**H14-80**
# CONSTRUCTION OF OBSERVATIONAL OPERATOR FOR CLOUDSHINE DOSE FROM RADIOACTIVE CLOUD DRIFTING OVER THE TERRAIN

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**Abstract**: We are presenting a specific method for real-time calculation of cloudshine dose used for purposes of online assimilation of model predictions with observations from terrain. Model predictions of cloudshine dose are calculated in an array of measurement sensors located on terrain around a nuclear facility. It enables to construct effectively the observational operator which according to assimilation terminology transforms cloudshine doses from model space (computational nodes) into measurement space (net of sensors). The dynamics of radioactive cloud propagation over the terrain is simulated by two approaches. In the near distances from the source of pollution (several hundreds meters covering the teledosimetric circle of sensors on the fence of a nuclear facility) we are presenting a certain modification of classical straight-line Gaussian solution of the near-field dispersion problem. Further movement driven by changing meteorological conditions is described according to segmented Gaussian scheme. In both cases the *n*/μ method introduced for photon transport in the ambient air ensures fast generation of predicted external irradiation doses/dose rates entering the assimilation procedures. Early stage of an accidental release of radioactivity into the living environment is examined with definitive intensions to utilise this effective software in the further process of Bayesian tracking during the cloud passage over the terrain.

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

## INTRODUCTION

Measured and calculated doses/dose rates of external irradiation from radioactive cloud are basic inputs to the assimilation methods of objective analysis. Specific approach is required in the emergency phase of an accident when crucial task insists in realistic calculation of cloudshine doses/dose rates. Mathematical model predicts the output values of irradiation in the computational nodes aggregated in a state vector **x** in model space (dimension N). Moreover, the assimilation techniques 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 of observations from all types of measuring devices during emergency situation (fixed stations, temporary deployed stations, mobile monitoring groups, pilotless aircrafts). In terminology of assimilation techniques all sensors form so called observational space represented by observational vector **y** of dimension P. Model values are known in a given discrete points and if we want to know the value of model in any point in observational space we need to apply a forward observation operator $H$, which transforms points from model space into the measurement space. The differences between model predictions and measurements are expressed by vector of innovations $\boldsymbol{e} = \boldsymbol{y} - H\,\boldsymbol{x}$ . The observation operator can be constructed either by means of some simple interpolation techniques or using more sophisticated spline interpolation procedures. An alternative way avoids any interpolation step and calculates the model predictions directly also in positions of the sensors using model algorithm for determination of cloudshine doses/dose rates. The transformation into observational space is thus accomplished implicitly.

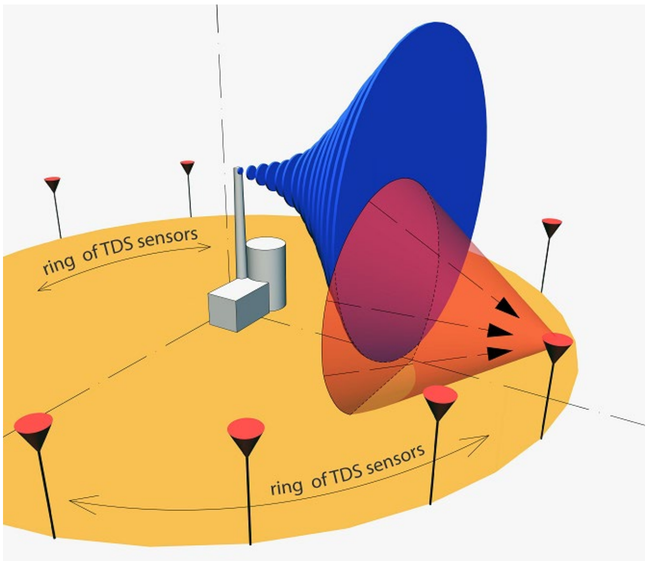

Figure 1. Schematic illustration of ring of TDS sensors around NPP.

Common principle of objective analysis for optimal blending of model predictions with observations can be formulated using relation $\boldsymbol{x_a} = \boldsymbol{x_b} + \mathrm{W} \cdot \boldsymbol{e}$ which represents the update step of data assimilation process based on constant statistical algorithm of optimal interpolation method. It says that we obtain analysis (new model prediction vector $\boldsymbol{x_a}$ corrected by incoming measurements) if we take a background field vector $\boldsymbol{x_b}$ (prior model predictions) and add it to the product of weight (gain) matrix W and vector of innovations $\boldsymbol{e}$. Similar inputs are required for more sophisticated advanced methods based on Bayesian recursive tracking of the toxic plume progression when the corresponding likelihood function $\mathrm{P}(\boldsymbol{y} \mid \boldsymbol{x})$ 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 presented for effective estimation of cloudshine doses/dose rates from radioactive cloud spreading onwards. 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 nuclear power plant (NPP) according to Figure 1. The aim of analysis is simulation of the time evolution of sensor responses from the same beginning of release. The innovation vector enters successive assimilation process with possibility of improving 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.

**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, S. R., G. A. Briggs and R. P. 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.

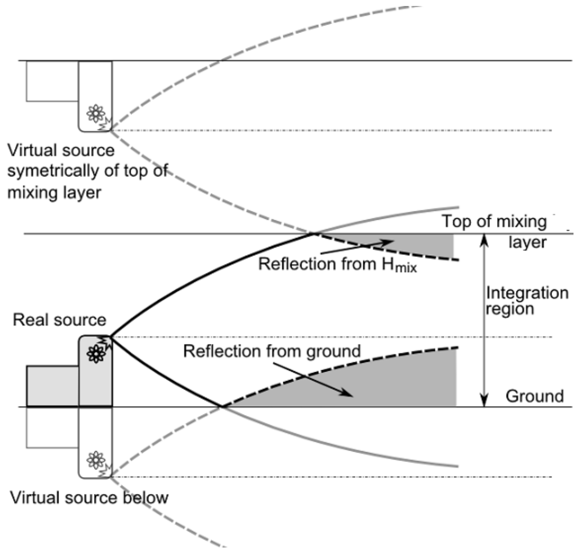

Figure 2. Chart of straight-line Gaussian solution with reflections.

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, R. and P. 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:

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

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

| | |
|---|---|
| $C^n(x,y,z)$ | 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).

**INTRODUCTION OF A NEW ALGOIRITHM FOR FAST EVALUATION OF 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 $E_\gamma$ from the source of emission to receptors R will be described by the quantity of photon fluency rate Φ( $E_\gamma$ , 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) or on specially constructed three-dimensional columned space divided on many finite grid cells (e.g. Wang, X.Y., Y.S. Ling and Z.Q. Shi, 2004). Moreover, an application of 5/μ method brought substantial improvement of calculation effectiveness. 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 Φ( $E_\gamma$ , R) from the whole plume based on the three-dimensional integration is given by the scheme (2b).

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

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

$B(E_\gamma, \mu \cdot |\vec{r}|)$ stands for build-up factor, we use its linear form $B(E_\gamma, \mu \cdot |\vec{r}|)$ = 1 + k.μ.r ; k=(μ-$\mu_a$)/ $\mu_a$ , μ and $\mu_a$ are linear and mass attenuation coefficients. More discussion and comparison with alternative Berger formula can be found in literature, e.g. in (Overcamp, T.J., 2007). f is branching ratio to the specified energy $E_\gamma$.

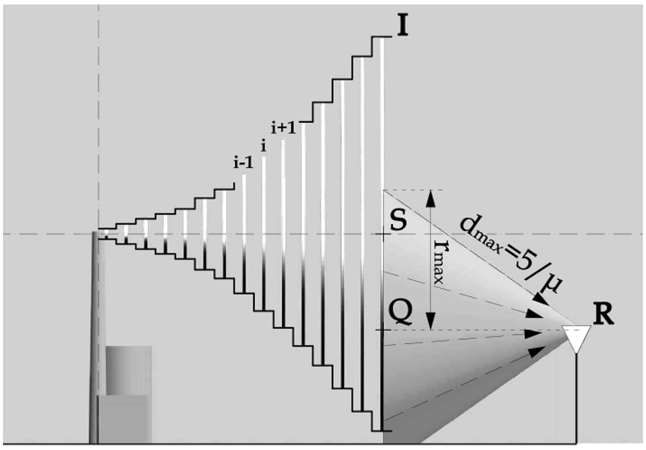

Figure 3:Segmentation of continuous release into equivalent disc sequence.

$|\vec{r}|$ 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 $\overline{u}$ is segmented into equivalent number of elliptic discs according to Figure 3. Thickness of discs is selected as Δx = 10m. Disc *i* reaches the position $x_i$ = (i-1/2)×Δx during $x_i$ / $\overline{u}$ 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 disc parameters (averaged on Δx) are substituted - $x_i$, $\sigma_y$ ($x_i$), $\sigma_z$ ($x_i$) and depletion $f_R(x_i) \cdot f_F(x_i) \cdot f_W(x_i)$ etc.

The 5/μ method (generally n/μ method) imposes integration limit up to $d_{max}$ and considers such significant only those sources of irradiation lying up to distance 5/μ 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 disk I. Only those points located inside contributes to the fluency rate at R. Substantial benefit has occurred with regard to the computational speed and capability to run the successive assimilation procedures in the real time mode. Traditional methods based on full 3-D integration techniques are computationally expensive (Raza, S.S., R. Avilla and J. Cervantes, 2001). Substantial performance improvement brings the 5/μ approach which predetermines its application in a nuclear emergency situations (Wang, X.Y., Y.S. Ling and Z.Q. Shi, 2004). Minor differences of results from other traditional methods are referred for broad range of input model parameters (Pasquill 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 <$x_i$; $x_i$+Δx> to be substituted by equivalent effect of the disc of thickness Δx with lumped model parameters on <$x_i$; $x_i$+Δx>. Let analyse contribution from the elliptical disk I from Figure 3 to the fluency rate at receptor R. In Figure 3 is demonstrated lateral view on the segmented plume propagation. The same situation is outlined in the front view in Figure 4. The boundary of integration region lying in the plane of disk I is based on 5/μ 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:

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

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-1/2)× Δx is a distance of centre of the disc I from the release point; y(M) = r×sin(φ); z(M) = z(R)+r×cos(φ). 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 $x_I$ / $\overline{u}$ 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 Φ($E_\gamma$, R, I) according to the equation (3), the following pre-processing of the array F provides the desired values. We are distinguishing two situations:

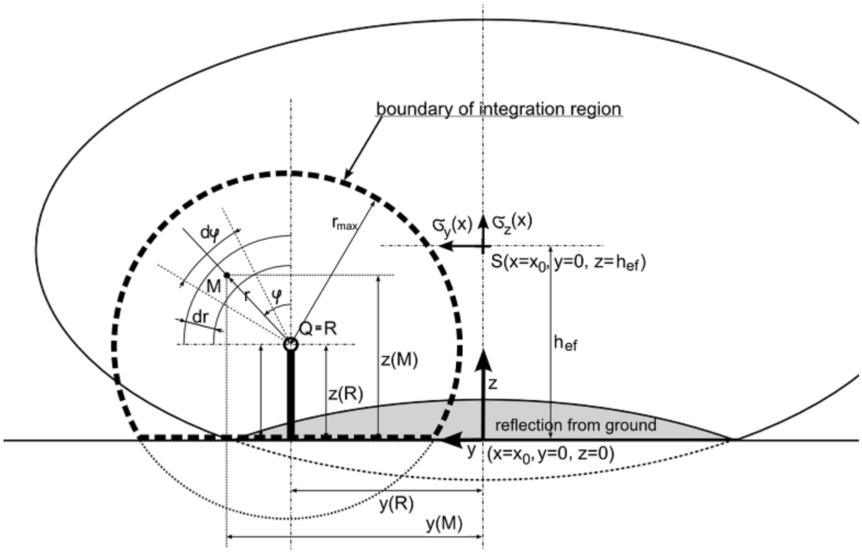


Figure 4. Frontal view from receptor point R to elliptical disk I and circular integration region.

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

$$\Phi(E_\gamma, R, i = 1 \div I+1) = \sum_{i=1}^{i=I} \Phi(E_\gamma, R, i) + \Phi(E_\gamma, R, I+1) \tag{4}$$

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

$$\Psi(E_\gamma, R, i = 1 \div I+1) = \sum_{i=1}^{i=I} \left[ (I+1-i) \cdot \Delta t_i \cdot \Phi(E_\gamma, R, i) \right] + \Delta t_i \cdot \Phi(E_\gamma, R, I+1)\,; \quad \Delta t_i = \Delta t = \Delta x / \bar{u} \text{ seconds} \tag{5}$$

**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 disks positions I+1, I+2, ..., I+j. Fluency rate Φ($E_\gamma$, R, I+j+1) for position I+j +1 is calculated from the previous position I+j according to recurrent formula Φ($E_\gamma$, R, I+j →I+j+1) = Φ($E_\gamma$, R, I+j) - Φ($E_\gamma$, R, j) + Φ($E_\gamma$, R, I+j+1). Hence, the leftmost disk of a parcel is skipped, the new rightmost one is calculated. Similar considerations lead to expressions for the total fluency Ψ.

## RESULTS

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 5. The calculations for n=5 are more than thrice faster in comparison with n=10. Furthermore, a verification of numerical algorithm of integration expressed by equation (3) has been accomplished on basis of comparison with analytical solution of equation

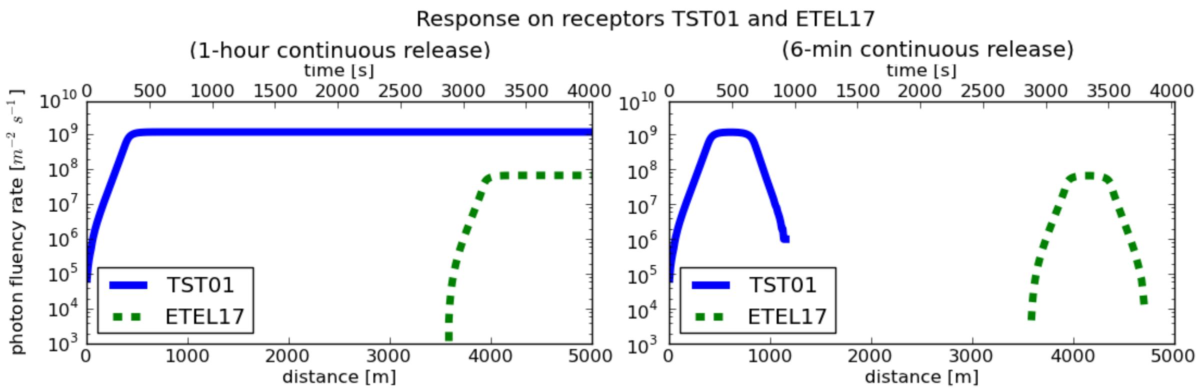


Figure 5. Sensor response in photon fluency rate on the plume drifting. Both sensors are roughly in direction of propagation, TST01 at distance about 400 m from the source, ETEL17 at about ten times larger). Left: Continuous one hour spreading (up to 4025 s ~ 4960 meters). Right: Spreading of smaller plume of 6 min duration. Interpretation: when front of the plume reaches the distance x from the source (~ time of spreading x/u) , then in that moment the whole plume induces at the sensor the response given on y axis.

(3) which can be found for case without absorption (μ=0) and built-up factor B=1 (simplified experiment - "irradiation in vacuum"). 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.

Here we present the responses on 40 sensors surrounding NPP (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 $E_\gamma$ = 0,3625 MeV (γ yield is taken to be 100 %, linear attenuation coefficient μ =1.40531E-02 ($m^{-1}$), mass attenuation coefficient $\mu_a$ = 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 release 9.0 E+14 Bq 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).

Irradiation dose rates $H(E_\gamma, R)$ ($Gy.s^{-1}$ ) for monoenergetic photons with energy $E_\gamma$ can be calculated from fluency rates:

$$H(E_\gamma, R) = \frac{\omega \cdot K \cdot \mu_a \cdot E_\gamma}{\rho} \cdot \Phi(E_\gamma, R) \tag{6}$$

Conversion factor $K$ = 1.6 $E10^{-13}$ Gy.kg.$Mev^{-1}$ ; $\omega$ = 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.

## CONCLUSION

Fast algorithm is presented for generation of the model responses from cloudshine irradiation on a net of sensors surrounding NPP including both from fixed stations and from potential mobile vehicles. The main branches of its utilization are 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 environmental monitoring network configuration for early emergency assessment and for verification of detection abilities of the networks.
- The advantage of the extremely fast model allows include a real discharged radionuclide mixture. For each nuclide all levels of emitted photons and its branching ratios could be considered and finally summed up. An alternative way is partitioning of the emitted photons into energetic subgroups and to consider the number of photons in each subgroup with average characteristics prepared for advance. A separation into 6 energy subgroups was realised when successive calculations and summations are based on effective energy determined by weighting photons from cascades.
- 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, R. and P. Pecha, 2011). The cloudshine doses from an arbitrary shape of the radioactive cloud are again estimated numerically using the 5/μ idea.
- The proposed technique accounts for depletion due to dry and wet deposition. In means that a simplified assessment of “contamination” of measured cloudshine dose rates caused by the activity deposited on the ground can be done.
- 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.

## ACKNOWLEDGMENTS

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