear Power Plants (NPPs), nuclear safety and security have become important issues. For example, the Chernobyl nuclear accident, which occurred in 1986, resulted in catastrophic consequences: 203 exposed persons had at least degree I acute exposure, 13.5 million people were evacuated, and a 5230 km<sup>2</sup> area was contaminated after 2 months. According to the United Nations Scientific

Committee on the Effects of Atomic Radiation (UNSCEAR) report published in 2010, the Chernobyl accident caused 0.065 million man-Sieverts (Sv) of radiation exposure to recovery workers and evacuees, 0.18 million man-Sv to the populace of Ukraine, Belarus, and Russia, and a dose to the majority of more distant European countries amounting to 0.13 million man-Sv (UNSCEAR, 2010). The total global collective dose from Chernobyl was estimated using UNSCEAR to be "600,000 man Sv, equivalent on average to 21 additional days of world exposure to natural background radiation" (Anspaugh *et al.*, 1988; Baverstock and Williams, 2006). The radiation effects from the Fukushima Dai-ichi nuclear disaster are the results of radioactivity release from the crippled Fukushima Dai-ichi Nuclear Power Plant (FD-NPP) after the magnitude 9.0 Tōhoku earthquake and the subsequent tsunami in 2011. Concerns regarding the possibility of a large scale radiation leakage resulted in a 20 km exclusion zone being established around the power plant, and people within the 20–30 km zone were advised to stay indoors (Arnab *et al.*, 2013). The UK, France, and some other countries told their nationals to consider

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leaving Tokyo in response to fears of spreading radioactive contamination (Cresswell, 2011). The Fukushima nuclear disaster led to trace amounts of radiation, such as iodine-131 and caesium-137, being detected in many places around the world (e.g., New York State, Alaska, Hawaii, Oregon, California, Montreal, Helsinki, Milano, Minsk, Vienna, UK and Austria) (MacKenzie, 2011; Yasunari *et al.*, 2011; Mason *et al.*, 2012; Stohl *et al.*, 2012b; Priyadarshi *et al.*, 2013; Kaeriyama *et al.*, 2014; Koo *et al.*, 2014). At the same time, large amounts of radioactive isotopes have been released into the Pacific Ocean (Madigan *et al.*, 2012; Eslinger *et al.*, 2014; Nair *et al.*, 2014). According to The World Health Organization (WHO) report (2012), the radiation effective doses in the most affected areas of Fukushima Prefecture for the first year were estimated to range from 10–50 mSv, and the thyroid doses were estimated within the band of 10–100 mSv. The nuclear accident caused by an unprecedented tsunami at Fukushima resulted in tens of thousands of people being evacuated and worldwide concern, and led to many countries re-assessing nuclear facility safety and energy policies (Huenteler *et al.*, 2012; Wittneben, 2012; Ramana, 2013). The Fukushima nuclear accident has aroused the attention of the world regarding nuclear safety. Furthermore, the global risk of nuclear power plant accidents may increase with the development of nuclear power in the coming decades, and the risk will become highest in China, followed by India and the USA (Christoudias *et al.*, 2014). Therefore, for nuclear accidents, it is important to explore how nuclear power plant hazards can be rapidly and accurately be predicted. At the same time, casualties, adverse health effects, control costs, and losses of environmental hazards must be minimized using cutting-edge methods to address concerns from the government and public. Studies on hazard prediction and optimal control of nuclear accidents have important practical and social significance to reduce the losses caused by nuclear accidents (Huang *et al.*, 2005; Galmarini *et al.*, 2011; Huang *et al.*, 2014).

Previous studies on nuclear accident hazard prediction and optimal control were closely related to meteorological and geographical conditions, as well as economic costs, environmental pollution, health effects, and many other societal influences, which involves both natural and social sciences. When a nuclear accident occurs, a wide range of health and environmental hazards may occur, mainly through atmospheric dispersion and deposition and contaminated water discharging into rivers, lakes and oceans (Buessler *et al.*, 2011; Lyons and Colton, 2012; Mason *et al.*, 2012; Nair *et al.*, 2012). Radioactive materials can damage the body's organs through various pathways, such as inhalation of radionuclides from plume, resuspended nuclide deposition, and external exposure to plume and ground deposition (Gofman and Fisher, 1983; Arvela, 1990; Olmos *et al.*, 1993; WHO report, 2012; Lenarczyk *et al.*, 2013). The WHO has assessed public health risks and radiation doses in Japan from external irradiation and from inhalation due to the Fukushima accident on the basis of measurements (WHO report, 2012, 2013). A comprehensive and systematic approach to estimating radiation doses and evaluating

short- and long-term health and environmental risks resulting from nuclear accidents need to be established to guide emergency activities (Christodouleas *et al.*, 2011; Bouville *et al.*, 2014). More importantly, to assess immediate threats to humans and the environment, environmental measurements and methods to simulate the dispersion and deposition of the released radionuclides serve as a platform to determine the source term and predict regional impacts of the releases.

In the event of a nuclear accident, emergency control includes accidental source disposal, protection, and decontamination. Disposal of the accident source may reduce the emission of radioactive materials, and thereby reduce the hazard range and rate. Protection may avoid or reduce damage to persons through specific emergency measures such as taking stable iodine tablets before exposure to radioiodine or as soon as possible afterwards, evacuation from radiation areas, and remaining indoors when radioactive materials disperse outside. Decontamination in access-restricted areas to which original residents are planned to return is given priority in government emergency policies (Yoshida and Kanda, 2012). Decontamination can reduce radioactive hazards to persons and the environment by removing radioactive materials that contaminate humans, equipment, and the environment. The proposed decontamination strategy focuses mainly on removal and isolation of the top land surface and cleansing of house walls and roofs with water (Yoshida and Kanda, 2012). An increased focus on nuclear accident source disposal or personnel and environmental hazard control ultimately decreases harm caused by the accident, but at the same time increases costs. Investment is significant and the overall effect may be better for emergency control. When emergency control reaches a certain level, control costs may sharply increase while control results show minimal improvement. Thus, it is important to explore control schemes that can achieve control objectives and minimize control costs, which is an important control problem. This problem is closely related to radioactive plume transportation, dispersion, deposition and emergency measures, and an optimal control theory method is indispensable.

The emergency system for nuclear accidents was developed in the 1980s. At the time, coinciding with the occurrence of the accident at Chernobyl nuclear power plant, governments of many countries prepared nuclear emergency plans and developed effective nuclear emergency decision support systems. During this period, the European Community developed the Real-time Online Decision Support System (RODOS) for nuclear emergency management (Bartzis *et al.*, 1999; Raskob and Ehrhardt, 2000), the United States developed the Atmospheric Release Advisory Capability (ARAC) (Sullivan *et al.*, 1993), and Japan developed the System for Prediction of Environment Emergency Dose Information (SPEEDI) (Imai *et al.*, 1985; Masamichi *et al.*, 2011). However, these systems, excluding RODOS (Ehrhardt, 1997; Bartzis *et al.*, 2000), had no emergency optimization function. Although the RODOS system had a decision-making subsystem entitled “Multi-Attribute Value and Utility Theory (MAV/UT)” (Ahlbrecht *et al.*, 1997; Ehrhardt, 1997; Raskob and Ehrhardt, 2000),

it is rather simple. At this time, some technologies and methods, such as high-resolution meteorological forecast, large eddy simulation, data assimilation based on ensemble Kalman filter, radioactive plume dispersion modeling, inverse modeling technique, emission dose calculation, and real-time GIS-based management systems, were developed systematically (Pan, 2007; Huang *et al.*, 2011b; Tang *et al.*, 2011; Wang *et al.*, 2011; Yan *et al.*, 2011; Wang *et al.*, 2014; Sheng *et al.*, 2015). However, nuclear accident source inversion, rapid and accurate hazard prediction, and optimal control are the primary challenges (Shanks *et al.*, 2012; Sugiyama *et al.*, 2012; Koo *et al.*, 2014). At this time, previous reviews have explored the topic of radioactivity release, environmental impacts, nuclear regulation, and health risks of nuclear accidents (Kinoshita *et al.*, 2011; Evangelidou *et al.*, 2014; Wang *et al.*, 2013; Zheng *et al.*, 2013; Steinhauser *et al.*, 2014). However, the results of these previous reports are not fully discussed and summarized. Thus, to increase our understanding of research issues, we systematically review current progress, uncertainties, and research needs for hazard prediction and optimal control of nuclear accidents (in Sect. 2). In addition, we propose a novel synthetic framework that integrates nuclear prediction, source determination, and optimal control systems for nuclear accidents (in Sect. 3).

## RESEARCH CONTENTS AND DEVELOPMENT SITUATION

Nuclear accident hazard prediction and optimal control can be divided into three components; identifying sources from nuclear or radiological incidents, predicting damage to humans and the environment, and optimally controlling accident damage.

### *Identification of Radioactive Sources*

Source determination, including location and strength, is important in decision-making and emergency planning. Regarding radionuclide dispersion events, the time evolution of the release rate and its distribution between radioisotopes have to be estimated to assess the sanitary and environmental impact of the events. The sources are the basic parameters for nuclear hazard prediction, but it is difficult to obtain precise data on sources in nuclear or radiological events (Shanks *et al.*, 2012). For example, the Japan Atomic Energy Agency (JAEA) assumed that release rate from FD-NPP was constant during certain periods, and estimated the sources based on determination data of radioactive material concentrations in the environment compared with the SPEEDI simulation results (Masamichi *et al.*, 2011) since information on the state of the facility and useful observations during the initial days of the accident when critical emergency response decisions were being made was not available. The actual release rate was not constant, and the estimation method of sources inevitably affects the prediction accuracy. In the case of the Chernobyl accident, the source term of the released radionuclides remains unclear (Devell *et al.*, 1995; Guntay *et al.*, 1996). For Fukushima, the released fraction of  $^{137}\text{Cs}$  into the atmosphere was

estimated to be 1.2–6.6% of the inventory, and it is calculated that 1.1–7.7% of the inventory of  $^{131}\text{I}$  was released into the atmosphere (Morino *et al.*, 2011; Hoeve and Jacobson, 2012; Stohl *et al.*, 2012a, b; Christoudias and Lelieveld, 2013). The total radiological source term of the Fukushima accident was estimated to be 340–800 PBq (Steinhauser *et al.*, 2014). Real accidents have shown that source determination may be a difficult task due to the large uncertainties involved.

While numerous studies have explored the source determination of airborne hazards, significant gaps still exist both in theory and practice. Whereas inversion methods such as the one presented by Stohl *et al.* (2012a) could theoretically be used in emergency response, they would require timely and constantly updated radiological measurements (and they should be also radionuclide specific) that limits the feasibility of such approach. Not only is the radioactivity discharge constantly evolving, but so are the meteorological conditions impacting the dispersion and deposition of radioactivity (Angevine *et al.*, 2014; Arnold *et al.*, 2014). Inverse modeling approaches that combine environmental measurements and atmospheric dispersion models are efficient in reducing uncertainty and improving assessment of atmospheric releases, and therefore are commonly used for source determination (Stohl *et al.*, 2012a; Saunier *et al.*, 2013; Eslinger *et al.*, 2014; Hamburger *et al.*, 2014; Winiarek *et al.*, 2014). Other source estimates of airborne radionuclides from the FD-NPP reactors apply Lagrangian particle dispersion (e.g., FLEXPART model; Stohl *et al.*, 2005) and a different calculation algorithm (Stohl *et al.*, 2012a; Benmergui, 2013; Eslinger *et al.*, 2014). Three categories of environmental measurements can be used for constraining the nuclear sources: airborne activity concentrations, surface activities, and gamma dose rates. Typically the fastest and most abundant type of data are gamma dose rate measurements which is sum of the contributions of airborne and fallout gamma-emitting radionuclides. Hofman *et al.* (2015) conducted source term retrieval using inverse modeling of instantaneous or time-integrated gamma dose rate measurements. The majority of estimates are designed to use one type of measurement; e.g., atmospheric trace constituents (Winiarek *et al.*, 2012; Benmergui, 2013; Eslinger *et al.*, 2014), but few studies use multi-measurements (Stohl *et al.*, 2012a; Saunier *et al.*, 2013). It is important to develop new modeling methods to assess the complex source term of real accidental situations using multi-data, including radiation dose rate measurements generated by most measurement facilities. To further increase the utilization of observations and improve the accuracy of estimates, a multi-scale simulation approach can be adopted to perform measurements close to the source, as well as at remote locations.

Recently, novel methods have been developed and applied to assess the sources of the accidents. Stohl *et al.* (2009, 2012b) utilized Lagrangian backward trajectory-based and Bayesian methods for source inversion in the Fukushima nuclear disaster. Tsuruta *et al.* (2014) presented a novel method for retrieving the hourly atmospheric  $^{137}\text{Cs}$  concentrations by measuring the radioactivity of suspended

particulate matter collected on filter tapes of operational air pollution monitoring stations. A data assimilation algorithm based on inverse modeling methods with an observation targeting strategy has been proposed for the sequential reconstruction of the nuclide plume (Abida *et al.*, 2009). In Winiarek *et al.* (2012, 2014), techniques were proposed to estimate prior errors for performing inverse modeling using air concentration and deposition observations. Chai *et al.* (2015) developed the emission inversion method based on a Lagrangian model and a cost function using the transfer coefficient matrix, and conducted sensitivity analysis for the inverse estimation by using the original concentration  $c$  and  $\ln(c)$  differences between model and observations in the cost function. By comparison, Zheng and Chen (2011) suggest that optimization modeling methods has advantages over probability modeling methods on source inversion. However, many estimates have been shown to be quite sensitive to the prior information on the source term used in the inversion. Some approaches in source determination are based on the simple assumption of a priori source parameters by the government, and subsequently applied the first guess to source estimation model (e.g., Yasunari *et al.*, 2011). Limitations associated with the fidelity and capability of the atmospheric transport and dispersion models (ATDMs) (Hanna, 2007; Sugiyama *et al.*, 2012; Bieringer *et al.*, 2013) also underlie the challenges of improving source determination.

We have successfully developed a Rapid Source Inversion Method (RSIM) based on the Lagrange model. According to the Lagrangian theory, spatial and temporal distribution of concentration may be achieved based on the statistics of particle or puff distributions in diffusion simulations. Once the time step and the calculation range are fixed, computing time only depends on the total number of particles. Thus, we can assume that the source strength is 1, and we can determine the concentration contribution rate  $\alpha$  for each time in the diffusion region at any position without changing the total number of particles. Several relevant well-known concepts have been documented as model sensitivities (Stohl, 1998; Stohl *et al.*, 1998; Stohl *et al.*, 2001; Hegarty *et al.*, 2013), concentration field analysis (Seibert *et al.*, 1994), source-receptor sensitivities (Seibert and Frank, 2004) and transfer coefficient matrices (Draxler and Rolph, 2012; Chai *et al.*, 2015). If a linear relationship between the source intensity and concentration is observed, the concentration at time  $t$  at a specific position is:

$$c(x, y) = \int_0^t \alpha(x, y, t) s(t) dt \quad (1)$$

For air pollution nuclear accidents, the predicting concentration and monitoring concentration of radioactive substances at the monitoring point  $j$  are  $c(x_j, y_j)$  and  $c_o(x_j, y_j)$ , respectively ( $\text{Bq m}^{-3}$ ),  $S_i$  is the release rate of a certain radioactive substance at time  $i$ , and  $\alpha_{i,j}$  is the concentration contribution rate of the source  $S_i$  for the monitoring result  $j$ :

$$c(x_j, y_j) = \sum_{i=1}^M \alpha_{i,j} S_i \quad (2)$$

$$\min J = \sum_{j=1}^N [c(x_j, y_j) - c_o(x_j, y_j)]^2 \quad (3)$$

We then solve for  $s_i$  for certain radioactive substances, where  $i = 1, \dots, M$ . We let

$$f(s_i) = \sum_{j=1}^N [\sum_{i=1}^M \alpha_{i,j} S_i - c_o(s_j, y_j)]^2$$

According to the principle of least squares method, we could obtain:

$$\frac{\partial f(s_i)}{\partial s_i} = 0 \quad (4)$$

$$\text{Let } A = \begin{bmatrix} \alpha_{1,1} & \alpha_{1,2} & \cdots & \alpha_{1,N} \\ \alpha_{2,1} & \alpha_{2,2} & \cdots & \alpha_{2,N} \\ \cdots & \cdots & \cdots & \cdots \\ \alpha_{M,1} & \alpha_{M,2} & \cdots & \alpha_{M,N} \end{bmatrix}, \text{ thus}$$

$$A^T = \begin{bmatrix} \alpha_{1,1} & \alpha_{1,2} & \cdots & \alpha_{1,N} \\ \alpha_{2,1} & \alpha_{2,2} & \cdots & \alpha_{2,N} \\ \cdots & \cdots & \cdots & \cdots \\ \alpha_{M,1} & \alpha_{M,2} & \cdots & \alpha_{M,N} \end{bmatrix}$$

$$\text{Let } S = [s_1 \quad s_2 \quad \cdots \quad s_M]^T, C_o = [c_{1o} \quad c_{2o} \quad \cdots \quad c_{No}]^T$$

and then we could obtain:

$$AA^T S = AC_o \quad (5)$$

Therefore, according to Eq. (5), we could rapidly calculate the source  $S$  as long as we come to the matrix  $A$  of the concentration contribution rate based on the Lagrangian dispersion model and the vector  $C_o$  of the monitoring results.

We have completed a test case using the RSIM. Supposed the matrix  $A$  of the concentration contribution rate

$$A(x,y) = |\text{random}(\text{Normal}, 1, 0.1, 1, 1) [\text{randn}(x) + 10] \times \frac{1}{10\sqrt{2\pi}} e^{-\frac{(y-50)^2}{200}}|, \text{ and the source } S_0 \text{ meeting Poisson}$$

$$\text{distribution } S_0(\lambda) = S_0(X = k) = \frac{\lambda^k}{K!} e^{-\lambda} \text{ where } \lambda = 4.02.$$

The monitoring results and the matrix  $A$  of the concentration contribution rate are multiplied by the variance of 0.01 normal random number, namely  $C = C_o \cdot \text{random}(\text{Normal}, 1, 0.01, 1, 99)$  and  $A_1 = A \cdot \text{random}(\text{Normal}, 1, 0.01, 1, 99)$ , and then the relative errors  $\delta_C$  and  $\delta_{A_1}$  of  $S$  and  $S_0$  are 1.5% and 1.5% respectively, their correlation coefficient  $R_C$  and  $R_{A_1}$  are 0.971 and 0.992 respectively (shown in Fig. 1). The results of the test case show that the error of monitoring results to the inversed sources is more sensitive to than the error of the concentration contribution rate. It is certain that when the errors of the contribution rate and the

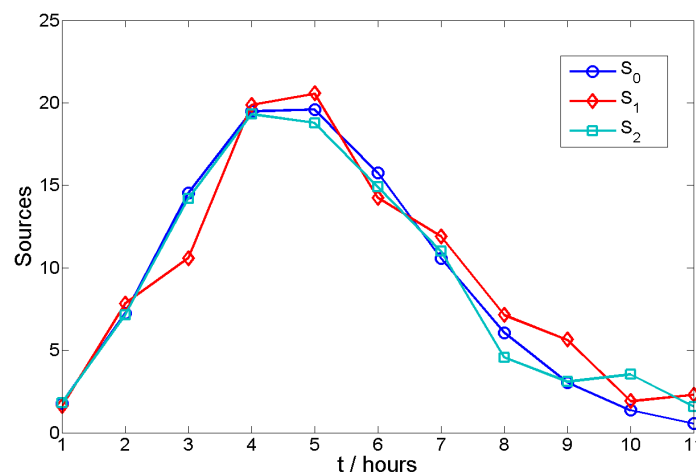
monitoring results are zero, the error of source inversion results is zero. This method has two obvious advantages: (1) the theoretical error of source inversion results is zero, and the errors are merely related to the errors of the contribution rate and the monitoring results; (2) the computing speed of source inversion is very rapid, which can be completed in a few seconds. More details on the equations are available in the supplementary materials (Supplement S1). Similarly, we can also realize source inversion using direct radionuclide specific measurements or gamma dose rate measurements through on-line spectrometric analysis and off-line radioactivity analysis. This method may require an assumption on the composition of the radionuclides contributing to the dose rates. For example, through the analysis of nuclide specific observations and information on the nuclear accident type, the nuclide ratios could be known at least approximately. The reconstruction of the source term can be described by the source-receptor equation based on atmospheric dispersion modelling (e.g., Saunier *et al.*, 2013). Finally, the release rate for each radionuclide could be estimated using the measurements of ambient dose rate. Hofman *et al.* (2015) and Saunier *et al.* (2013) have presented similar methods of source inversion using gamma dose measurements.

#### High-Precision Hazard Prediction for Nuclear Accidents

At present, nuclear accident hazard models are mainly global and mesoscale models, but nuclear accidents may actually harm the zone within the range of a few to hundreds of kilometers, which belongs to multi-scale transport problems, and the spread of radioactive materials is affected by a variety of meteorological elements and topographies (Declan, 2011; Morino *et al.*, 2011; Yasunari *et al.*, 2011; Koarashi *et al.*, 2014). For example, precipitation determines the wet scavenging of airborne particles and soluble gases, and thus their wet deposition onto the surface. Because wet deposition is a very efficient process, it is particularly important in identifying areas with the worst surface-level contamination, and therefore radiological consequences (e.g., Clark and Smith, 1988; Arnold *et al.*, 2014). Deposition

patterns of radionuclides are significantly impacted by spatially and temporally varying of precipitation and associated scavenging processes both in-cloud and below-cloud (Sportisse, 2007; Sugiyama *et al.*, 2012). For the modeling approach, the deposition of radionuclides is very sensitive to the microphysics schemes and wet deposition parameterizations (Sportisse, 2007; Hu *et al.*, 2014; Draxler *et al.*, 2015). Seibert and Arnold (2013) have developed and implemented a new wet deposition scheme in the FLEXPART model, and evaluate the simulated aerosol lifetime of radionuclides using observations from the Comprehensive nuclear Test Ban Treaty (CTBT) network. Comparing of five different ATDMs using different meteorological analyses, Draxler *et al.* (2015) suggest that the ensemble mean result of wet deposition is better than any one model.

The numerical simulation of contamination dispersion remains challenging for small- and medium-scale over complex terrains and low wind conditions. Because subgrid-scale flux exchanges and boundary layer eddies can affect dispersion simulations on local and mesoscales (Quan and Hu, 2009; Pagano, 2010), high-resolution model simulation outputs are used as input meteorological conditions for atmospheric dispersion models. Simulations with high time and space resolution based on mesoscale meteorological models are capable of resolving regional mesoscale circulations (e.g., land-sea breeze; urban heat island circulation; mountain-valley wind) and significantly improve the accuracy of dispersion calculations over complex topographies (Pagano, 2010; Zhang *et al.*, 2012; Srinivas *et al.*, 2014; Arnold *et al.*, 2015). In addition, data assimilation methods that optimize the match between an observed and predicted field are known to be an effective means to reduce hazard prediction error (Zheng *et al.*, 2007; Astrup *et al.*, 2004; Tang *et al.*, 2011). Recently, novel assimilation techniques, such as ensemble Kalman filter (Zheng *et al.*, 2009; Tang *et al.*, 2011) and ensemble simulations of meteorology (Hu *et al.*, 2014; Sheng *et al.*, 2014), have been applied to enhance the hazard estimation using synthetic dose rate data (Tsiouri *et al.*, 2012) and air



**Fig. 1.** Sensitivity analysis of the inversed sources to the error of monitoring results and the concentration contribution rate in the test case.

concentration and deposition measurements (Winiarek *et al.*, 2014). However, more in-depth theoretical studies and comparison tests on the hazard prediction mechanism based on observational and experimental simulations are required (Bieringer *et al.*, 2013; Draxler, *et al.*, 2015). For example, appropriate dispersion models and parameterization schemes have been developed to adapt to local weather and geographic conditions (Galmarini *et al.*, 2011). Moreover, a multi-scale models approach can be developed to further improve the accuracy of real-time forecasts.

### Optimal Control for Nuclear Accident Harm

Optimal control theories examine control strategies for nuclear accident hazards. The key issue in optimal control for nuclear accident hazards is to minimize accident loss and emergency action costs, which is required to establish the optimal control model and its solution method based on nuclear and radioactive accident hazard predictions and emergency response resources.

Prediction and optimal control for nuclear accident hazards is a complex system engineering that integrates meteorological field prediction, radioactive pollution transportation, dispersion and deposition modeling, emergency control measures, and optimization methods. Available studies exploring optimal control for nuclear accidents are rarely considered. Nuclear accident emergencies are a typical problem when natural law and human activities interact. Huang *et al.* (2013, 2015b) conducted the initial theoretical and practical studies on the prediction and optimal control of nuclear accident hazards based on an adjoint method for the optimal planning of industrial pollutant sources by Liu *et al.* (2005a), which provided the universal theoretical equation of optimal control of nuclear accident emergencies, developed their mathematical models, proposed specific expressions on control costs and disaster losses for the nuclear accident emergency so they could quantify the costs and losses, and provided a calculation method of warning, evacuation, protection, decontamination, casualties, and medical treatment. More details regarding the formulation of optimal control of nuclear accidents are available in the supplementary materials (Supplement S2). Using the similar approach of optimal control based on natural cybernetics (Zeng, 1996a, b), Huang *et al.* (2015a) have performed a real case to predict and optimally control the infectious diseases of Severe Acute respiratory Syndrome (SARS). However, combined research on source inversion, hazard prediction, optimal control theories, and nuclear emergency management are required.

### ARCHITECTURE OF APPOCS

The architecture of Atmospheric Pollution Prediction and Optimal Control System for nuclear accident (APPOCS) is shown in Fig. 2. APPOCS can examine four components: weather field predicting, pollution transportation, dispersion and deposition modeling, optimal control based on natural cybernetics (Zeng, 1996a) for nuclear accident hazards, and integration of GIS-based real-time information systems.

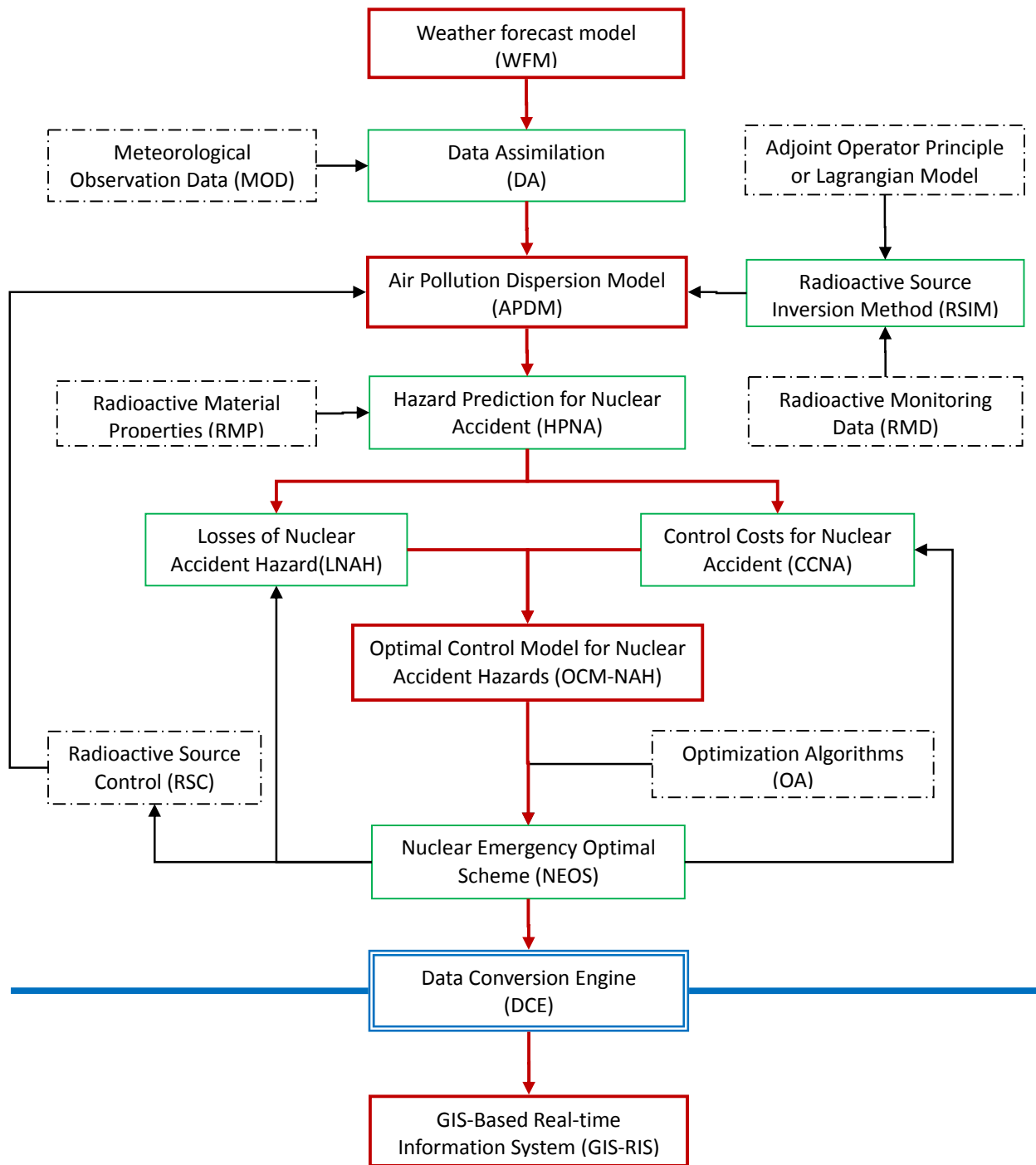
First, we predicted mesoscale meteorological fields

using Weather Forecast Models (WFM), such as WRF, based on NECP or ECMWF data, and developed coupling technologies for atmospheric boundary layer models and WFM for downscaling simulations (Tong *et al.*, 2005; Zhang *et al.*, 2012). At the same time, Data Assimilation (DA) was used to generate accurate initial conditions for WFM using Meteorological Observing Data (MOD). Second, transportation, dispersion, and deposition simulations were performed using Air Pollution Dispersion Models (APDM), such as the Comprehensive Air Quality Model with Extensions (CAMx) and the FLEXPART model (Stohl *et al.*, 2005). Based on the results of WFM, nuclear emissions may be determined based on the Radioactive Source Inversion Method (RSIM) (e.g., Adjoint Operator Principle and Lagrangian Model) using Radioactive Monitoring Data (RMD) (Marchuk, 1995; Liu *et al.*, 2005b; Liu *et al.*, 2007). We conducted Hazard Prediction for Nuclear Accidents (HPNA) based on the results of APDM and Radioactive Material Properties (RMP). Third, we established the Optimal Control Model for Nuclear Accident Hazards (OCM-NAH) and its solution method (Huang *et al.*, 2015b). The model takes into account the Losses of Nuclear Accident Hazards (LNAH) and the Control Costs for Nuclear Accident (CCNA) based on optimal control theory (Qian, 1954; Zeng, 1996a, b). We may address the nuclear emergency optimal control problem and formulate the Nuclear Emergency Optimal Scheme (NEOS) through Optimization Algorithms (OA) such as Lagrange model and Genetic Algorithm. At the same time, we provide feedback on NEOS to Radioactive Source Control (RSC) and LNAH, after which APDM re-simulates radioactive material transportation, dispersion, and deposition. Finally, we develop the universal algorithm of the Data Conversion Engine (DCE) to achieve automatic conversion of scalar data of the numerical model and vector data of GIS system, and then realize that GIS-based Real-time Information System (GIS-RIS) coupled the multi-platform, multi-system, and multi-model by applying heterogeneous platforms, virtualization, and hybrid programming technologies to provide intuitive decision-making support. The dynamics of APPOCS are described as follows.

We can obtain wind fields and turbulent kinetic energy or diffusivity using DA based on WFM and MOD, such as  $u$ ,  $v$ ,  $w$ ,  $Tke$ . We get the matrix  $B$  of the dose contribution rate using APDM and sources  $Q_0$  using RSIM, and then obtain dose  $d$  ( $Bq\ s\ m^{-3}$ ). We can calculate the people and scope of the impact of accidents by the distribution of dose  $d$ , and then LNAH  $G_2(Bd, Pd, En)$  may be calculated using formula (6).

$$G_2 = (Bd, Pd, En) = \sum_{i=1}^N s_j \lambda_j Bd(j) + \sum_{i=1}^N \sum_{k=1}^M \eta_k Pd(j, k) + \sum_{i=1}^N s_j En_j \quad (6)$$

where,  $Bd(j)$  is the gathering degree of property in  $j$  area,  $1 \leq j \leq N$ ,  $N$  is a positive integer greater than or equal to 1,  $\lambda_j$  is the property loss coefficient in the  $j$  contaminated area,  $s_j$  is the size of  $j$  contaminated area,  $Pd(j, k)$  is the number of



**Fig. 2.** Architecture of Atmospheric Pollution Prediction and Optimal Control Systems for nuclear accidents (APPOCS).

people exposed to pollution hazard level  $k$  in  $j$  contaminated area,  $\eta_k$  is the compensation costs for each person exposed to pollution hazard level  $k$  (including medical expenses, pensions, mental damages, etc.), and  $En_j$  is the loss of ecological environment in the  $j$  contaminated area. The objective function  $J$  of total loss of nuclear accidents is:

$$J = G_1(Eu, Eq, Em) + G_2(Bd, Pd, En) \quad (7)$$

In which,  $G_1(Eu, Eq, Em)$  is CCNA:

$$G_1(Eu, Eq, Em) = \sum_{i=1}^{N_1} t_i Eu_i + \sum_{i=1}^{N_2} \tau_i Eq_i + \sum_{i=1}^{N_3} Em_i \quad (8)$$

where,  $Eu_i$  is the  $i$  branch emergency unit cost per unit time,  $1 \leq i \leq N_1$ ,  $N_1$  is a positive integer greater than or equal to 1;  $t_i$  is the response time of the  $i$  branch measured in hours or days,  $Em_i$  represents the value of the  $i$  class emergency-depleting substances,  $1 \leq i \leq N_3$ , and  $N_3$  is a positive integer greater than or equal to 1. The cost of the

nuclear accident itself can be separated into three components; namely, loss of property in contaminated area, personal injury, and the ecological environment damage. The control objective is to minimize the objective function  $J$  of total loss of nuclear accidents, when the dose finally reaches a certain threshold within the control area, namely OCM-NAH:

$$\begin{aligned} \min J = \min [G_1(Eu, Eq, Em) + G_2(Bd, Pd, En)] \\ \text{s.t. } d(x_j, y_j, z_j, t) \leq d_{j0}, j = 1, 2, \dots, N \end{aligned} \quad (9)$$

where  $(x_j, y_j)$  represent the horizontal coordinates of the  $j$  geographic regions and  $z_j$  is the vertical coordinate.

We use penalty function method to construct the optimal control model for the loss of nuclear accident and the cost of emergency operations:

$$\begin{aligned} J_{new} = G_1(Eu, Eq, Em) + G_2(Bd, Pd, En) \\ + \gamma \sum_{j=1}^N w [d(x_j, y_j) - d_{j0}] \end{aligned} \quad (10)$$

In which

$$w(p) = \begin{cases} p^2 & p \geq 0 \\ p^2 \exp(-p^2 / \beta) & p < 0 \end{cases} \quad (11)$$

$\gamma, \beta$  is the coefficient; its value can be adjusted according to the actual situation. Using OA to solve this model, we can obtain the key data  $Eu, Eq$  and  $Em$  of NEOS. At the same time, we can calculate the source control factor  $U$ , and obtain the dose contribution after the optimal control:

$$d(x, t, z; t) = BQ_0(1 - U) \quad (12)$$

More details regarding NEOS available in the supplementary materials (Supplement S2), and we have achieved a similar algorithm in optimal control of infectious diseases (Huang et al., 2015a).

Application of APPOCS is outlined in Appendix A: Theoretical Framework of APPOCS (Supplement S2). By controlling the source terms, we can prevent the release of radioactive substances into the air or reduce emissions into the atmosphere, which protects OTC personnel and the environment. By accurately predicting hazards from the transportation, dispersion and deposition of radioactive substances, we may develop timely scientific evacuation programs, including the scope, occasion, and routes of evacuation to avoid or reduce personnel exposure to radiation hazards in the region. Through scientific emergency resource deployment, we can effectively control accident source terms and provide the necessary scientific guidance for evacuation, protection, and decontamination of radioactive material to reduce control cost and improve control efficiency. The core issues for responding to nuclear accidents are scientific and effective emergency actions, and APPOCS proposes the theoretical framework for how to systematically approach the problem.

## CONCLUSIONS

In this paper, we conducted a systematic review of studies and methods for source determination, hazard prediction, and optimal control in response to nuclear disasters. We discuss the strengths and weaknesses of the current professional systems or models predicting and controlling nuclear accident hazards. The outstanding problems in atmospheric pollution prediction and control for nuclear accidents are that rapid and accurate source inversion technologies require further development, hazard prediction accuracy is not high, and optimal control is complicated. Therefore, the APPOCS framework integrates the meteorological field forecasting, diffusion modeling, emergency optimal control, and some key theories and technologies, as well as challenges, to realize high-precision hazard prediction and optimal control for nuclear accidents. To achieve nuclear accident hazard prediction and optimal control, further studies are required, including: (1) development of a rapid and accurate source inversion model, with source inversion algorithms based on monitoring data analysis; (2) development of a multi-scale hazard prediction model for nuclear accidents, where the models should be validated by applying meteorological observation experiments, wind tunnel experiments, water tank experiments, and monitoring data of nuclear accidents; (3) characterization of the impact of radioactive plume transportation, dispersion, and deposition over complex terrain, non-uniform underlying surfaces, and precipitation; (4) construction of an optimal control model and an algorithm for rapidly solving the optimal control problems by developing the optimization algorithm; (5) establishment of the quantitative relationship between emergency action and control effect of the source terms, as well as calculation methods on relieving pressure and cooling measures (external water cooling, circulating water cooling, and anti-zirconium water reaction) for affecting the release of radioactive substances; (6) development of a system integration technology and real-time promulgation. This article provides novel concepts to promote the development of nuclear and radioactive hazard control.

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## DISCLAIMER

The authors declare no competing financial interests.

## SUPPLEMENTARY MATERIALS

Supplementary data associated with this article can be



found in the online version at <http://www.aaqr.org>.

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