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Real-time Computing of the Environmental Consequences of an Atmospheric Accidental Release of Radioactive Material: User's Point of View

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INTRODUCTION

Previous papers presented in this workshop have discussed methods for calculating doses from radiological accidents ranging from simple to complex models. Although dose is an important aspect of model utilization for emergency response purposes, other uses of models should be noted.(1) These are:

- Determine source term.
- Provide guidance for deploying field measurement teams.
- Evaluate the consequences of *assumed* release mechanisms and rates.
- Provide a consistency check on measurements.
- Interpolate and extrapolate measurements. However, discussions in this paper will be focused on the dose calculations as the major use of models. It should also be noted that the word user, in the context of this paper, is defined broadly to mean in-plant personnel, health physicists, emergency response planners, authorities changed with decision making responsibilities and implementing protective measures.

All calculations of the consequences of an atmospheric release must start with atmospheric dispersion calculations. Thereafter, calculations must be undertaken for:

- External exposure to the plume (immersion dose).
- Inhalation of the plume.
- External exposure to deposits on the ground.

- Ingestion of contaminated food and water.
- Contamination of ground, pasture and agricultural crops.

Time factors make external and inhalation dose estimates of immediate concern closely followed by ground contamination of land, pastures and onch agricultural crops. In general, the difficulties in modeling the source term and atmospheric transport and diffusion account for most of the error in calculating the dose to man. Thus, sophisticated treatment of the dose part of the calculating is not usually justified, though the relative distribution of dose in individual organs may be needed for correct decision marking. This paper emphasizes the atmospheric transport and diffusion part of the dose estimate and relates how this calculation can be used to estimate dose.

Atmospheric Transport and Diffusion

When a radioactive effluent cloud is released to the atmosphere, it is transported in three dimensions by the mean wind field and it is dispersed due to the turbulent motion of the atmosphere.(2) The mean wind field generally determines the direction of travel of the effluent cloud and the time it takes for the effluent to arrive at a particular location. The dispersion causes the cloud to spread by mixing in both the horizontal and vertical directions and is largely responsible for determining the concentration at a particular location. Definitions of the mean wind and turbulence depend on the time and distance scales involved for a particular problem of interest. For this reason it is difficult to clearly separate factors that contribute to each process. The user of models needs to relate the local factors that can effect the mean wind near a site to their requirements for a model. For example:

- Complexity of the underlying terrain, e.g. mountain valleys.
- Relationships between land masses and large bodies of water.
- Thermal structure of the atmosphere.

Other important factors affecting the dispersion of an effluent cloud are:

- Roughness of the underlying terrain, e.g. forrested areas versus grassland.
- Thermal stability of the atmosphere, e.g. a stable atmosphere at night versus an unstable atmosphere during the day, when the sun is heating the ground.
- Effects of buildings on air flow near the release point that can trap the effluent in the building wake or can cause extra dispersion of the effluent cloud before it is transported by the mean winds.
- Plume rise due to momentum and/or thermal energy of the emitted activity.
- Depletion of the effluent radioactivity due to decay.
- Chemical and physical properties of the released material, such as solubility and particle size distribution.
- Dry deposition of particulates onto the ground due to effects of the surface roughness at the interface.
- Deposition of particulates by precipitation (wet deposition) due to washout or rainout when the radioactive material intercepts a precipitations system.

Levels of Atmospheric Transport and Diffusion Model Complexity

As previously discussed a variety of models exists for evaluating the consequences of a release of radioactivity to the atmosphere.[3–9] The simplest of these models is the Gaussian, which only requires the wind speed and direction at the release location, plus information about the atmospheric stability, plume height, and source rate. On the other end of the spectrum are complex three-dimensional models that use information about the terrain shape, all available wind measurements in both horizontal and vertical space and time and information about the surface roughness and thermal structure. This spectrum of model capability can be divided into the following three generic categories:

Gaussian model

This model is a simple analytic expression used to estimate air concentration, given a minimal set of meteorological data. The model assumes a straight line plume in the downwind direction and does not directly take into account wind direction changes in space and time.

Given the limitations and recognizing the possible errors, the Gaussian model is a useful tool for providing timely dose calculations to distances up to 5 or 10 km from release point, depending on the complexity of the local terrain and the prevailing meteorology at the time of the accident.

The Gaussian model can be programmed in various forms on a hand-held or mini-computers depending on the needs and capabilities of the user. It has been tested and compared with experimental data in many different locations under a variety of different meteorological conditions. Further it is widely used and easy to apply. This model is, however, limited in its ability to handle dispersion in complex terrain or complex meteorological conditions such as horizontal or vertical wind shear or at coastal sites where the sea-breeze has an important influence on local transport and dispersion conditions. Studies over the past several years have shown estimated uncertainties associated with predictions given by the Gaussian model. A recent study[10] shows that Gaussian models predict concentrations within a factor of 2 for hourly values at highly instrumented sites or for long term averages within 10 km of the source. It is within an order of magnitude for hourly comparisons in flat terrain under steady-state meteorological conditions. For complex terrain or meteorology, the Gaussian model calculations can differ from observations by 2 orders of magnitude or more.

Lagrangian Puff Model (LPM)

The most important information for a real-time emergency response, beyond the initial close-in dose assessment provided by the Gaussian model, is the trajectory of the emitted effluent after it leaves the close-in environs, i.e., beyond 5 or 10 km.[8,11] The LPM has the capability of accepting more than one wind measurement in the region surrounding the nuclear facility. It interpolates and extrapolates these measurements to a grid and uses the interpolated wind field to transport the emitted radioactivity. Some of these models assume that the wind field is constant in the vertical direction while others define the wind field by connecting the surface layer wind field to an upper level wind field through the atmospheric layer containing the radioactivity (or other toxic pollutant).

With the computer resources presently available from a variety of sources, implementation of a LPM for real-time emergency response purposes is feasible at a relatively low cost. For example, a fairly complete model has a total program length of about 150,000 bytes. Distribution of the memory allocation is approximately 30,000 bytes for the executable code, 25,000 bytes for local data storage and 95,000 bytes for data storage in common blocks. A typical minicomputer or work station with a good graphic capability will provide the computer requirements. A simple version of the LPM can be run on smaller computers. Other continuing requirements for implementing this level of model sophistication include program start-up, continued software maintenance, a knowledgeable staff to (a) develop and quality control the input data and (b) interpret output calculations.

To gain full advantage of this level of modeling capability, the staff should be well trained in meteorology so they can review the input data and use their experience to supplement "measurements" of the meteorological variables under conditions where the measurements are sparse. Also, the real-time dose assessments can be made in less time if the meteorological measurement system is tied directly to the computer and the wind data are automatically formulated in the computer. By automatically collecting the wind field data, the analyst can spend more time quality controlling the input data and providing supplemental data if required.

Three – dimensional model

A limited number of three-dimensional models are presently available for real-time dose assessment purposes if the complexity of the terrain and meteorology induce complex flow patterns.[6,9] These models are more difficult to implement because they require larger computers than the LPM; they normally require more input data, and they require more time for preparing the input files and quality controlling the input and output data. If these models are integrated into the data collection network, they can be run in 30 to 45 minutes after the initial notification of an accident.

An important advantage of a three-dimensional model is that the vertical variation of wind speed and direction can be directly included in the calculations. This information can come from doppler acoustic sounders, pibals, rawinsondes and meteorological towers. Also, the vertical temperature structure, e.g. inversion layers, can be parameterized in these models. By including terrain directly in the model, the coupling between the wind field, temperature structure and terrain can be more directly modeled than with the other two types of models.

This class of model can simulate flow around terrain under stable conditions and over terrain for unstable conditions. Diurnal valley flows can be modeled and sea breeze affects (e.g., with return flows) can also be modeled, provided measurements are made that document these effects. At this time there are no known meteorological models that can operationally forecast wind speed and direction and temperature structure on scales of 10 to 100 km; therefore, emergency response models are dependent on measured meteorological data and input data synthesized from large scale forecast models. The final assessment however, should be based on both the model output and a meteorological forecast made by an experienced meteorologist.

Additional resources beyond those required for maintaining and operating an LPM are required for three-dimensional models. Most of these models can be run only on large class computers, although a move to smaller computers has been made recently. To take advantage of the three-dimensional aspects of these models requires additional input data and judgments on parametric input values, such as surface layer mixing height, boundary layer height and upper level wind field, than those required for the LPM. For nuclear facilities located in complex areas, the benefit derived from a three-dimensional real-time dose assessment model can be greater than the cost associated with implementing advanced capabilities for estimating doses to the public, should an accident occur at the facility. Considerable experience with these models has been gained in the last four years by several member countries[10,11] and their experience base is expected to increase as these models continue to be used for emergency response purposes. A proper balance between requirements and available resources can be determined only on an individual basis.

Selection of Real-time Transport and Diffusion Models

Given that three basic levels of atmospheric and diffusion model sophistication are available for use in emergency response dose assessment, emergency response planners should consider selecting a real-time model from each of two categories for their dose calculation capability. The simpler model is used in the initial phases of an accident for quickly providing dose estimates to workers at the facility and members of the public that live within a few kilometers of the facility. The advanced model is used to provide a more complete dose assessment at greater distances from the release point where meteorological conditions may be different from those in the local area near the release point. The complexity chosen for the higher level model depends on the complexity surrounding the nuclear facility of interest and on the computer resources and manpower available to the emergency response planner.

There are no simple, general rules for selecting real-time models to use in all accident situations. Suggested guidelines for this selection process are:

- Plume transport and dispersion behavior for the area corresponding to the outer boundary of the emergency planning zone should be adequately represented by the models.
- The first model results should be available to users within 5–10 minutes of initiation.

- The models should have a known field evaluation history appropriate to the site, and known standards of accuracy or desired conservatism.
- Estimates of dispersion of short-term releases (instantaneous to 2 hours) and intermediate duration releases (2–24 hours) should be considered.
- Models should include plume depletion mechanisms, such as wet and dry deposition.
- Models should have the flexibility, within their input stages, for accepting real-time sequences of the meteorological conditions from meteorological sensors, and should also have the capability to operate using forecast data.

Finally, ensuring accurate concentration predictions may not be the most important issue. To initiate an emergency plan to protect the public, timely information about the plume trajectory (i.e. plume transport) is needed. In this case the model's ability to make timely predictions of plume transport may take precedence over the model's overall accuracy. For example, if there is confidence in the model's ability to bound the areas of plume transport and dispersion, it should be possible to define zones for implementation of protective actions.

In general, it is difficult to satisfy the criteria listed above with one model. The requirement of a rapid initial real-time response limits the complexity that can be included in the first response calculations. For this reason, model type 1 and a simple version of type 2 are candidates for an initial response model, particularly when they are coupled to the data collection system with a mini-computer. A more complex type 2 or type 3 is recommended for the next level response (15 45 minutes after notification), particularly for sites that have complex meteorology and terrain.

Calculation of Projected Dose

As was mentioned at the beginning of this chapter the five important dose calculations for estimating public exposure to a release of radioactive material are:

- External exposure to the plume.
- Inhalation of the plume.
- External exposure to ground deposition.
- Ingestion of contaminated food and water.
- Contamination of ground, pasture and agricultural crops.

Of these five pathways the first two are the most important because of the time factors involved in the potential for public exposure (Δt_1) and the decision making process for implementing protective measures (Δt_2). The decision maker strives for $\Delta t_2 < \Delta t_1$; however, a wide range of variables including time factors of the accident, implementation of assessment methods such as measurements and dose calculations, and execution of the protective measures contribute to the reduction of Δt_2 and thus to the effectiveness of public protection from radiation exposure. The next section is concerned with converting the results of air concentration and ground deposition calculations produced by the atmospheric dispersion models discussed previously to dose calculations for public exposure.

Dose calculation for external exposure

Individual dose from radiation is received in two basic ways: (1) directly from a puff or plume passing overhead or to the side of the person (sometime called cloud-shine) and (2) immersion in the radioactive material. Exposure from the first pathway is the most difficult to estimate because the relationship between population at each point on the ground near the release point and the location and shape of the concentration pattern of nearby radioactive material (within several hundred metres) must be known as a function of time. For each ground location the γ-energies, emitted by the radionuclides, are summed over space and time and converted into individual dose. Methods are available for calculating dose from this pathway;[5] however, most of these methods are complex and require considerable effort to implement satisfactorily.

Once the radioactive material has reached ground level and is dispersed uniformally throughout a hemisphere several hundred metres radius, with respect to the location of a point on the ground, the receptor is assumed to be immersed in the cloud. This is usually referenced to as the "semi- infinite cloud" approximation. Once this assumption is made, then the product of standard dose conversion factors (usually in units of $Sv.m^3/Bg.s$ $(Rem.m^3/Ci.s)$) and integrated air concentration values ($Bg.s/m^3$ $(Ci.s/m^3)$), calculated by the atmospheric dispersion and transport models, provide dose estimates.(11)

Since the close-in dose is difficult to calculate for an elevated effective release height, it may be estimated by using the semi-infinite cloud approximations in the dose calculations. Using this method can underestimate the dose up to several kilometers from the release point for a release height of 100 m and for a stable (F) atmosphere. This underestimate occurs at distances where the material has not reached ground level, thereby producing zero or low air concentration values and dose, although the receptor is receiving a dose from the cloud shine. On the otherhand, near where the plume first makes contact with the ground, the semi-infinite cloud method can overestimate dose because the local concentration pattern does not satisfy the semi-infinite cloud assumption of a uniform distribution of material throughout a hemisphere of several hundred metres radius. If these restrictions are recognized and allowances are made for differences that can occur when dose estimates are made for elevated releases of γ-emitters, then the semi-infinite cloud approximation is a reasonable approximation to use for dose calculations for external exposure. Doses from β-emitters can be calculated using the semi-infinite cloud approximation with little error because of the relatively short (up to several metres) mean free path of the radiation produced by β-emitters.

Dose calculations for inhalation exposure

The dose calculation for inhalation exposure is more straightforward than it is for external exposure, since exposure is directly related to the air concentration at the receptor location as a function of time. The integrated air concentration value (Bg.s/m^3 (Ci.s/m^3)) is the amount of material available during time (t) inhaled by an individual at the receptor location with a specified breathing rate (m^3/s).[12] Therefore, the total activity inhaled by an individual, located at point p, is obtained by multiplying the breathing rate by the integrated air concentration value. Given the dose conversion factor Sv/Bg (Rem/Ci) inhaled for the particular organ and radionuclides of interest, a dose can be calculated for the total activity inhaled. Differences in breathing rates can result in as much as a factor of 5 variation between infant and adult dose.

Dose calculation for ground deposition exposure

Radioactive material can be deposited on the ground by dry or wet deposition and by gravitational settling of particulates. Dry deposition is caused by material (for example, the halogens in the near surface layer of the plume), being deposited on ground level surfaces through impaction with vegetation, buildings and soil. This process continues to deplete the plume as it travels away from the source which is parameterized in models by a deposition velocity.

Wet deposition is caused by radioactive material coming in contact with a precipitation system whereby the reactive gases and particulates (not the noble gases) are scavenged by the precipitation process and deposited on the ground. This is an efficient scavenging process which can lead to high ground levels of radioactivity. Wet deposition is usually parameterized in models by exponentially depleting the radioactive plume and depositing the depleted material on the ground as a function of the precipitation rate.

Gravitational settling of particulates, e.g., cesium or plutonium, is parameterized in some models by calculating a fall velocity of the material based on Stoke's Law, which estimates the fall velocity of a particle as proportional to the radius. Simple models assume a uniform fall velocity for all the particles; the more complex models can specify a particle size distribution that allows larger particles to deposit close to the release point, while smaller particles travel longer distances before deposition occurs.

After the material on the ground has been accounted for by each of the processes mentioned above, the dose at a receptor is calculated by summing the exposure of an individual to each radionuclide deposited on the ground surface. Units of deposition are usually expressed in Bg/m^2 (Ci/m^2) or g/m^2. If g/m^2 are the units used by a model to estimate deposition, then the specific activity, Bg/g (Ci/g), can be used to estimate the activity per unit area deposited on the ground surface. Since most dose conversion constants for deposition are given in $Sv.m^2/Bg.s$ ($Rem.m^2/Ci.s$), the individual dose Sv(Rem) can be calculated by multiplying the dose conversion factor by the activity level per unit area and the time of exposure. The basis for most ground deposition dose conversion factors is the infinite plane assumption, where the receptor point, assumed to be 1 m above the surface, is exposed to γ- radiation (and sometimes β-radiation) emitted from radioactive material uniformally distributed in an infinite plane.

Another potential lower priority exposure pathway resulting from ground deposition, is resuspension of the activity by winds blowing across a contaminated area. Exposure can occur by inhalation of or external exposure to the resuspended material or by ground deposition for the redeposited material. Resuspension processes are not well understood and additional exposure from this mechanism is secondary to the primary exposure from the initial deposition.

Dose calculation for contaminated food and water exposure

Although important for estimating total dose to the exposed population and for estimating requirements for clean-up, if necessary, these dose calculations are secondary in importance to the external, inhalation, and ground deposition dose calculations, particularly in the early phases of an accident. These calculations can be used, for example, in a significant iodine release to determine if milk distribution should be limited, modified or replaced with milk from an uncontaminated region. These dose calculations can also be used to determine if washing vegetables will reduce levels to a safe point or should not be consumed if radiation levels are substantial or if drinking water should be placed under controlled usage due to deposition on the water surface.

Dose conversion factors for the food and water pathways can be found in publications and are also available as a part of dose models that couple ground and water deposition calculations directly to the appropriate dose conversion factor for each nuclide of interest. These dose conversion factors have been developed on the basis of the physical and chemical processes that determine the pathway or pathway through the body and the exposure of the effected organs along this pathway.

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