AN EFFECTIVE METHOD FOR CLOUDSHINE DOSE CALCULATION FROM RADIOACTIVE CLOUD DRIFTING OVER THE TERRAIN

Petr Pecha and Radek Hofman

Abstract: One specific method is proposed for fast real-time calculations of cloudshine doses/dose rates used for purposes of online assimilation of model predictions with observations from terrain. Model predictions of cloudshine doses are calculated in an array of measurement sensors located on terrain around a nuclear facility. A certain modification of classical straight-line Gaussian solution of the near-field dispersion problem is proposed. Further radioactive cloud movement driven by changing meteorological conditions is described according to segmented Gaussian scheme. The n/μ method introduced for photon transport in the ambient air ensures fast generation of predicted external irradiation doses. Application on accidental release scenario with mixture of discarded nuclides and large sensor network predetermines the proposed procedure such a proper tool for data assimilation analysis.

Key words: *Radioactivity release, photon fluency, cloudshine doses, data assimilation.*

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INTRODUCTION

Decision-making staff should be provided on time by reliable predictions of time and space evolution of contamination. It can be achieved on basis of optimal blending of all information resources including prior physical knowledge given by model, observations incoming from terrain, past experience, expert judgment and intuition. According to these prognoses the urgent emergency actions have to be planned and launched in the most impacted areas. Measured and calculated doses/dose rates of external irradiation from radioactive cloud are basic inputs to the objective analysis of data assimilation techniques. Assimilation procedures require as accurate as possible determination of the values of interest in positions of measurement devices (sensors). The sensors are part of Early Warning Network (EWN) and ground and airborne mobile monitoring groups. Stable fixed net of sensors is represented by teledosimetric system (TDS) on fence of a nuclear facility and additional circles of measuring devices in the outer distances. Emergency preparedness procedures should account for integration

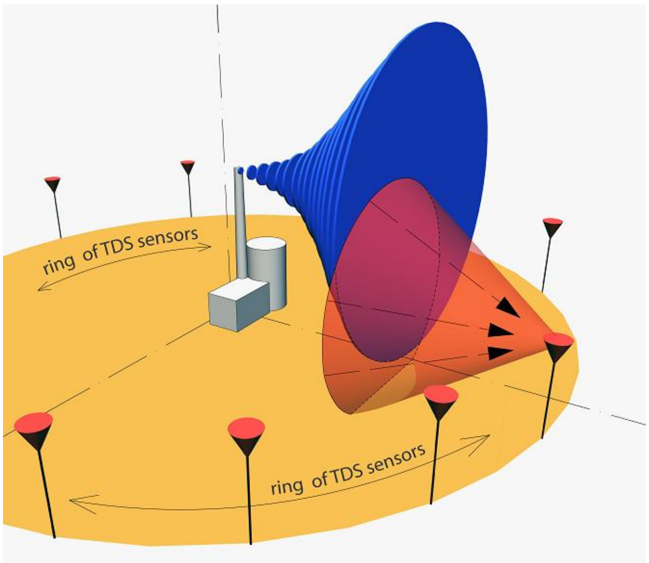

Figure 1. Schematic illustration of ring of TDS sensors around NPP.

of observations from all types of measuring devices during emergency situation (fixed stations, temporary deployed stations, mobile monitoring vehicles, pilotless aircrafts). The differences in measurement locations between model predictions and measurements are expressed by the vector of innovations. Common principle of the objective analysis for optimal blending of model predictions with observations includes the update step with data incoming from terrain followed by the model prediction in the next time step. Sophisticated advanced statistical methods are based on Bayesian recursive tracking of the toxic plume progression. The corresponding likelihood function used within Bayes' theorem relates measured data to the model parameters. In all cases the realistic dose/dose rate estimation is crucial.

In this article a special fast algorithm is proposed for effective estimation of cloudshine doses/dose rates from radioactive cloud spreading over idealised flat terrain. In the early phase of accident the pollution from the source passes the ring of TDS sensors surrounding a nuclear facility. Recurrence scheme is proposed for substitution of three-dimensional integration by stepwise two-dimensional one. We assume a ring of sensors on fence of a nuclear power plant (NPP) according to the sketch in Figure 1, more detailed scheme belonging to the real NPP is in Figure 5 below. The aim of analysis is simulation of time evolution of sensor responses from the same beginning of release. The innovation vector enters successive assimilation process with aim to improve the estimation of source term characteristics and further important model parameters (wind field characteristics given by initial short term meteorological forecast, dispersion characteristics of the plume, dry deposition velocity etc.). Taking into account the model and measurement structure of errors an actual forecast of expected movement of the cloud and extent of dangerously affected areas can be anticipated properly.

PREDICTIONS OF HARMFUL ADMIXTURES PROPAGATION AT NEAR DISTANCES FROM THE SOURCE

We shall adopt a classical solution of diffusion equation for description of the initial phase of radioactive discharges drifting (near-field model). 3-D distribution of specific radioactivity concentration C^n of nuclide *n* in air [$Bq.m^{-3}$] is expressed by the straight-line Gaussian solution. The approach has long tradition of its use for dispersion predictions. Even simple, the Gaussian model is consistent with the random nature of turbulence (Hanna, Briggs and Hosker, Jr.,1982), it is a solution of Fickian diffusion equation for constant diffusivity coefficient *K* and average plume velocity $\bar{u}$, the model is tuned to experimental data and offers fast basic estimation with minimum computation effort. Proved semi-empirical formulas are available for approximation of important effects like interaction of the plume with *near-standing buildings*, momentum and buoyant *plume rise* during release, power-law formula for estimation of wind speed *changes with height*, *depletion* of the plume activity due to *removal processes* of dry and wet deposition and decay, dependency on *physical-chemical forms* of admixtures and *landuse characteristics*, simplified account of *inversion* meteorological situations and plume *penetration of inversion*, plume *lofting* above inversion layer, account for small changes in *surface elevation, terrain roughness* etc.

It is evident, that straight-line solution is limited for its use to short distances from the source (up to several kilometres corresponding to the first hour (half an hour) of the short term meteorological forecast). In the further phases of the plume drifting the meteorological conditions have to be considered more realistically. For this purposes a segmented Gaussian plume model (SGPM) is introduced (Hofman and Pecha, 2011) which takes into account the hourly (half-hourly) changes of meteorological conditions given by short term forecast (48 hours forward) provided by the meteorological service. Complicated scenario of release dynamics is synchronized with the available meteorological forecasts so that drifting of radioactive plume over the terrain can be approximated satisfactorily. Let return to the initial interval of propagation, when the shape of the plume spreading is simulated by “Gaussian droplet” coming out from the simplified solution of the diffusion equation in the form:

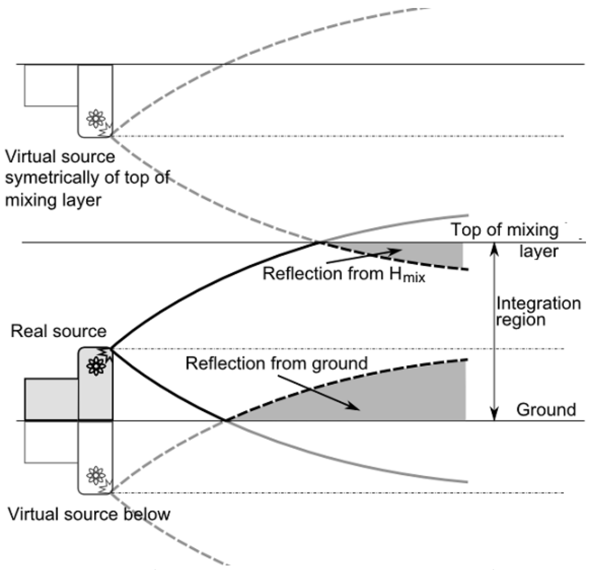

Figure 2. Chart of straight-line Gaussian solution with reflections.

$$C^n(x,y,z) = \frac{A^n}{2\pi \cdot \sigma_y(x) \cdot \sigma_z(x) \cdot \bar{u}} \cdot \exp\left(-\frac{y^2}{2\sigma_y^2(x)}\right) \left[\exp\left(-\frac{(z-h_{ef})^2}{2\sigma_z^2(x)}\right) + \exp\left(-\frac{(z+h_{ef})^2}{2\sigma_z^2(x)}\right) + \right. \quad (1)$$

$$\left. + \exp\left(-\frac{(z-2H_{mix}+h_{ef})^2}{2\sigma_z^2(x)}\right) + \eta_{JV}(z) \right] \cdot f_R^{\,n}(x) \cdot f_F^{\,n}(x) \cdot f_W^{\,n}(x)$$

$C^n(x,y,z)$	Specific activity of radionuclide *n* in spatial point (*x,y,z*) in [Bq/m^3]; *x* – direction of spreading; *y, z* – horizontal and vertical coordinates
$\sigma_y(x)$, $\sigma_z(x)$	Horizontal and vertical dispersions at distance x from the source [*m*]; expressed by empirical formulas
A^n	Release source strength of radionuclide *n* [*Bq/s*]; constant within time interval
$\bar{u}$	Mean advection velocity of the plume in direction *x* [*m/s*]
h_{ef} , H_{mix}	Effective height of the plume axis over the terrain [m], height of planetary mixing layer [m]
$\eta_{JV}(z)$	Effect of additional multiple reflections on inversion layer/mixing height and ground (for this near-field model hereafter ignored)
f^n_R , f^n_F , f^n_W	Plume depletion factors due to radioactive decay and dry and wet deposition - dependant on nuclide *n* and its physical-chemical form (aerosol, organic, elemental). The factors stand for “source depletion” approach introduced into the classical straight-line Gaussian solution. Release source strength at distance *x* is depleted according to $A^n(x, y=0, z=h_{ef}) = A^n(x=0, y=0, z=h_{ef}) \cdot f^n_R(x) \cdot f^n_F(x) \cdot f^n_W(x)$.

The exponential terms in equation (1) mean from left to right the basic diffusion growth of the plume, its reflection in the ground plane and its reflection from the top of mixing layer H_{mix} . The reflections are illustrated schematically in Figure 2 (shaded areas).

A NEW ALGOIRITHM FOR FAST EVALUATION OF EXTERNAL IRRADIATION FROM THE CLOUD

We shall consider physical quantity of photon fluency which represents number of γ photons passing thru a specific area. Transport of photons with energy E_γ from the source of emission to receptors R will be described by the quantity of photon fluency rate $\Phi(E_\gamma , R)$ in units ($m^{-2}.s^{-1}$). External exposure from finite plume is estimated when applying traditional methods based on three-dimensional integration over the cloud (e.g. ADMS 4, 2009) or on specially constructed three-dimensional columned space divided on many finite grid cells (e.g. Wang, Ling and Shi, 2004). Moreover, an application of $5/\mu$ method brought substantial improvement of calculation effectiveness. Photon fluency rate in the receptor point R from a point source with release strength A (Bq/s) is calculated according to equation (2a). Estimation of the fluency rate $\Phi(E_\gamma , R)$ from the whole plume based on the three-dimensional integration is given by the scheme (2b).

$$\Phi\left(E_\gamma, R\right) = \frac{A \cdot B\left(E_\gamma, \mu \cdot |\vec{r}|\right) \cdot \exp\left(-\mu \cdot |\vec{r}|\right)}{4\pi\, |\vec{r}|^2} \qquad (2a)$$

$$\Phi_{total}\left(E_\gamma, R\right) = \iiint_{V_{mrak}} \frac{f \cdot C(\vec{r}) \cdot B\left(E_\gamma, \mu \cdot |\vec{r}|\right) \cdot \exp\left(-\mu \cdot |\vec{r}|\right)}{4\pi\, |\vec{r}|^2} dV \qquad (2b)$$

$B\left(E_\gamma, \mu \cdot |\vec{r}|\right)$ stands for build-up factor. We use either its linear form $B\left(E_\gamma, \mu \cdot |\vec{r}|\right)$ = 1 + k.μ.r ($k=(\mu-\mu_a)/\mu_a$, μ and μ_a are linear and mass attenuation coefficients) or alternative Berger formula. Comparison of the two options can be found in literature, e.g. in (Overcamp 2007). f is branching ratio to the specified energy E_γ .

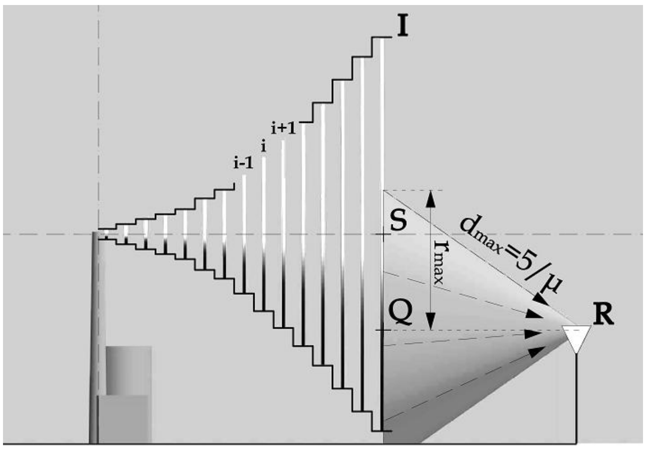

Figure 3:Segmentation of continuous release into equivalent disc sequence.

$|\vec{r}|$ is distance between receptor point R and element of the plume. Activity concentration is given by analytic equation (1) and its Gaussian shape is schematically illustrated in Figure 1. Continuous and constant release in direction of axis x with average velocity $\bar{u}$ is segmented into equivalent number of elliptic discs according to Figure 3. Thickness of discs is selected as Δx = 10m. The centre of the disc *i* reaches the position $x_i = (i\text{-}1/2)\times\Delta x$ during $x_i / \bar{u}$ seconds. Lumped parameter technique is introduced when model parameters are averaged within interval Δx on the disc i. Distribution of the activity concentration in the disc i on plane $x = x_i$ (it means the average value on Δx) is driven according to the straight-line equation (1) where the corresponding averaged disc parameters are inserted (e.g. x_i, $\sigma_y (x_i)$, $\sigma_z (x_i)$ and depletion $f_R(x_i) \cdot f_F(x_i) \cdot f_W(x_i)$ etc.).

The $5/\mu$ method (generally n/μ method – we have tested n=5,10,15) imposes integration limit up to d_{max} and indicates such significant only those sources of irradiation lying up to distance $5/\mu$ from the receptor R. Integration boundary (see also integration circle in Figure 4) is formed by intersection of the cone (receptor R in the cone vertex) and the plane of the newest disc I. Only those points located inside contribute to the fluency rate at R. This accelerates markedly computational speed and improves capability to run successfully the assimilation procedures in the real time mode. It overtakes the computationally expensive traditional methods based on full 3-D integration techniques (Raza, Avilla and Cervantes, 2001). Substantial performance improvement predetermines the $5/\mu$ approach for its application during nuclear emergency situations (Wang, Ling and Shi, 2004). Minor differences from other traditional methods are referred for broad range of input model parameters (stability classes, axial distances, source term characteristics etc.).

REPLACEMENT OF TRADITIONAL 3-D INTEGRATION BY STEPWISE 2-D COMPUTATIONAL SCHEME BASED ON A LUMPED PARAMETER APPROACH

Following the above considerations we have assumed the external irradiation from the plume segment on interval <x_i-$\Delta x/2$; x_i+$\Delta x/2$> to be substituted by equivalent effect of the disc of thickness Δx with lumped model parameters on <x_i-$\Delta x/2$; x_i+$\Delta x/2$>. Let analyse contribution from the elliptical disc I from Figure 3 to the fluency rate at receptor R. A lateral view of the segmented plume propagation is demonstrated in Figure 3. The same situation is outlined in the front view in Figure 4. The boundary of integration region lying in the plane of disc I is based on $5/\mu$ approximation (bold dashed line composed of the part of circle above ground with radius r_{max} and centre in the point Q). For r_{max} holds true the relationship $r_{max}^2 = (5/\mu)^2 - [x(R) - x(Q)]^2$. Contribution of the disc I to the photon fluency rate at receptor R is given by:

$$\Phi\left(E_\gamma, R, I\right) = \frac{\Delta x}{4\pi} \int_{r=0}^{r\max} \int_{\varphi=0}^{2\pi} \frac{C^I\left(x_I; r, \varphi\right) B\left(E_\gamma, \mu.d\right) \exp\left(-\mu.d\right)}{d^2}\, r\, d\varphi\, dr \qquad (3)$$

Referring to Figure 4, d is distance between points R(x(R),y(R),z(R)) and M(x(S), y(M), z(M)); $d^2 = (x(S) - x(R))^2 + (y(M) - y(R))^2 + (z(M) - z(R))^2$; $x(S) = x_I = (I\text{-}1/2)\times \Delta x$ is a distance of centre of the disc I from the release point; $y(M) = r\times\sin(\varphi)$; $z(M) = z(R)+r\times\cos(\varphi)$. The equivalent mean activity concentration $C^I(x_I , y, z)$ in disc I is expressed using equation (1) where index n is omitted. Valid values of coordinate z should be positive, dispersion coefficients and depletion factors are calculated for position x_I (it means for time $x_I / \bar{u}$ seconds) in dependence on physical-chemical form of nuclide. Equivalent disc source strength substitutes the original discharge according to A (x_I, y=0,z= h_{ef}) =A (x=0, y=0,z= h_{ef})· $f_R (x_I) \cdot f_F (x_I) \cdot f_W (x_I)$. During computation the values of photon fluency rates are successively stored into the array F(1:N_{sens}, 1:I_{total}). N_{sens} means the number of receptors being simultaneously taking into account, I_{total} stands for total number of the 10-meter segments of the plume separation (so far selected value I_{total} = 720). Total fluency rates, total fluency and corresponding total cloudshine doses/dose rates are generated by summing up the values in particular time steps. Taking $\Phi(E_\gamma, R, I)$ according to the equation (3), the following pre-processing of the array F provides the desired values.

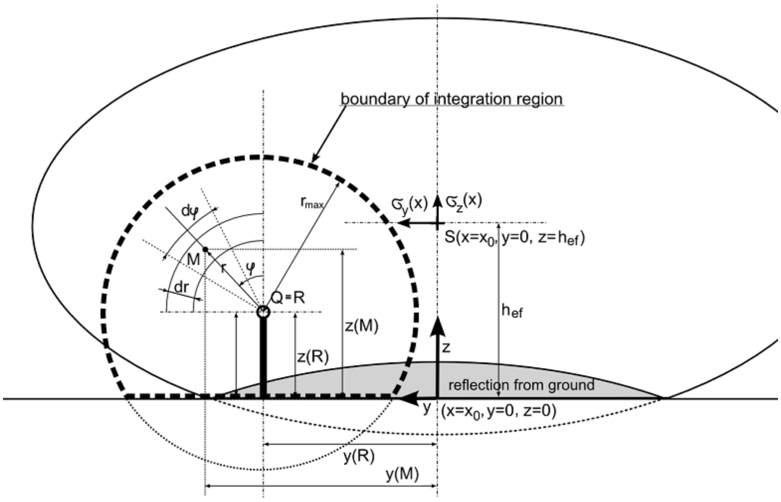

Figure 4. Frontal view from receptor point R to elliptical disc I and circular integration region.

We are distinguishing two situations:

Continuous release of admixtures still lasts: The plume has reached position of the disc I. Propagation to the I+1 disc is in progress. Contribution of each elemental disc i=1, ..., I to the fluency rate $\Phi(E_\gamma, R, i)$ at receptor R was calculated in the previous steps and stored in the array F. The new contribution $\Phi(E_\gamma, R, I+1)$ from disc I+1 is calculated using integration (3). Recurrent formula for overall fluency rate at receptor R can be formally rewritten as:

$$\Phi\left(E_\gamma, R, i=1,\ldots,I+1\right) = \Phi\left(E_\gamma, R, i=1,\ldots,I\right) + \Phi\left(E_\gamma, R, I+1\right)$$
$$\textit{where} \qquad \Phi\left(E_\gamma, R, i=1,\ldots,I\right) = \sum_{i=1}^{i=I} \Phi\left(E_\gamma, R, i\right) \tag{4}$$

Then, the only computation effort insists in evaluation of 2-D integration of the latest disc I+1. Analogously, the recurrent formula for entire photon fluency at receptor R from the same beginning of release is given by:

$$\Psi\left(E_\gamma, R, i=1,\ldots,I+1\right) = \Psi\left(E_\gamma, R, i=1,\ldots,I\right) + \sum_{i=1}^{i=I+1} \Delta t_i \cdot \Phi\left(E_\gamma, R, i\right)$$
$$\textit{where} \qquad \Psi\left(E_\gamma, R, i=1,\ldots,I\right) = \sum_{i=1}^{i=I} \left[\left(I+1-i\right)\cdot \Delta t_i \cdot \Phi\left(E_\gamma, R, i\right)\right] \tag{5}$$

$\Delta t_i = \Delta t = \Delta x / \bar{u}$ seconds

Release terminated, propagation continues: Let the plume has reached position of the disc I just at moment when the release has terminated. Propagation continues to the discs positions I+1, I+2, ..., I+j. Fluency rate $\Phi(E_\gamma, R, I+j+1)$ for position I+j +1 is calculated from the previous position I+j according to recurrent formula:

$$\Phi\left(E_\gamma, R, i=1,\ldots,I+j+1\right) = \Phi\left(E_\gamma, R, i=1,\ldots,I+j\right) + \Phi\left(E_\gamma, R, I+j+1\right) - \Phi\left(E_\gamma, R, j+1\right) \tag{6}$$

Hence, contribution from the leftmost disc of a parcel is skipped, the new rightmost one is calculated. Similar considerations lead to recurrent expression for the total fluency Ψ:

$$\Psi\left(E_\gamma, R, i=1,\ldots,I+j+1\right) = \Psi\left(E_\gamma, R, i=1,\ldots,I+j\right) + \sum_{i=j+1}^{i=I+j+1} \Delta t_i \cdot \Phi\left(E_\gamma, R, i\right) \tag{7}$$

SIMULATION OF RESPONSES FROM SENSOR NETWORK

Here we present the responses on 40 sensors surrounding NPP according to Figure 5 consisting of a ring of 24 TDS sensors on fence of NPP with distances roughly about 450 meters from a hypothetical source, the rest of sensors are situated in larger distances inside emergency planning zone. Our approach is demonstrated on release of nuclide ^{131}I with E_γ = 0,3625 MeV (γ yield is taken to be 100 %, linear attenuation coefficient μ =1.40531E-02 (m^{-1}), mass attenuation coefficient μ_a = 3.30969E-03 ($m^2.kg^{-1}$)). Mean free path 1/μ= 7.12E+01 m, 5/μ = 3.56E+02 m, 10/μ = 7.12 E+02 m. Time evolution of fluencies/ fluency rates and cloudshine doses/dose rates from one hour continuous release strength 9.0 E+14 Bq/hour of ^{131}I activity are simulated on all 40 sensors at one course. Effective height h_{ef} of the release is 45 m, Pasquill categories of atmospheric stability F and D are examined (wind velocity in 10 m height u_{10}=1.0 m.s^{-1} resp. 3.0 m.s^{-1}). Short term meteorological forecast belongs to 20080114_18 (January 11th, 2008, 18.00 CET), wind blows in direction 273 deg. In Figure 5 are illustrated the results for sensors TST 01 resp ETEL17 (roughly 400 meters resp 4 000 m in direction of the plume propagation). Many various outputs were generated covering both the tests of algorithms and routine scenario analysis. The method n/μ was examined for n=5 and n=10 but the differences are too small (no more than 1%) to be visualised in Figure 6. The calculations for n=5 are more than thrice faster in comparison with n=10. Verification of numerical algorithm of integration expressed by equation (3) has been accomplished here in Appendix A on basis of comparison with analytical solution of the equation (3) for a special case without absorption (μ=0) and built-up factor B=1 (simplified experiment - "irradiation in vacuum").

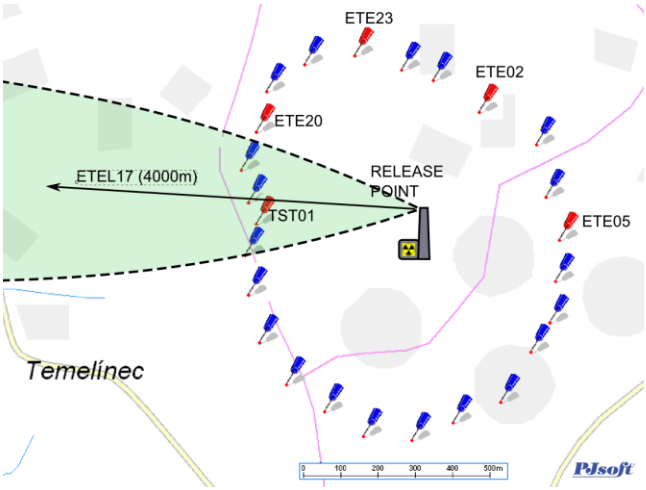

Figure 5. Configuration of sensor network around nuclear facility

As for atmospheric stability, Pasquill classes F and D were analysed. At the same time the contribution of reflections from ground and top of mixing layer were estimated. The values of fluency rates at ground-level sensors are more than twice lower when the reflections are incorrectly neglected.

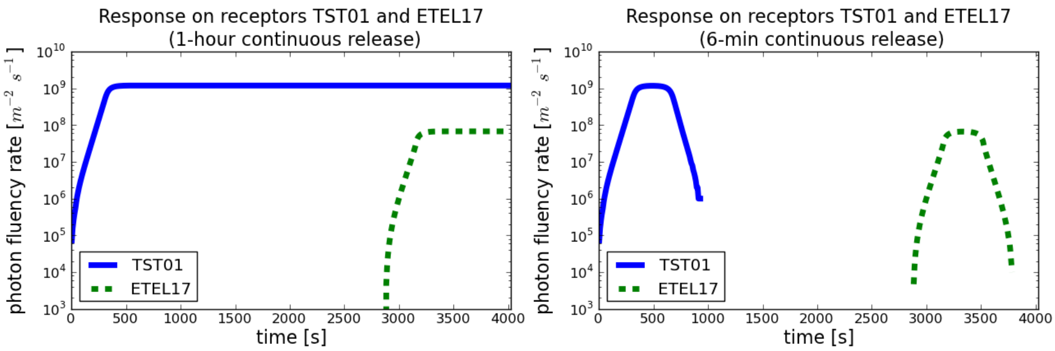

Figure 6. Sensor response in photon fluency rate on the plume drifting. Both sensors are roughly in direction of propagation, TST01 at distance about 400 m from the source, ETEL17 at about ten times larger). Left: Continuous one hour spreading (up to 4025 s ~ 4960 meters). Right: Spreading of smaller plume of 6 min duration. Interpretation: Responses on receptors from the whole plume at time t (from the beginning of release).

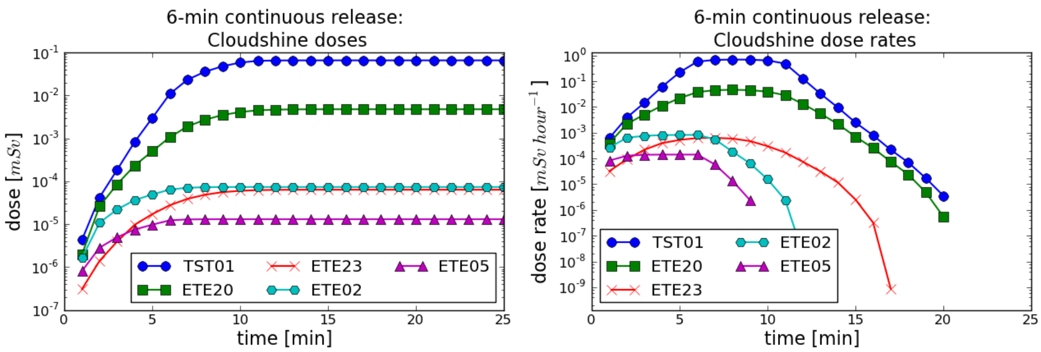

Figure 7. Sensor response in doses and dose rates from smaller 6-minute release duration. Selection of sensors according to Figure 5.

Irradiation dose rates at receptor R is marked as $H(E_\gamma, R, I)$ (Gy.s^{-1}) and results for monoenergetic photons with energy E_γ emitted from disc I . It can be calculated from fluency rates (see equation (3)) according to:

$$H(E_\gamma, R, I) = \frac{\omega \cdot K \cdot \mu_a \cdot E_\gamma}{\rho} \cdot \Phi(E_\gamma, R, I) \qquad (8)$$

Conversion factor K = 1.6 E10^{-13} Gy.kg.Mev^{-1} ; ω = 1.11 is a ratio of absorbed dose in tissue to the absorbed dose in air, air density ρ=1.293 kg.m^{-3} , other quantities were described above. In fact, the equation (8) stands for absorbed doses expressed in grays. Common practice in the radiation protection field is to multiply absorbed doses by relative biological effectiveness factor F_q which accounts for different biological damage with regards to different types of ionizing radiation. Corresponding radiological quantity is expressed in Sv (sieverts). F_q =1 for photons and therefore we shall express doses in the following text and graphs rather in units of Sv.

ACCOUNTING FOR MULTIPLE NUCLIDE GROUP

For radionuclide n emitting multiple photons p of different energies E^n_p we assume those photons having noticeable yields f^n_p (e.g. greater than 0.01). Following the equation (8) the general expression for dose rate in $Sv.s^{-1}$ from multiple nuclides/multiple photons case can be rewritten as:

$$H(R,I)=\sum_{(n)} H^n(R,I)=\frac{\omega\cdot K}{\rho}\sum_{(n)}\sum_{(p)}\mu_a\left(E_p^n\right)\cdot f_p^n\cdot E_p^n\cdot\Phi\left(E_p^n,R,I\right) \qquad (9)$$

Corresponding dose in Sv can be calculated when substituting fluency rate Φ by entire photon fluency Ψ expressed by equation (5) or (7). Reduction of computational load can be done by averaging the photon energies for nuclide n according to:

$$\overline{E}^n=\sum_{(p)} f_p^n\cdot E_p^n \Big/ \sum_{(p)} f_p^n \qquad (10)$$

Subsequent simplified formulation for dose rate is assumed according to:

$$H(R,I)=\sum_{(n)} H^n(R,I)=\frac{\omega\cdot K}{\rho}\sum_{(n)}\mu_a\left(\overline{E}^n\right)\cdot\overline{E}^n\cdot\Phi\left(\overline{E}^n,R,I\right) \qquad (11)$$

Hypothetical release of nuclide mixture is illustrated in the Table 1. Subdivision to six energetic groups is supposed with energies in intervals 0.03-0.1, 0.1-0.6, 0.6-1.2, 1.2-1.8, 1.8-2.4, >2.4 MeV.

Table 1: Hypothetical source term and averaged photon energy according to equation (10) .

radionuclide	^{41}Ar	^{88}Kr	^{131}I	^{132}I	^{135}I	^{132}Te	^{133}Xe	^{135}Xe	^{134}Cs	^{137}Cs
activity release strength (Bq/hour)	1.2E15	1.2E17	9.0E14	2.2E15	2.2E15	5.5E13	8.2E17	6.6E17	3.2E13	7.9E13
$\overline{E}^n$ - eq. (8) in MeV	1.2930	1.3483	0.3625	0.7622	1.1923	0.1359	0.0523	0.2501	0.6954	0.6139
half-time of decay	1.8 h	2.8 h	8.01 d	2.3 h	6.6 h	78.6 h	5.2 d	9.1 h	2.06 y	30.0 y

Part of results extracted for sensor id. TST 01 is demonstrated for each nuclide in Figure 8. Due to dependency of H from equation (11) on energy, the figures for photon fluency rates (left) somewhat differs from corresponding dose rates (right). The calculations run for all nuclides and for all sensors in one course. Significant outcome consists in computation effectiveness when the whole run for all nuclides and all sensors lasts about 90 seconds.

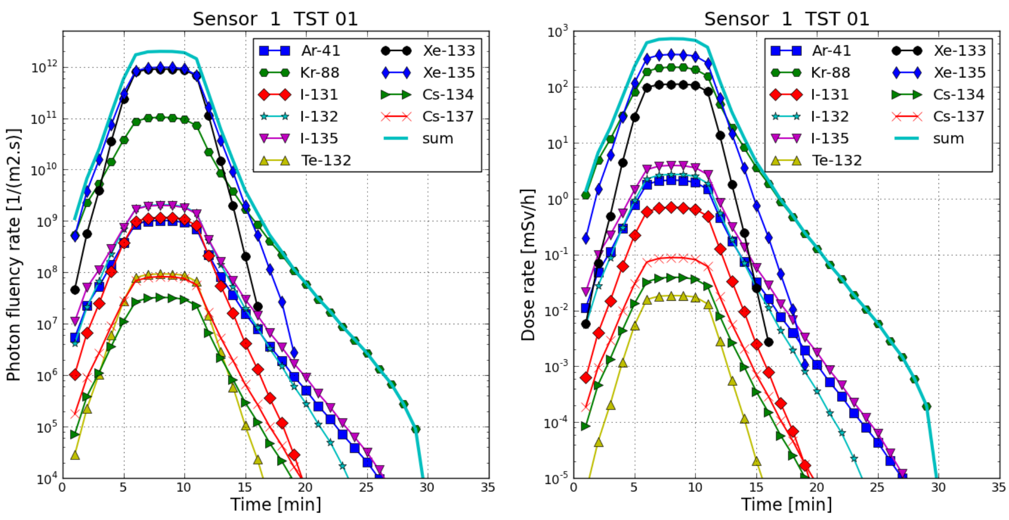

Figure 8: Sensor TST01 response in photon fluency rate (left) and dose rate (right) on short release of 6-minute duration. Sensor TST01 is located at distance about 400 m from the source, roughly in the direction of the plume propagation (see Figure 5).

An alternative method is proposed with aim to accelerate further calculations which is based on partitioning of the whole energetic interval into G energetic groups. Let $^nE^g_p$ stands for energy of each photon p emitted by nuclide n having energy belonging to the group g with yield $^nf^g_p$. Mean energy $\overline{E}^g(I)$ averaged over all photons emitted to energy interval g from all radionuclides n at downwind distance x_I can be found using "source depletion" approach introduced in equation (1): $A^n(x_I, y=0, z=h_{ef})$ = $A^n(x=0, y=0, z=h_{ef})\cdot f^n_R(x_I)\cdot f^n_F(x_I)\cdot f^n_W(x_I)$. The values of $\overline{E}^g(I)$ are determined according to equation

(12). Depletion factors for dry and wet deposition $f^n{}_F(x_I)$ *and* $f^n{}_W(x_I)$ have to be distinguished according to physical-chemical forms of radionuclides.

$$\bar{E}^g(x_I) = \sum_{n=1}^{N} A^n(x_I) \left[\sum_{(p(n))} {}^nE_p^g \cdot {}^nf_p^g \right] \Bigg/ \sum_{n=1}^{N} A^n(x_I) \left[\sum_{(p(n))} {}^nf_p^g \right] \tag{12}$$

The denominator in equation (12) represents the total number of photons emitted in disc I per second from all nuclides belonging to the group g. An alternative calculation comes from equation (3). Photon fluency rate from the total number of photons belonging to the energetic group g can be rewritten as:

$$\Phi^g\left(\bar{E}^g(x_I), R, I\right) = \frac{\Delta x}{4\pi} \int_{r=0}^{r\max} \int_{\varphi=0}^{2\pi} \frac{C_g^I(x_I; r, \varphi)\ B\left(\bar{E}^g(x_I), \mu(\bar{E}^g(x_I)\cdot d\right) \exp\left(-\mu(\bar{E}^g(x_I)\cdot d\right)}{d^2}\, r\, d\varphi\, dr \tag{13}$$

$C_g^I(x_I; r, \varphi)$ is expressed in analogy with equation (1), but specifically stands for distribution of fluency rate of photons from all nuclides contributing to the energetic group g. Linear and mass attenuation coefficients μ and μ_a are interpolated from more detailed table for 24 energetic groups constructed on basis of (RadDecay, 1996). The resulting values are given by summation over all energetic groups g. The outlined technique illustrated by equations (12) and (13) is still in development. It is assumed to accelerate calculations for scenarios with large number of discharged nuclides.

CONCLUSION

Fast algorithm is presented for generation of the model responses on external irradiation from radioactive cloud drifting over the idealised flat terrain. Net of sensors surrounding a nuclear facility includes both fixed stations and various receptors on potential mobile vehicles. The main results achieved can be summarized:

- The algorithm is designed for purposes of application of computationally expensive assimilation methods based on particle filtering techniques.
- Another significant field of application can be an optimisation of configuration of environmental monitoring network for early emergency management and for verification of detection abilities of the networks.
- Presented method is designed for the near field model. For distances beyond the TDS ring within zone of emergency planning (up to 15 km) or longer, the SGPM dispersion model was developed which can include short term forecast of meteorological conditions (Hofman and Pecha, 2011). The cloudshine doses from an arbitrary shape of the radioactive cloud are again estimated numerically using trilinear interpolation.
- The proposed technique accounts for depletion due to dry and wet deposition. In enables simplified assessment of "contamination" of measured cloudshine dose rates caused by the activity deposited on the ground.
- The fast model allows include large mixtures of discharged radionuclides. For each nuclide all levels of emitted photons and its branching ratios could be considered and finally summed up. A separation into 6 energy subgroups was realised when successive calculations and summations are based on effective energy determined by weighting photons from cascades.
- Transition from the idealised flat terrain to the real configuration of near-standing buildings is in progress. The first rough approach introduces "attenuation coefficients" whenever between points R(x(R),y(R),z(R)) and M(x(S), y(M), z(M)) – see equation 3) – a certain obstacle occurs. Availability of detailed 3-D layout of NPP is necessary.
- Finally, the originated plume segmentation method based on lumped parameter approach according to Figure 3 can be proposed as a basic scheme for formulation of a certain dispersion scheme alternative to the puff model with methodical extension to the medium range distances.

APPENDIX A. TESTS OF INTEGRATION PROCEDURE

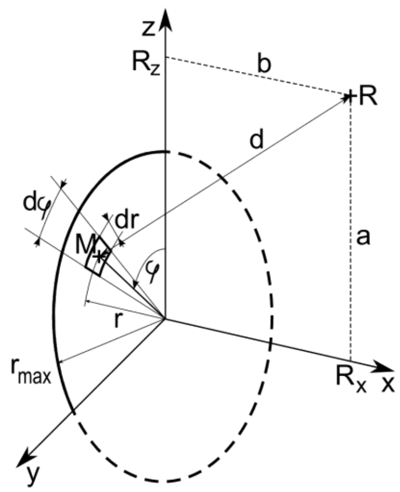

Figure 9. Disc in plane (z; y) irradiating receptor R.

The photon fluency rate given by expression (3) is integrated numerically using Gauss-Legendre integration formula which is the most commonly used form of Gaussian quadratures. The Gaussian quadratures provide the flexibility of choosing not only the weighting coefficients but also the locations (abscissas) where the functions are evaluated. The Gauss-Legendre formula is based on the Legendre polynomials of the first kind $P_n(x)$. For chosen degree *n* of the polynomial we have tested the limits of its applicability on a given experimental configuration illustrated in Figure 9. Emitting disc with optional radius r_{max} is located in the plane (x,z) with centre in the origin of coordinate system. We assume that without restriction to generality we can simplify the expression (3) in three manners:

- Uniform radioactivity concentration deposited on the disc surface is assumed ($C(x; r, \varphi) = 1$ Bq/m^2)
- Photon absorption in medium between disc and receptor point R is not taken into account (μ=0)
- Photons are emitted from the disc elements isothrophicly and without any secondary collision during its path from the source up to the receptor point (built-up factor is 1)

(With exaggeration, it can be perceived as a "vacuum experiment" for disc and receptors located in the outer space.)

Photon fluency rate (m^{-2} s^{-1}) is now expressed by simplified equation (3):

$$\Phi(E_\gamma, R) = \frac{1}{4\pi} \int_{r=0}^{r_{max}} \int_{\varphi=0}^{2\pi} \frac{1}{d^2}\, r\, d\varphi\, dr \tag{14}$$

According to Figure 9 the distance *d* between sensor R and elemental surface $r \cdot d\varphi \cdot dr$ equates to

$$d = d(r,\varphi) = \sqrt{a^2 + b^2 + r^2 - 2 \cdot r \cdot a \cdot \cos\varphi}$$

The equation (14) can be integrated analytically and number of photons crossing 1 m2 per second at position of the sensor R is expressed as:

$$\Phi(E_\gamma, R) = \frac{1}{4} \ln\left(\frac{{r_{max}}^2 + b^2 - a^2 + sqrt\left({r_{max}}^4 + 2{r_{max}}^2 (b^2 - a^2) + \left(a^2 + b^2\right)^2 \right)}{2b^2} \right) \tag{15}$$

30 points of Gauss-Legendre integration formula is used to integrate numerically the equation (14) for various ranges of constants *a* and *b*. Partial comparison of numerical and analytical values are presented in Table 2. Additional tests revealed a certain numerical instability for case when the sensor R lies in plane of the disc (*b*=0) and constant *a* is approaching to zero. In this instance we are using the lowest value of constant *b* slightly above zero (b≅0.2 m).

Table 2. Comparison of numerical and analytical values of photon fluency rate for various values a, b of the sensor R positions. Radius of radiating disc is r_{max}=49 m.

a (m)	b (m)	fluency rate Φ (m^{-2} s^{-1}) numerically (T1)	fluency rate Φ (m^{-2} s^{-1}) analytically (T2)
144	144	1.446555 E-02	1.446555 E-02
100	100	2.994087 E-02	2.994087 E-02
60	60	8.189546 E-02	8.189548 E-02
40	40	1.733492 E-01	1.733493 E-01
20	20	4.547102 E-01	4.547104 E-01
10	10	7.950500 E-01	7.950501 E-01
4	4	1.252774 E+00	1.252774 E+00
1.0	1.0	1.945767 E+00	1.945910 E+00
0.5	0.5	2.290156 E+00	2.292484 E+00
0.2	0.2	2.744151 E+00	2.750629 E+00
0.1	0.1	3.064821 E+00	3.097203 E+00

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