RADIATION MODELING AND FINITE CLOUD EFFECTS FOR ATMOSPHERIC DISPERSION CALCULATIONS IN NEAR-FIELD APPLICATIONS: MODELING OF THE FULL SCALE RDD EXPERIMENTS WITH OPERATIONAL MODELS IN CANADA, PART II

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Abstract—**Three radiological dispersal devices were detonated in 2012 under controlled conditions at Defence Research and Development Canada's Experimental Proving Grounds in Suffield, Alberta. Each device comprised a 35-GBq source of ^{140}La. The dataset obtained is used in this study to assess the MLCD, ADDAM, and RIMPUFF atmospheric dispersion models. As a continuation of Lebel et al. (2016), this paper examines different methodologies for making dose estimates with atmospheric dispersion models.**
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Key words: contamination, environmental; dose; emergencies, radiological; modeling, environmental

INTRODUCTION

ATMOSPHERIC DISPERSION models calculate the transport and eventual deposition of material released into the air. The models calculate how the airborne material is diluted as the releases mix with the surrounding air, and air concentrations in g m^{-3} or Bq m^{-3} are determined from this. The models track how much material settles out of the plume onto the ground, and the models report ground concentrations in g m^{-2} or Bq m^{-2}. In either case, the dispersion calculations are basically a mass balance, tracking how much material is released and where it goes.

From the point of view of radiological protection, during, for example, the deployment of a radiological dispersal device (RDD), the most important protection quantities would not be those based on the mass of the radioactive material, but would rather be the radiation doses that people in the area would receive. Making predictions of dose parameters from concentration parameters is not totally straightforward, because radiation can be transmitted beyond the boundaries of a radioactive plume. The dose calculations made by a dispersion model depend on the mass and activity concentrations that are predicted but also require that some additional physics be taken into account.

This paper presents Part II of a larger study to evaluate how well currently deployed, operational atmospheric dispersion models can model the dispersion of material released from an RDD. Building on Part I (Lebel et al. 2016), which evaluated the predictive capability of the *Modèle Lagrangien à Courte Distance* (MLCD; Flesch et al. 2002), Atmospheric Dispersion and Dose Analysis Method (ADDAM; Scheier 2009), and Risø Mesoscale Puff model (RIMPUFF; Thykier-Nielsen et al. 1999) atmospheric dispersion models, this paper evaluates how dose-related parameters are obtained and reviews the methodologies that are employed in the context of RDD events. For a validation set, this paper will compare results with the measurements taken during the Full Scale RDD Experiments (Green et al. 2016).

ATMOSPHERIC DISPERSION MODELING METHODOLOGY

Three atmospheric dispersion models were evaluated in Part I of this study (Lebel et al. 2016), and the design and capabilities of each model are presented in detail in that paper. Likewise, a review of how meteorological parameters, the initial cloud size, and the material deposition velocity were handled is given in Part I as well. The three models were MLCD (Flesch et al. 2002), ADDAM (Scheier 2009), and RIMPUFF (Thykier-Nielsen et al. 1999). Each of these tools employs fundamentally different underlying models

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and is used for a variety of purposes by different agencies in Canada.

One of the purposes of Part I of this study was to evaluate how sensitive each of the models would be to different input parameters, with the goal of identifying which factors are the most important in order to obtain reasonably realistic predictions. The main conclusions were:

- In terms of obtaining reasonable predictions for ground deposition, the deposition velocity is the single most important parameter. Since the deposition velocities of the hazardous particles depend very strongly on particle size, having a good understanding of (i) the material properties of the radioactive source material, (ii) the explosive device geometry, and (iii) the overall aerosolization efficiency that results, in advance of obtaining dispersion model predictions, is essential for obtaining realistic results;
- Meteorology is generally important for air concentration predictions, but wind direction, specifically, is vital for knowing the overall direction of the plume; and
- The shape of the cloud and the cloud top height are generally less important than the other parameters, although they can still change predicted results to a certain degree.

RADIATION DOSE MEASUREMENTS FROM THE FULL SCALE RDD EXPERIMENTS

The Full Scale RDD experiments were very comprehensive and well instrumented, and they provide a wealth of information on different aspects of the dispersion, deposition, and dose rates resulting from the RDD releases. Fixed point radiation monitoring, in particular, was carried out using an array of RadEye radiation monitors (Korpach et al. 2016; Erhardt et al. 2016).

There were 225 RadEye monitors deployed, and each recorded the local radiation fields 1 m above ground level on a second-by-second basis. The cumulative cloud shine dose could be determined by integrating the dynamic dose rate measured during the plume passage, while the ground shine dose rate was evaluated as the average dose rate immediately following this dynamic phase. More details on these measurements are given in Korpach et al. (2016) and Erhardt et al. (2016).

PREDICTING GROUND SHINE DOSE WITH ATMOSPHERIC DISPERSION MODELS

In order to obtain realistic predictions of the ground shine dose rates in the aftermath of an RDD event, the most important thing to start with is realistic predictions of the concentration of deposited material on the ground. This was discussed in detail in Part I of this study (Lebel et al. 2016). The most important factor, in addition to having good knowledge of the overall wind direction, is the deposition velocity. Overall deposition predictions are highly dependent on the deposition velocity that is provided to the model being used as input, and this in turn is based on a priori information of the expected particle size and aerosolization effectiveness of the explosive device.

In addition, obtaining realistic ground concentration predictions is non-trivial. For example, decent ground concentration predictions were obtained in Part I (Lebel et al. 2016) for MLCD and ADDAM, but RIMPUFF predicted concentrations that were far below observations. The reason for this was that, in the model, there was a maximum deposition velocity set point, and this value was well below what was expected from source term characterization experiments that were done prior to the full-scale tests (Green et al. 2016; Lebel et al. 2012). Obtaining realistic ground concentration predictions is one issue, but after this, it is another step to extend those predictions into ground shine dose rate predictions.

For radioactivity that is deposited on the ground, the dose rate for a receptor location, $\dot{D}_g = (x_r, y_r)$ and at a height h above ground, the general equation for the ground shine dose rate would be (Lamarsh and Baratta 2001; Thykier-Nielsen et al. 1995):

$$\dot{D}_g = kE_\gamma \frac{\mu_a}{\rho_a} \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} c_g(x,y)\frac{B(\mu\ell)}{4\pi\ell^2}e^{-\mu\ell}dx\,dy, \quad (1)$$

where:

$\dot{D}_g$ = the ground shine dose rate at the receptor;

$c_g(x, y)$ = the concentration of contamination on the ground at position (x, y)

k = a constant equal to 1.602×10^{-16} J·keV^{-1}

E_y = the average gamma ray energy

μ_a, μ = are the linear energy absorption and the linear attenuation coefficients for air

ρ_a = is the density of air

$B(\mu\ell)$ =is the buildup factor

ℓ = the distance magnitude between position (x, y) on the ground and the receptor, where $\ell = \sqrt{x^2 + y^2 + h^2}$.

In polar coordinates, this expression is:

$$\dot{D}_g = kE_\gamma \frac{\mu_a}{\rho_a} \int_0^{\infty}\int_0^{2\pi} c_g(\ell,\theta)\frac{B(\mu\ell)\,r}{4\pi\ell\;\ell}e^{-\mu\ell}d\theta\,dr \quad (2)$$

where $\ell = \sqrt{r^2 + h^2}$.

Solving eqn (2) exactly for a general case, when contamination is heterogeneously distributed on the ground, can be challenging. A common simplifying assumption is to consider that contamination in view of the detector is uniformly

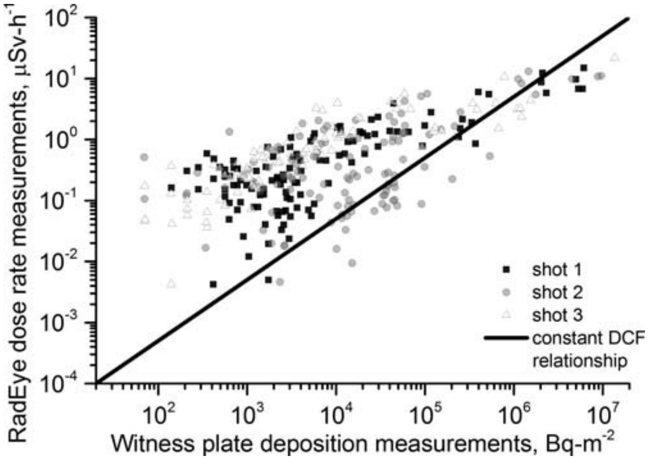

Fig. 1. Co-located ground shine dose rate and ground deposition observations, as measured with the RadEye fixed point detector (Korpach et al. 2016) and on witness plates (Erhardt et al. 2016), respectively. These are compared with the constant dose conversion factor relationship.

distributed along a flat plane. With the concentration term in eqn (2) spatially constant, that expression reduces to:

$$\dot{D}_g = \left[kE_\gamma \frac{\mu_a}{\rho_a}\int_h^\infty \frac{B(\mu\ell)}{2\ell}e^{-\mu\ell}d\ell\right]\cdot c_g = DCF\cdot c_g. \qquad (3)$$

This effectively separates the concentration term from the other terms that contain information about the detector geometry, radiation energy, etc., and this, in turn, allows the non-concentration terms to be collected together and evaluated beforehand as a constant dose conversion factor, *DCF.*

The type of relationship expressed in eqn (3) is very simple to deploy in a dispersion model because dose rate is directly proportional to ground concentration, and it may be reasonable to do so given some of the other uncertainties involved in making atmospheric dispersion model predictions. At large distances from the source, concentrations on the ground would likely be quite uniform, and therefore, as long as the ground is reasonably flat as well, this constant *DCF* methodology would likely be quite accurate. At shorter distances, however, concentration gradients on the ground would be much sharper, and therefore the accuracy of the constant *DCF* methodology would depend on the sensitivity of the general dose-concentration relationship in eqn (2).

As a start, the validity of the constant *DCF* methodology for ground shine can be examined by comparing the dose measurements for ground shine as obtained with the RadEye detectors (Korpach et al. 2016) to co-located field measurements of ground concentration (Erhardt et al. 2016). This is shown in Fig. 1, which demonstrates that, although the constant *DCF* methodology reasonably captures the overall trend, there are areas where it fails to do so. For example, many of the array locations that had fairly low ground concentrations were adjacent to much more highly contaminated areas. As such, the observed radiation dose rates can be much higher than what they would be if the local ground concentration directly below the detector were uniformly distributed around it. This is especially important for areas just off from the main plume, where observed dose rates and those expected by applying the constant *DCF* methodology to the local ground concentration measurements can be different by a factor of up to 10^3.

The validity of the constant *DCF* methodology for ground shine is highly dependent on the uniformity of the ground contamination around the detector, as well as the view factor between the detector and the radioactive material deposited on the ground. For a detector that is 1 m above ground level, its sensitivity to contamination at different radial distances is given by

$$\frac{1}{\dot{D}_g}\cdot\frac{\delta\dot{D}_g}{\delta\ell} = \frac{\frac{B(\mu\ell)}{2\ell}e^{-\mu\ell}}{\int_h^\infty \frac{B(\mu\ell)}{2\ell}e^{-1\mu\ell}d\ell}. \qquad (4)$$

The cumulative contribution of the total dose received by the detector from material up to a certain radial position would, in turn, be

$$\frac{\dot{D}_g(L)}{\dot{D}_g} = \frac{\int_h^L \frac{B(\mu\ell)}{2\ell}e^{-\mu\ell}d\ell}{\int_h^\infty \frac{B(\mu\ell)}{2\ell}e^{-\mu\ell}d\ell}. \qquad (5)$$

The sensitivity and cumulative contribution of radiation given off at different radial locations are shown in Fig. 2. Practically speaking, this shows that, although the detector is more sensitive to contamination that is close by, the radiation given off by material deposited a large distance away could still contribute significantly to the total

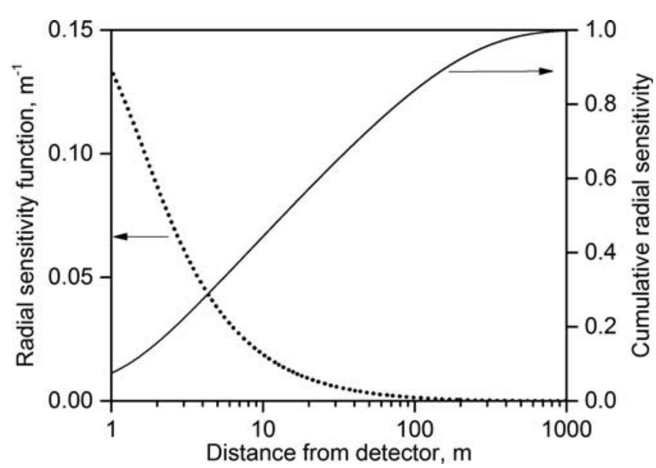

Fig. 2. Sensitivity of a 1-m-high detector to the radiation received from different radial locations from an infinite plane of uniform ground contamination.

dose received by the detector. For a uniform disc of deposited material around a 1-m-high detector, 50% of the radiation dose comes from regions beyond a 14-m radius, 25% of the radiation dose comes from regions greater than 55 m away, and 10% comes from beyond 160 m.

When radioactivity is distributed uniformly enough for these assumptions to hold, the simple constant dose conversion factor should work reasonably well. However, at what length scale is that appropriate? The answer to that, how appropriate it would be to apply these expressions to the near-field modeling of RDD dispersion where there is a high degree of spatial inhomogeneity in the cloud and ground contamination profile, is one of the factors that will be tested in this study.

ADDAM/CSA-ERM (Canadian Standards Association-Emergency Response model, which is the developmental version of ADDAM used in this study) employs a constant dose conversion factor of 7.78×10^{-6} (μSv h^{-1}) (Bq m^{-2})$^{-1}$ to convert its ground deposition predictions into ground shine dose rate values (Scheier 2009). MLCD does not explicitly have this capability, but since it is a simple conversion factor, the same *DCF* as used in ADDAM/CSA-ERM was manually applied to the deposition predictions presented in Part I of this study (Lebel et al. 2016).

RIMPUFF uses a more advanced methodology to calculate ground shine dose from its ground deposition predictions, in that it can solve eqn (2) numerically based on its 50-m by 50-m grid nodalization and does not have to rely on applying a constant *DCF*. That being said, because the current version of RIMPUFF was not able to apply a realistic deposition velocity to its deposition calculations of the full-scale RDD trials, calculated ground concentrations were unrealistically low. Ground shine calculations from RIMPUFF are not presented here as a result.

The ground shine predictions from ADDAM/CSA-ERM and MLCD along the plume centerline and 100 m azimuthal cross section are compared to measurements in Fig. 3. Although predictions along the plume centerline agree quite well, the model predictions using the constant *DCF* methodology for off-centerline locations differ quite significantly from observations.

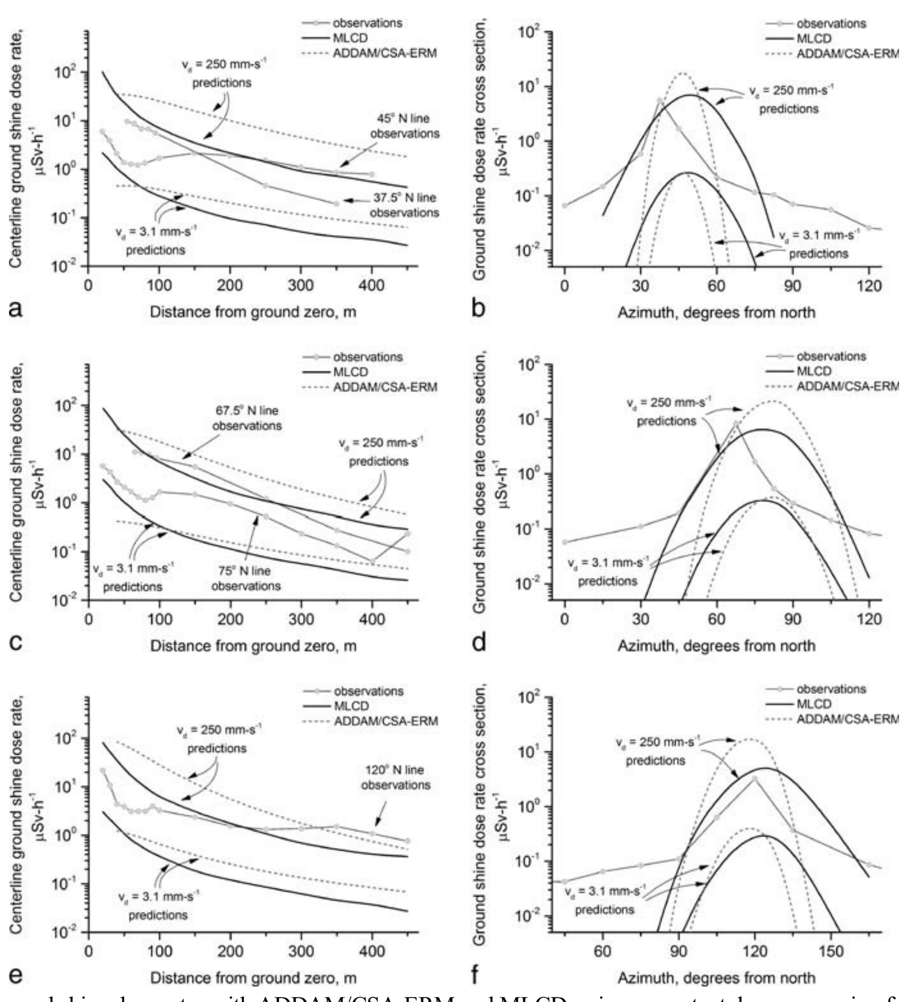

Fig. 3. Predictions of ground shine dose rates with ADDAM/CSA-ERM and MLCD, using a constant dose conversion factor of 5×10^{-6} (μS h^{-1}) (Bq m^{-2})$^{-1}$, and with deposition velocities set to 250 mm s^{-1} and 3.1 mm s^{-1}, and plume centerline height to 5 m: (a) shot 1 centerline, (b) shot 1 cross-section at 100 m, (c) shot 2 centerline, (d) shot 2 cross-section at 100 m, (e) shot 3 centerline, and (f) shot 3 cross-section at 100 m.

The dispersion models employed in this paper have been designed to model atmospheric dispersion processes over much larger length scale than they are being applied to in this study. When examining ground contamination kilometers and tens of kilometers from the release point, it is likely that concentrations would be fairly uniform over length scales of tens of meters. In such far-field cases, employing a constant *DCF* would be a reasonable and robust approach.

In the near-field situation, however, the constant *DCF* methodology does have its shortcomings. In the most important areas of the plume, near the source and along the plume centerline where the ground contamination and dose rates are the highest, the constant *DCF* methodology does perform reasonably well. The caveat and limitation to that is that outside of these regions, where there are steep gradients in the local ground concentration, the constant *DCF* methodology underpredicts dose rates.

That being said, off-centerline dose rates are typically orders of magnitude less than on-centerline dose rates, and from a radiation protection standpoint, being able to realistically model the higher dose rate regions is more important. As long as the limitations associated with off-centerline dose rate predictions are understood, the constant *DCF* methodology would be a reasonable approach to use in near-field situations.

PREDICTING CLOUD SHINE DOSE WITH ATMOSPHERIC DISPERSION MODELS

The radiation transport equations for predicting cloud shine dose from air concentration are analogous to those for ground shine dose from ground concentration (Lamarsh and Baratta 2001; Thykier-Nielsen et al. 1995). The geometric configuration of the radioactive volume, however, is different for the case of cloud shine. At times, the detector can be immersed in the cloud, and the cloud can be above, to the side, and around the detector. Likewise, the cumulative cloud shine must be integrated over time as well. where:

$$D_c = \int_0^\infty \left[kE_\gamma \frac{\mu_a}{\rho_a} \int_0^\infty \int_{-\infty}^\infty \int_{-\infty}^\infty c_a(x,y,z,t) \frac{B(\mu r)}{4\pi r^2} e^{-\mu r} dx\,dy\,dz \right] dt, \quad (6)$$

D_c = the cumulative cloud shine dose at the receptor

c_a (x, y, z, t) = the air concentration of radioactive material at position (x, y, z) and at time t

r = the radial distance from the detector, where $r = \sqrt{x^2 + y^2 + z^2}$

In spherical coordinates, eqn (6) can be expressed as:

$$D_c = \int_0^\infty \left[kE_\gamma \frac{\mu_a}{\rho_a} \int_0^{2\pi} \int_0^{\frac{\pi}{2}} \int_0^\infty c_a(x,y,z,t) \frac{B(\mu r)}{4\pi} e^{-\mu r} \sin\theta\, dr\, d\theta\, d\phi \right] dt. \quad (7)$$

By the same arguments as for ground shine, it is possible to simplify this expression and separate the parameters relating to the cloud geometry and radiation energy from the concentration parameter by assuming that concentration is spatially uniform around the detector:

$$D_c = \left\{ kE_\gamma \frac{\mu_a}{\rho_a} \int_0^\infty \frac{B(\mu r)}{4\pi r^2} [2\pi r(r+h)] e^{\mu r} dr \right\} \cdot \int_0^\infty c_a dt = DCF \cdot < \overline{c_a t} >, \quad (8)$$

where $< \overline{c_a t} >$ is the time integrated air concentration.

The applicability of eqn (8) to a near field, RDD-type scenario once again depends on the validity of the uniform concentration assumption. The sensitivity of eqn (8) to airborne radioactivity at different radial distances in a hemisphere around the detector is given by:

$$\frac{1}{D_c} \cdot \frac{\delta D_c}{\delta r} = \frac{\frac{1}{2} B(\mu r) e^{-\mu r}}{\int_0^\infty \frac{1}{2} B(\mu r) e^{-\mu r} dr}. \quad (9)$$

The cumulative contribution of different radial locations to the dose received by the detector would be as follows, and both of these functions are plotted in Fig. 4:

$$\frac{D_c(R)}{D_c} = \frac{\int_0^R \frac{1}{2} B(\mu r) e^{-\mu r} dr}{\int_0^\infty \frac{1}{2} B(\mu r) e^{-\mu r} dr}. \quad (10)$$

Unlike ground shine, where the sensitivity to contamination at large distances is limited by the view factor between the ground and the detector, the only limitation to far-off sources in the cloud from contributing to the total dose in the detector is the attenuation of radiation in the air. In a uniform cloud, for ^{140}La, 50% of the dose received by the detector would be from airborne radioactivity within about a 200-m radius. To account for 75% and 90% of the total radiation received by the detector, those distances would be about 425 m and 700 m, respectively.

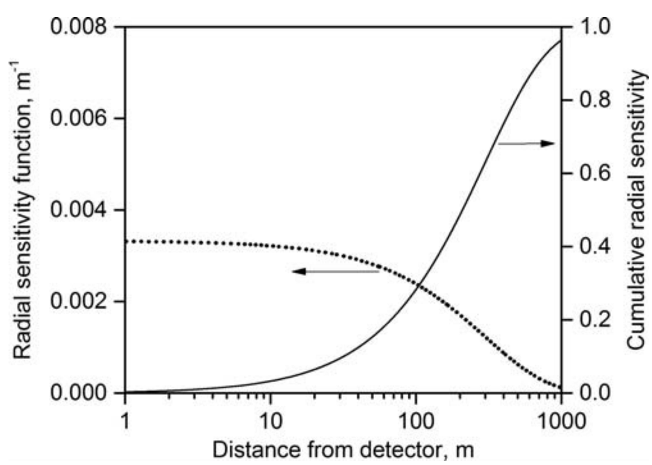

Fig. 4. Sensitivity of the radiation received from different radial locations in a semi-infinite cloud of uniform air concentration for a detector 1 m above ground level.

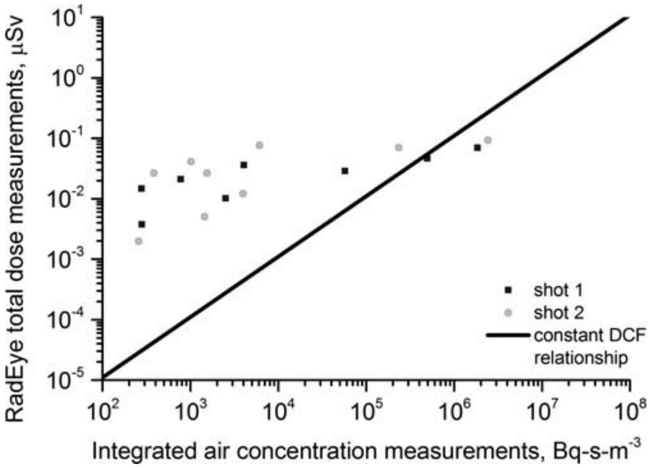

Fig. 5. Co-located ground cloud shine dose and air concentration observations, as measured with the RadEye fixed point detector (Korpach et al. 2016) and with high volume air samplers (Okada et al. 2016), respectively. These are compared with the constant dose conversion factor relationship.

Just by comparing the air concentration (Okada et al. 2016) and cloud shine dose (Korpach et al. 2016) measurements taken during the full scale RDD experiments, as shown in Fig. 5, it is immediately apparent that the constant *DCF* methodology in this case does not accurately describe the relationship between concentration and dose. It is clear from the co-located measurements that the relationship between the two parameters is non-linear and that the cloud shine dose changes much more slowly than air concentration values. Achieving uniformity in the air concentration over length scales of hundreds of meters would not occur in a near field, RDD-type situation. The size of the cloud and the location of the receptor relative to the plume centerline, therefore, would be essential parameters to consider as well.

Taking finite cloud effects into account, therefore, is essential in taking the air concentration predictions made by the atmospheric dispersion engines of the models and using them to determine cloud shine doses. ADDAM/CSA-ERM

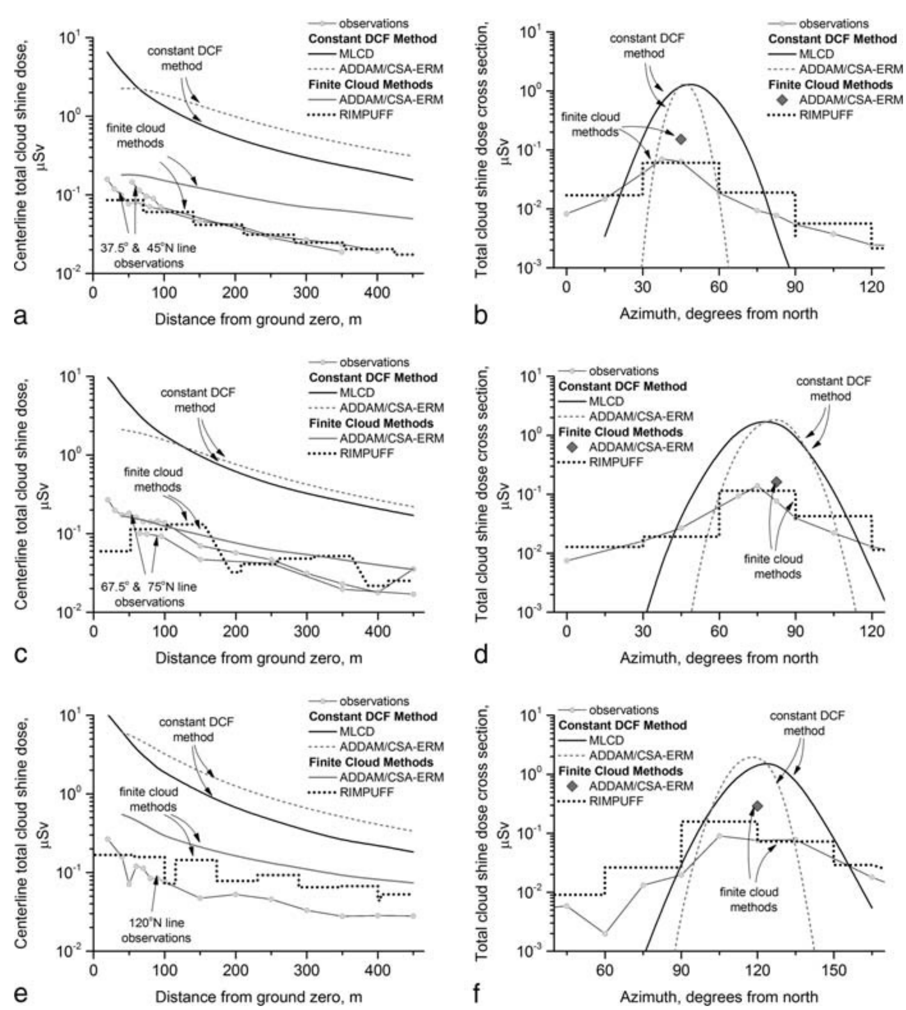

Fig. 6. Predictions of total cloud shine dose, including those with ADDAM/CSA-ERM and MLCD that use a constant dose conversion factor of 1.1×10^{-7} (μSv) (Bq s^{-1} m^{-3})$^{-1}$, and those with ADDAM/CSA-ERM and RIMPUFF with a finite cloud dose calculation method, and with deposition velocities set to 3.1 mm s^{-1}, and plume centerline height to 5 m: (a) shot 1 centerline; (b) shot 1 cross-section at 100 m; (c) shot 2 centerline; (d) shot 2 cross-section at 100 m; (e) shot 3 centerline; and (f) shot 3 cross-section at 100 m.

and RIMPUFF are each able to consider finite cloud effects in their calculations, although they do that in different ways. ADDAM/CSA-ERM, for example, integrates eqn (6) numerically using a 10-m spatial discretization (Scheier 2009). It only has the capability to do this for dose predictions along the plume centerline. RIMPUFF, on the other hand, nodalizes all of its predictions in 50-m by 50-m grids and uses this nodalization to numerically integrate eqn (6) (Thykier-Nielsen et al. 1995).

Cloud shine predictions along the plume centerline and 100-m azimuthal cross section are shown in comparison to dose measurements in Fig. 6. For comparison, results obtained with the finite cloud models in ADDAM/CSA-ERM and RIMPUFF are presented in contrast to those that would be obtained by applying a constant *DCF* of 1.1×10^{-7} (μSv) (Bq s^{-1} m^{-3})$^{-1}$ to the air concentration predictions presented for MLCD and ADDAM/CSA-ERM in Part I of this study (Lebel et al. 2016).

It is apparent in Fig. 6 that, when the finite cloud effects are taken into account, there is much better agreement between the model predictions and the measurements. This applies to both the RIMPUFF and ADDAM/CSA-ERM centerline predictions, as well as the off-centerline predictions made by RIMPUFF. None of the predictions made using the constant *DCF* methodology match observations with centerline predictions that are orders of magnitude higher, and the cross-wind profile drops off much more steeply than observations along the azimuthal cross-sections. These results underline the importance of taking finite cloud effects into account when making cloud shine dose predictions. The results also demonstrate that atmospheric dispersion models can make excellent predictions of cloud shine if finite cloud effects are taken into account.

CONCLUSION

This paper presents Part II of a study to take existing operational atmospheric dispersion models and assess how well they could be applied to the special, near-field case of modeling the dispersion from an RDD. One of the main goals was to identify how realistic and reasonable the sub-models and methodologies within the dispersion models are when applied to near-field situations, and how well different parameters, when applied as inputs to the models, must be defined in order to produce realistic model outputs.

In any model, simplifying assumptions are made to one degree or another in order to make the calculations solvable. Anytime that is done, however, it is also essential to assess the validity of those assumptions and check what the total impact of employing a simplified model vs. a more complicated one would be in trying to best describe reality.

In this paper, the validity of the constant dose conversion factor methodology, which is a simple and fast way to convert concentration predictions into dose and dose rate predictions, is examined. For ground shine, employing a constant *DCF* is fairly reasonable in high concentration regions, like along the plume centerline and near the release point. This is especially true given some of the other uncertainties related to ground deposition, like those associated with the definition of the deposition velocity and particle size. The constant *DCF* methodology, however, does not capture radiation transport from high activity areas to low activity areas and therefore tends to systematically underpredict dose rates in regions that are off from the main centerline of the plume. This is the main limitation of the constant *DCF* methodology when applied to ground shine. That, nevertheless, does not take away from the fact that in the more important areas, which are those along the plume centerline and near the release point where activities are higher, the constant *DCF* methodology does work quite well.

For cloud shine, on the other hand, employing a constant *DCF* methodology for a near-field, RDD-type event would be inappropriate. Given the limited size of the radioactive clouds that would be produced from an RDD, the semi-infinite cloud assumption does not work, especially since the detectors are still relatively sensitive to far off radiation emissions. Uniformity in the air concentration would be required over length scales of hundreds of meters. Finite cloud radiation models must be employed instead, and those in ADDAM/CSA-ERM and RIMPUFF were both able to produce successfully predictions that matched fairly well to the observations made in the full-scale RDD experiments.

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