SIMULATION OF THE PLUME GAMMA EXPOSURE RATE WITH 3D LAGRANGIAN PARTICLE MODEL *SPRAY* AND POST-PROCESSOR *CLOUD_SHINE*

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CONTEXT AND OBJECTIVES

The exposure rate assessment following a release of radionuclides into the atmosphere from a nuclear facility during an accident or under normal operation conditions is an important step regarding the regulatory requirements and the health risk evaluation of such releases.
For computing the exposure rate at a given location, the plume shape and the radionuclides concentration distribution are main parameters. And yet, for the sake of simplicity, an uniform concentration distribution is usually assumed with a plume extending semi-infinitely in all hemispheric directions over a flat terrain. The same principle of modelling is applied to each radionuclide. A 'global' coefficient is calculated in advance taking into account both the flux of gamma rays in the idealized semi-infinite geometry with an unit activity concentration in the atmosphere, and factors to convert the activity flux into the irradiation dose.
Nevertheless, in case of complex meteorological conditions or non-flat terrain with obstacles, it is worth performing a more precise approach. For example, *Ichikawa et al.* (1981) & *Weng et al.* (2003) made use of a Gaussian puff dispersion modelling to evaluate the distribution of the concentration in a radioactive plume and the gamma exposure rate. *Raza and Avila* (2001) implemented a 3D Lagrangian particle model for direct gamma dose rate computations.
Following *Raza and Avila* (2001), we suggest here to use a Lagrangian particle model to take account of the gamma radiation of 3D continuous or transient radioactive plumes. The spatial distribution of discrete particles is computed with *SPRAY*, and the dispersion results are post-processed by a new module called *Cloud_Shine*, especially developed to evaluate the plume exposure rate. In the following, the paper describes the way to use directly *SPRAY* results in order to compute the gamma radiation with *Cloud_Shine*. Some examples of calculations are presented aiming to assess *Cloud_Shine* results in simple geometrical configurations. At the end, the interest of *SPRAY* and *Cloud_Shine* is enlighten in more complicated cases, including a simple relief, a realistic topography, and the presence of buildings with their shadow effects.

DESCRIPTION OF *SPRAY 3.0* DISPERSION MODEL

SPRAY 3.0 (*Tinarelli*, 2001) is a 3D Monte Carlo dispersion code developed by ARIANET & ARIA Technologies. In *SPRAY* modelling, the release of radionuclides from each source is represented by emitting packs of Lagrangian particles whose 3D trajectories in the turbulent flow are computed. *SPRAY* is able to reproduce the advection, dispersion, dry deposition, wet deposition and radioactive decay of particles released in complex meteorological conditions at several spatial scales including the distances between buildings at the urban scale (*Moussafir*, 2004). The velocity of the particles is characterised by a mean component resulting from a wind field prediction or diagnostic, and a stochastic component calculated by *SPRAY* along *Thomson* (1987) theory. *SPRAY* accounts for the vertical and horizontal inhomogeneities of the turbulence, and the asymmetry of the vertical velocity fluctuation distribution in case of convective conditions.

The time history of the *SPRAY* particles positions in the atmosphere is stored, and utilized by *Cloud_Shine* in order to evaluate the direct gamma exposure rates, as explained below.

DESCRIPTION OF *CLOUD_SHINE* POST-PROCESSOR

Equation of the gamma rays flux

The gamma radiation corresponds to the emission of photons during the radioactive decay of nuclides. The energy of the gamma rays ranges from around 10 keV to 10 MeV. The equation describing the photons flux, at the energy level E, emitted by a given radionuclide cloud is:

$$\Phi(E) = \iiint \frac{C(r)\,B(E,\mu r)\exp(-\mu r)}{4\pi r^2}\,d^3r \qquad \textbf{(1)}$$

where $\Phi(E)$ (in Bq.m^{-2}) designates the flux of photons at the energy level E, C (in Bq.m^{-3}) the activity concentration of the radionuclide, B (unitless) the build-up factor representing the scattering of the flux, μ (in m^{-1}) the linear attenuation coefficient in the air and r (in m) the radial coordinate whose origin is the point where the flux of photons is estimated.

There are many equivalent forms of the build-up factor available in the literature. We take the above formula of Berger where *a (E)* and *b (E)* are coefficients depending on the energy level:

$$B(E,\mu r) = 1 + a(E)\mu r \exp\left[b(E)\mu r\right] \qquad \textbf{(2)}$$

Resolution of the equation of the gamma rays flux in a Lagrangian model

In a Lagrangian model, the concentration is not computed directly but is derived from a set of particles positions and masses (in Bq). Therefore, it is less convenient to use equation (1) than to evaluate the flux from the particles themselves. That is why the continuous integral has to be transformed into a discrete sum of all the particles surrounding the location where the flux of photons (or flux or gamma rays) is calculated. This yields to the formula (3):

$$\Phi(E) = \sum_{particles\ i} \frac{B(E,\mu r_i)\exp(-\mu r_i)}{4\pi r_i^2}\,Q_i \qquad \textbf{(3)}$$

where Q_i stands for the radioactivity of the particle *i* (in Bq).

Computation of the gamma exposure rate

The gamma exposure rate *D(E)* (in Sv.s^{-1}) for the specified energy level E is defined as:

$$D(E) = C_b(E)\,I(E)\,E\,\mu_a(E)\,\Phi(E) \qquad \textbf{(4)}$$

where $\mu_a(E)$ (in m^2.kg^{-1}) is the mass coefficient of energy absorption in the air, E (in MeV) the energy level and $I(E)$ (unitless) the gamma rays intensity at the given energy level. $C_b(E)$ (in Sv.Gy^{-1}) converts the dose absorbed in the air to the dose absorbed in the body tissues.

If instead of a continuous spectrum, a set of discrete values E_j is considered for the gamma energy range, the total exposure rate D (in Sv.s^{-1}) reads:

$$D = \sum_{energy\ level\ j} D(E_j) \qquad \textbf{(5)}$$

For a particular radionuclide emitting gamma rays of different energy levels, the parameters contained in formulae (1-5) must be interpolated into the tabulated values given in *Weng et al.* (2003). In the computations described in the paper, the considered radionuclide is xenon 133 (^{133}Xe) whose principal energy levels are 79.61 keV and 80.99 keV with the corresponding intensities of 0.2179% and 36.33%.

Threshold distance

In practice, it is useless to take into account the particles located far from the point where the gamma rays flux is estimated as their contributions become negligible. Thus, a threshold has been defined as the distance beyond that the calculated dose rate is less than about 10^{-20} Sv.s^{-1}. Some numerical tests have been performed to optimize this ‘cutting distance’ which is used in the algorithm to save CPU time.

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VALIDATION OF *CLOUD_SHINE* POST-PROCESSOR

The first assessment of *Cloud_Shine* is achieved by considering the uniform distribution of an irradiating radionuclide in the atmosphere over a flat terrain. As explained in the introductory part of the paper, this academic configuration corresponds to the semi-infinite cloud for which gamma dose rate coefficients were computed and are available in the literature (*Eckerman & Ryman*, 1993). With an unit activity concentration in ^{133}Xe (1 Bq.m^{-3}), the exposure rate takes the value of 1.56 10^{-15} Sv.s^{-1}.
The same computation has been done with *SPRAY* and *Cloud_Shine*. The calculation domain whose dimensions are 50 m x 50 m x 25 m is filled with particles in order to create an uniform cloud of ^{133}Xe with an activity concentration of 1 Bq.m^{-3} (Figure 1). The gamma dose rate is computed on a receptor point located at the bottom of the domain. The results obtained with *Cloud_Shine* are given in Table 2 where the 'cutting distance' is varied to study the sensitivity to this parameter. The results obtained with *Cloud_Shine* and with *Eckerman et al.* dose rate coefficients agree very well, and validate our approach and implementation of *Cloud_Shine.*

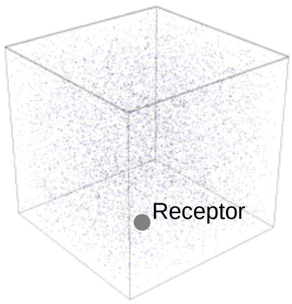

Figure 1: Calculation domain for the validation case.

Table 2: Comparison of the gamma dose rate results with the semi-infinite cloud and Cloud_Shine.

	Semi-infin. Cloud (*Eckerman et al.*, 1993)	*Cloud_Shine*		
		Threshold = 10^{-21} Sv.s^{-1}	Threshold = 10^{-22} Sv.s^{-1}	Without threshold distance
Dose rate (x 10^{-15} Sv.s^{-1})	1.56	1.48	1.49	1.49

EXAMPLES OF USE OF *SPRAY* AND *CLOUD_SHINE*

In the following, *SPRAY* and *Cloud_Shine* are used for more realistic radionuclides releases and meteorological data. The configurations and sites are chosen essentially to point out the shadow effects of topography or obstacles located on the trajectories of radionuclides plumes.

Case #1: Virtual wall along the axis of a plume

In this case, we consider the continuous release of 10^{13} Bq.d^{-1} in ^{133}Xe from a source located at the ground level. The resulting plume extends over a flat terrain in a calculation domain of 500 m x 500 m x 250 m. Some receptors are placed crosswise the plume axis, with the central receptor located at 250 m from the source.
Preliminary to the exposure rate calculation, a virtual 'gamma rays-proof' wall (*i.e.* with zero thickness) is potentially superimposed along the plume axis (Figure 2). The role of the virtual wall is to hide each half-domain from the other half of the total domain.
Figure 3 shows the crosswise profiles obtained on the receptors respectively without any wall and with the virtual wall. As expected when no wall is considered, the maximum dose rate is obtained on the plume axis. On the other hand, with the virtual wall, the maximum dose rate occurs off-axis at the place where the gamma radiation is the most efficient. Indeed, the ^{133}Xe gamma rays are 'short range' and there are less and less particles to contribute to the radiation while reaching the wall. Otherwise, the exposure rate with the virtual wall is a factor of two of the dose rate without wall, only on the axis of the calculation domain. When the crosswise distance to the wall increases, the gamma exposure rate tends to its value with no wall. Notice also that the exposure rate results would be quite different with a real wall (*i.e.* of non zero thickness).

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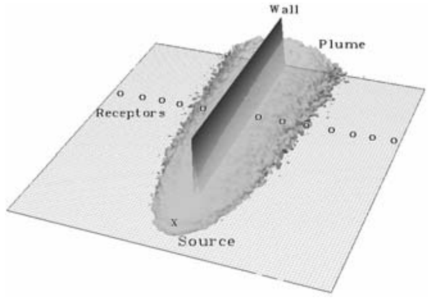

Figure 2: Calculation domain for case #1.Wind velocity 5 m.s^{-1}. Neutral atmosphere.

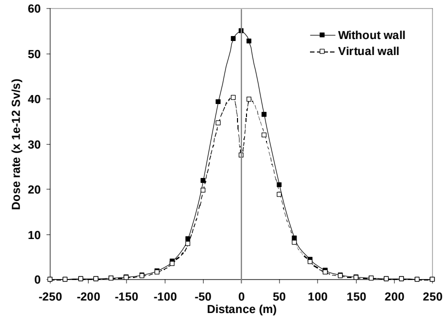

Figure 3: Dose rate against cross distance.

Case #2: Geometrical hill

As in the previous configuration, we consider the plume due to the continuous release of 10^{13} Bq.d^{-1} in ^{133}Xe from a source located at 20 m above the ground level (AGL). The horizontal dimensions of the calculation domain are 10 km x 10 km.

A geometrical hill is placed just beyond the plume axis, at 1.8 km to the right. The hill is 800 m high, and 2 km large at the ground level.

As shown on opposite Figure 4, the hill produces a noticeable modification in the gamma dose rate close to the ground level for points located in the shadow of the academic relief. This configuration clearly illustrates the influence of the topography on the gamma exposure.

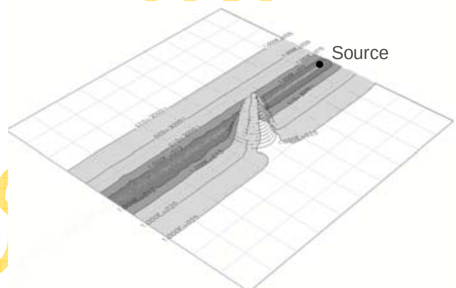

Figure 4: Dose rate near the ground level. Wind velocity 5 m.s^{-1}. Neutral atmosphere.

Case #3: Real topography

In this case, a continuous release of ^{133}Xe is performed at 100 m AGL, with an activity rate of 10^{14} Bq.s^{-1}. A 'real' topography is taken into account in a calculation domain with horizontal dimensions 30 km x 30 km x 10 km. Figure 5 gives a 3D view of the xenon plume extending over the considered relief. Figure 6 presents two 2D views of the gamma dose rates. For the same distribution of particles, the left part of the figure addresses the topography effect on the dose rate computation whereas the right side ignores the terrain configuration. The two results are significantly different as the ridge separates a 'leeward' part of the relief from the rest of the topography. The mountainous nature of the terrain is propitious to the shielding from the gamma radiation of some places in the domain.

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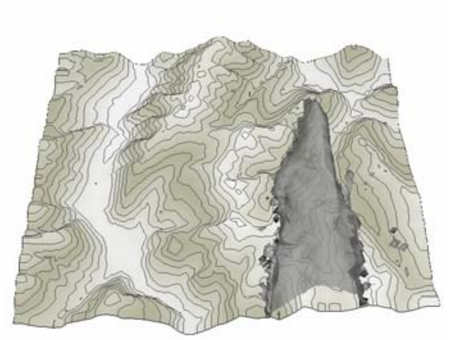

Figure 5: Dispersion of the ^{133}Xe plume. Contour lines of the real topography.

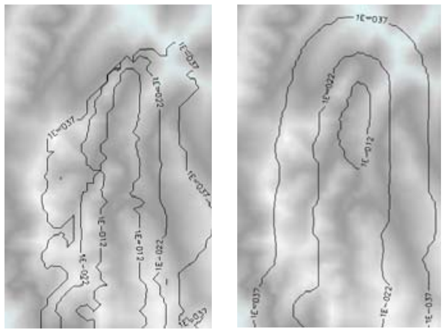

Figure 6 : Influence of the topography on the gamma exposure at ground level.

Case #4: Influence of buildings

Work in progress on *Cloud_Shine* concerns the influence of buildings on the gamma exposure rate. Figure 7 is an example of a configuration with particles trapped in a cubic box (with edge 30 m; 10^{17} Bq in ^{133}Xe) between two buildings (40 m long x 10 m large x 40 m high).

One will notice that on both lateral sides of the buildings, the dose rate is different from zero even though there aren't any particles. On the other hand, the gamma exposure rate is none in two large areas in the shadow of the buildings. Indeed, at this scale, the dose rate computation with *Cloud_Shine* appears extremely different from the semi-infinite cloud approach.

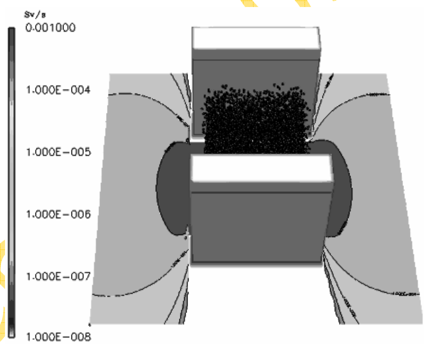

Figure 7: Influence of buildings on the gamma dose rate. Domain: 100 m x 100 m x 200 m

CONCLUSION AND PERSPECTIVES

The computation of 3D radioactive plumes gamma exposure is carried out making use of the Lagrangian particle model *SPRAY* and the especially developed *Cloud_Shine* post-processor. The modelling suite has been assessed for an uniform distribution of a radionuclide over a flat terrain where *SPRAY* & *Cloud_Shine* results are directly comparable with values of the semi-infinite irradiation dose coefficients tabulated in the literature.

Several configurations have been studied principally to demonstrate the shadow effects of the relief or obstacles located on the trajectories of the radionuclides plumes. In the whole cases, the impingement of the radioactive plume on the obstacles clearly modifies the exposure rates respectively at the both sides of an artificial wall, in the leeward of an academic hill or a real topography, and behind the protected sides of buildings and streets.

Having a routine algorithm to compute gamma dose rate in acceptable CPU time opens new perspectives to assess the impact of radioactive releases in the vicinity of buildings and in the urban context. As the direct measurement is most often the gamma exposure rate, this method should also be relevant to improve the inverse algorithm used to determine a source term from available measurements.

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