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Article

Guidance on monitoring and data assimilation

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ABSTRACT **Decision makers must react in a prompt and appropriate manner in various emergency situations. The bases for decisions are often predictions produced with decision support systems (DSS). Actual radiation measurement data can be used to improve the reliability of the predictions. Data assimilation is an important link between model calculations and measurements and thus decreases the overall uncertainty of the DSS predictions. However, different aspects have to be taken into account for the optimal use of the data assimilation technique: different countries may have differing measurement strategies and systems as well as differing calculation models. The scenario and the amount and composition of radionuclides released may vary. In this paper we analyse the situation during and after an accident and draw up a list of recommendations that can help modellers to take into account the measurements that are best suited for data assimilation.**

1. Introduction

It is the aim of emergency preparedness to enable decision makers to react in a prompt and appropriate manner before, during and immediately after an accidental (or intentional) contamination of the environment. For this purpose it is urgent to create a rapid overview of the contamination situation and the actual and projected potential dose to man. Decision supporting systems (DSS) are needed for prognostic estimations of the likely evolution of the environmental contamination and especially of the expected dose to man. Measurements indicate the severity and extent of the actual radiological situation.

In a pre-release phase it is important to be able to confirm that no radioactive release is taking place and to detect releases rapidly should they occur. The main task is to determine the area likely to be affected by a possible release and to obtain an estimate of the potential maximum environmental consequences. Before and during releases various dispersion models with versatile weather data and

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best-estimate source terms can be used. When results of radiological measurements are available they can be used to improve model calculations by data assimilation. After the plume passage the main emphasis naturally lies on measurements for evaluating the contamination of the environment. Models predicting the terrestrial transfer of radionuclides are used to estimate the dose to man. The actual release characteristics and exposure pathways, however, vary according to the scenario and its development in time. Therefore, different kinds of information are requested from the simulation models during an ongoing event. Furthermore, the measurement strategy must also be adapted to the actual situation. It will be different in the case of a severe nuclear accident as compared to the detonation of a small radiological dispersion device containing only beta or alpha emitters.

The steps from monitoring data and model calculation results to a comprehensive situation analysis and further to recommendations on countermeasures are not always obvious. There are several sources of errors and uncertainty. When performed in a proper way, data assimilation can help to improve the assessment of the situation.

The role of measurements and calculated predictions and their associated uncertainties have been discussed to some extent *e.g.* in Lahtinen *et al.* (2007). The general interaction between off-site decision making, modelling and monitoring in a nuclear emergency has been addressed by Zähringer and Wirth (2007).

The discussion and conclusions presented here are based on the work of the CAT2RTD12 work package of the EURANOS Integrated Project (European Commission, 2006). The paper and the methods described focus on nuclear accidents but most of the following can also be extended to cover other types of situations involving radioactivity.

2. Use of measurements and calculated predictions

In a nuclear or radiological emergency, the main purpose of measurements and model calculations is to provide decision makers with data and information that – combined with other relevant data (demographic, social, economic, etc.) – can be used to decide on countermeasures for reducing the dose. Depending on the case, the decisions may affect the well-being of thousands of people and involve very large sums of money. All monitoring data, calculation results and other information should therefore be as accurate as possible.

Recommendations and decisions are based in the pre-release phase of a nuclear accident on model predictions and mostly on measurement data during the late phases. In the threat phase of a nuclear accident there might be specific triggers that initiate early emergency actions that are solely based on information about the plant status regardless of any environmental measurements or model calculation. During and shortly after a release both calculations and measurements provide important information for decision making.

In the early phases of an accident the main goal of emergency-related activities is to provide the authorities with a prediction of the magnitude and geographical coverage of the potential environmental consequences. It is important to know the prevailing and forecasted meteorological conditions in the local area and close to the site. Also the status of the plant should be known in detail for first source term estimations. Depending on the meteorological situation and the model used, trajectories may be calculated first to give a rough estimation of the plume transport. Alternatively, dispersion calculations are performed using a simplified source term designed to show the largest extent of the spread of the plume. When moving further to the first assessment of concentrations and doses, dispersion calculations with quantitative source terms are needed. If information on the source term is not available, a first (preferably conservative) dose assessment can be carried out assuming some predefined accident sequences and source terms. Having a catalogue of predefined source terms and calculated predefined weather situations might be also helpful in the first estimation of the consequences.

As the situation evolves, different state-of-the-art dispersion models with versatile weather data can be used. These models can be distinct dispersion/dose calculation systems or advanced decision support systems like RODOS (Ehrhardt and Weis, 2000; Raskob, 2008) and ARGOS (Hoe *et al.*, 2000). Meteorological data are usually available from the meteorological stations of the nuclear facility or from the national weather services. Best-estimate source terms, depending on the situation inside the plant, should be used in the calculations. When data from radiological measurements are available, they should be taken into account in the consequence assessment and used to correct and update model calculation results (data assimilation). After the radioactive plume has passed and deposition onto the ground has ceased, all situational analyses are primarily based on radiation measurements, and the need for models will decrease. But models are still important, for example, for the dose assessment or for predicting the long-time behaviour of radionuclides in the environment.

The basic monitoring programmes can be summarised as follows (Wirth and Kirchner, 2008; Tab. I).

– During the passage of a cloud, when direct radiation and inhalation are the relevant exposure pathways, the external dose rates and the radionuclide concentrations – especially those of iodine isotopes – in the ground-level air should be measured. The dose rate measurements indicate the affected area and the related health risk due to external radiation. The nuclide-specific

TABLE I

Important measurements (based primarily on Wirth and Kirchner, 2008).

Time scale	Purpose of measurements[a]	Measurements and equipment
Before releases	To predict affected area	Meteorological parameters for dispersion models (meteorological tower, data from the weather services)
During radionuclide release and passage of a cloud	To observe dispersion, to estimate contaminated areas	External dose rate (automatic systems)
	To identify radionuclides and their amounts in the air	Radionuclide concentration in the air (automatic or semi-automatic systems)
After cloud passage	To estimate overall contamination patterns (dose rate maps)	External dose rate (automatic on-line systems, airborne measurements, car-borne measurements)
	To estimate nuclide-specific contamination patterns	Spectrometric in-situ measurements (various automatic and/or mobile systems, interpolation with the help of local dose-rate measurements)
	To estimate radionuclides in food, feed and drinking water	Nuclide-specific alpha, beta and gamma measurements in laboratories

[a] The estimation of radiological quantities will give models the possibility to predict the future doses to man.

measurements of the air show the radionuclide composition and indicate the dose to man due to inhalation.

– External radiation and ingestion are the most relevant exposure pathways after the deposition of radionuclides on the ground. External dose rate measurements in connection with *in-situ* spectrometric measurements are needed for creating contamination maps that are used for evaluating the radiological situation and for deciding on the further measurement strategy. These two measurements also form the basis for long-term prognoses of the external dose and for the expected time-dependent contamination of food and feed. Analyses of radioactivity in food and feed are valuable for deciding whether products can be safely consumed or have to be banned. For decision making it is necessary to know the origin of the samples and to ensure that samples from different origins are not mixed. Regarding milk, however, mixing cannot always be avoided.

Other measurements, such as radioactivity in precipitation or in daily total food, are interesting but not urgent with respect to decision making. Whole body counting and excretion measurements are useful for verifying dose calculations and estimating individual exposures. In addition, various contamination measurements of surfaces and goods as well as measurements of resuspended radioactivity (for the protection of rescue and recovery workers) have to be initiated after the release.

There are potential sources of error and uncertainty that are part of the assessment of the radiological situation and thus may possibly influence to some extent the countermeasure recommendations. Some of these sources are associated with radiation measurements (*e.g.* equipment malfunctions, variations in natural background radiation, general statistical uncertainties of radioactive decay, effects of natural or man-made structures on the measured quantities) and some with calculated predictions (such as generic weaknesses and limitations of different models, and incorrectness or limitations of meteorological data within the area of interest). The source term, however, is often the biggest source of uncertainty in the first assessments during a nuclear accident – at least in the early phase. Therefore, it is obvious that measurements and model calculations will differ in reality. One way forward – a very simple one – is the presentation and comparison of measured and predicted results in a manner (taking into account *e.g.* the number of details shown, choice of colours on the screen and in printouts) that supports the ability of the decision making team to better evaluate the situation rapidly and in an optimum way. It also helps to quickly check whether the model predictions can be used or are totally out of range.

3. Data assimilation in an emergency

Going one step beyond such simple comparison there exist several more developed methods that can be applied in data assimilation in connection with radiation monitoring and consequence calculation models (or DSSs). A few of them have to some extent been utilised, for example, in the RODOS system. These include Kalman filtering (Rojas-Palma *et al.*, 2003; Astrup *et al.*, 2004), probability-based Bayesian analysis (French and Smith, 1997) and a method utilising so-called location factors (Meckbach and Jacob, 1988; Meckbach *et al.*, 1988; Kaiser and Pröhl, 2007). Each method has its advantages and drawbacks. The current status and practices are described elsewhere in this issue (see the paper by Kaiser *et al.*, 2010).

Data assimilation should only be undertaken when the predictions can be significantly improved, and combining measurements and predictions must reduce the overall uncertainty in analysing the radiological situation. A basic precondition for successful application is that model developers of assimilation routines are aware of what kind of measurements (see previous chapter) are available and of their characteristics (spatial distribution of measuring devices, measurement frequency, measurement time, data amount, format, uncertainty, detection limits).

One practical problem in adapting data assimilation is that spatial and temporal resolutions of measurements are not always the same as those of models, which makes it necessary to apply averaging, interpolation and/or extrapolation. Models should be designed to use internal grids of different sizes reflecting the structure of measurement systems and needs for protecting the population. On one hand, spatial grids should be dense when there are many measuring locations in a certain limited area, as is the case of dose-rate measuring systems around nuclear power plants. On the other hand, a dense temporal grid should be applied in those geographical areas where measuring frequencies are known to be high (*e.g.* when there are in use automatic continuously monitoring systems). In major cities and their surroundings both grids might be dense. Grid sizes could also be determined dynamically on the basis of the gradients of various quantities (that are known to be measured) calculated with an initial static grid. As to measurements, their frequencies should be increased when the predictions suggest it. Of course, at least the locations of all existing important fixed measuring sites (specifically those monitoring dose rates and radioactive substances in the air) should be incorporated in models in advance.

The internal procedures of the models should also be tailored to handle cases with only a few measurements (*e.g.* at the beginning of a release when dose rate data from fixed stations can be used to correct the predicted transport direction) and cases with a large amount of data (airborne fallout mapping).

As a rule, monitoring data should be put to data assimilation systems as soon as they are available, of good quality and representative (the providers of data are naturally responsible for their quality). External dose rates are received continuously from automatic measurement networks but automatic on-line spectrometry networks exist only in a few countries. Therefore spectrometric measurements of radionuclides in the air carried out at the site are very important and their results should be taken into account in the calculated predictions as soon as possible.

There are still many simple models (often of the straight-line Gaussian type) in use that could perhaps also benefit from data assimilation techniques (Quélo *et al.*, 2005). Gaussian models and other fast running models are useful for vulnerability studies in which many cases must be simulated in a limited amount of time or for emergency response when the first estimate of consequences is needed very quickly. Simple models also serve as back-up utilities in case more advanced systems cannot be used for one reason or another.

Preparation of proper interfaces between monitoring data and models requires that the modelling and radiation monitoring communities are aware of each other's activities, specific needs and operational and planned systems. Important in this respect is the existence of networks of experts and easy-to-understand documentation that can be accessed by competent parties when necessary. This kind of arrangements would also facilitate solving the opposite problem: using model calculations in designing monitoring systems and measurement practices.

4. Conclusions

During emergencies radiation protection authorities and decision makers need numerous information and data when evaluating the overall situation and deciding on possible countermeasures. Both the calculated predictions and real measurement data are important. As they differ, a common picture has to be established. This can be achieved with procedures for correcting predictions on the basis of measurements (data assimilation). These methods should be reliable and should reduce the uncertainty in the assessment of the radiological situation. In addition, the way of expressing or displaying the uncertainty of the final output should be an issue in this context and appropriate for decision making.

In order to make best use of data assimilation several aspects have been identified:

- Models must be optimised to utilise the measurement data that are most likely to be available, *i.e.* primarily external dose rates, airborne and deposited activity concentrations. There might be other models designed for specific purposes that use further radiation monitoring results.
- Data assimilation procedures should be designed to handle cases with only a few measurements (*e.g.* at the beginning of a release when dose rate data from fixed stations can be used to correct the transport direction) and cases with a large amount of data (airborne fallout mapping).
- Simple fast running models may also benefit from data assimilation (on certain conditions).
- Time is a limited resource in the release phase of an accident. The practical interface between measurements and prediction models (*e.g.* incorporation of locations of all fixed important measuring sites) must be established before an accident happens.
- The fact that spatial and temporal resolutions of measurements are not the same as those of the models must be recognised. In an optimal case a model would:
    - Use a denser spatial grid in pre-defined important areas (*e.g.* in large population centres), in areas in which there are many measuring locations and in (dynamically determined) areas in which the calculated quantities show strong spatial gradients.
    - Use a denser temporal grid in geographical areas in which the measurement frequencies are known to be high, or during time periods in which the calculated quantities show strong temporal gradients (dynamically determined grid).

– Monitoring systems should allow increasing measurement frequencies when the predictions suggest it.
– Monitoring data should be put to data assimilation systems as soon as they are available (the providers of monitoring data are responsible for the quality of measurement results).

Most important, establishing proper data assimilation practices presumes that the modelling and radiation monitoring communities are aware of each other's activities, specific needs and installed operational and pre-planned systems.

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