

#### **4.17 RISK ASSESSMENT OF RADIONUCLIDE RELEASES DURING EXTREME LOW-WIND ATMOSPHERIC CONDITIONS**

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##### **INTRODUCTION**

Several issues in the field of atmospheric modelling remain so far essentially unresolved. The problems are connected with treatment of missing data periods, dispersion of admixtures during extreme weather situations, trends in long-term changes of climate and potential synergistic effects between physical-chemical forms of pollutants. The paper deals with radiological consequence assessment of radioactive releases from nuclear facilities at low-wind speed (calm) atmospheric conditions. The developed technique anticipates evolution of situation taking into account possible cumulation of conditions in the most adverse way. Such information has great importance for decision support of nuclear emergency management, even if the occurrence of such extreme situations is less probable. The calm situations can be formed when wind speed drops below a threshold about 0.5 m/s. Wind direction becomes undefined and the plume of admixtures can fluctuate anywhere or the puffs are diffused and grown at the point of release without being advected. The latter scenario can be especially hazardous and can lead to the highest peak ground level concentrations of radionuclides.

Program tool for quick consequence assessment of atmospheric releases during calms belongs to the bunch of strongly locally dependant procedures covering so called “worst case” scenarios, the area of which is not sufficiently analysed by commonly used general codes. It namely relates to the stable atmospheric stratification when ground level releases remain close to the surface and dilute slowly. The paper comes out from literature review of atmospheric dispersion modelling of passive admixtures at low-wind speed conditions and its application in risk assessment. Proper techniques of mathematical modelling are resumed and recommended modifications of common models (namely Gaussian solution) are accepted in order to avoid possible pitfalls of their direct unqualified application. Two simple numerical approaches are adopted and applied to the hypothetical scenario of radioactive releases. The first one is based on step-wise release of partial 3-D Gaussian puffs and superposition of results in all steps of release. The second approach modifies semiempirical formulas of the common Gaussian plume model (for dispersion coefficients and plume rise) according to the recommendations for low-wind speed conditions. A certain low wind speed is chosen in this case and periodic multiple plume travel over the point of release is modelled using segmented plume approximation.

##### **APPROXIMATION BASED ON DISCRETE RELEASES : PUFF MODEL**

Continuous release of radionuclides during low-wind speed conditions is here substituted by equivalent discrete chain of puffs and treated as time step-wise release of mixture of radionuclides from the elevated source. Each puff has its own strength of activity source and follows changes in thermal capacity of the release, weather category, mixing height and possible occurrence of precipitation in the further phases. The whole release is assumed to proceed under zero horizontal wind speed and each puff has shape of gradual-spreading disc having centre in the source of pollution. Activity concentration in air is described by Gaussian-puff distribution where vertical and horizontal dispersion coefficients are expressed by time-dependant empirical recommendations based on field measurements at a low-wind

speed conditions (*Okamoto, S., H.Onishi, Yamada T., et al., 1999*). Each puff is modelled in all successive time stages taking into account depletion of activity due to removal mechanisms of radioactive decay and washout caused by precipitation. Dry deposition is estimated very roughly when only a certain fraction corresponding to gravitational setting is considered

. Let us assume continuous activity release with source strength  $S^n(t)$  (in Bq/s) from elevated source of height  $H$  ( $x=0; y=0; z=H$ ) for time period equal to calm duration  $T$ . The total time  $T$  is divided into  $M$  time subintervals  $\Delta t_m$  ( $m=1, \dots, M$ ) and continuous process is substituted by  $M$  discrete instantaneous releases with equivalent total activity release  $Q_m^n$  (in Bq). The following relations hold true:

$$T = \sum_{m=1}^{m=M} \Delta t_m \quad ; \quad Q_m^n = \int_{(\Delta t_m)} S^n(t) \cdot dt \quad (1)$$

The  $m^{\text{th}}$  puff is assumed to be born immediately in the middle of interval  $\Delta t_m$  at time

$t_m = \Delta t_m / 2 + \sum_{k=1}^{k=m-1} \Delta t_k$ . It propagates within successive time intervals  $i$ , ( $i= m+1, \dots, M$ ) and

“age” of the puff in interval  $i$  can be denoted as:  $t_{mi} = \Delta t_m / 2 + \sum_{k=m+1}^{k=i} \Delta t_k$  (2)

Ground level activity concentration ( $\text{Bq/m}^3$ ) of radionuclide  $n$  in the puff born in interval  $m$  which has reached time interval  $i$  is describe by modified 3-D Gaussian puff formula:

$$C_{mi}^n(x, y, z = 0 ; t_{mi}) = \frac{Q_m^n}{(2\pi)^{3/2} \cdot \sigma_x(t_{mi}) \cdot \sigma_y(t_{mi}) \cdot \sigma_z(t_{mi})} \cdot \exp\left[-\frac{1}{2} \left( \frac{x^2}{\sigma_x^2(t_{mi})} + \frac{y^2}{\sigma_y^2(t_{mi})} \right)\right] \times \left\{ \exp\left(-\frac{(z - h_{ef,m})^2}{2 \cdot \sigma_z^2(t_{mi})}\right) + \mathfrak{R}_{refl}^m \right\} \cdot f_R^n(t_{mi}) \cdot f_F^n(t_{mi}) \cdot f_W^n(t_{mi}) \quad (3)$$

The above  $C$  means time-averaged concentration within interval  $\Delta t_i$ .  $\mathfrak{R}_{refl}^m$  denotes the contribution of puff reflection from ground plane and from top of the boundary layer to the Gaussian solution ( e.g. *Carruthers, D. J., ..., 2003*). The equation (2) represents modification of commonly used expression in so called “source depletion” approach where factors  $f_R, f_F, f_W$  represent depletion of radionuclide concentration in the puff due to radioactive decay, dry activity deposition and washout of activity induced by possible atmospheric precipitation. Radioactive decay and washout by precipitation are accomplished in the whole puff volume and corresponding depletion coefficients are calculated as:

$$f_R^n(t_{mi}) = \exp(-\lambda^n \cdot t_{mi}) \quad ; \quad f_W^n(t_{mi}) = \prod_{k=m}^{k=m+i} \exp(-\Lambda_k^n \cdot \Delta t_k) \quad (4)$$

where  $\lambda^n$  ( $\text{s}^{-1}$ ) denotes constant of radioactive decay and  $\Lambda_k^n$  ( $\text{s}^{-1}$ ) represents washing coefficient expressed as  $\Lambda_k^n = a \cdot v_k^b$ . Constants  $a$  and  $b$  depend on physical-chemical form of the radionuclide  $n$  (different for aerosol, elemental, organic form, zero for noble gases).  $v_k$  is precipitation rate (mm/h) averaged within partial time intervals  $\Delta t_k$ . The puff activity concentration depletion due to dry deposition comes out both due to gravitational setting and interaction in the surface layer. The smaller aerosol particles (0.1 to 1  $\mu\text{m}$ ) survive for a long time in the plume and their depletion from the plume is caused mainly by interaction with

surface structures (in dependency on roughness and friction velocity). For calm conditions we shall limit our consideration on simplified recommendation related only to process of gravitational setting for aerosol particles. The process is significant for particles with higher diameter which don't remain airborne for a long time. The value  $v_g = 0.01$  m/s has been selected for further calculations. It can be accepted for aerosol particles with radii about 5-10  $\mu\text{m}$  (more precise review in *Hanna R.S., 1982*). Let us assume again the puff born at interval  $m$  which propagates and reaches the time interval  $i$ . Stepwise procedure used here means that the puff "stays on" here for the time period  $\Delta t_i$  and then the time averaged (on the  $\Delta t_i$ ) near ground activity concentration expressed by simplified equation (3) ( $\sigma_x = \sigma_y = \sigma_r$ ,  $x^2+y^2 = r^2$ , only one reflection from ground level is accepted) has form:

$$C_{mi}^n(r; z = 0) = \frac{2 \cdot Q_{mi}^n}{(2\pi)^{3/2} \cdot \sigma_r^2(t_{mi}) \cdot \sigma_z(t_{mi})} \cdot \exp\left(-\frac{r^2}{2 \cdot \sigma_r^2(t_{mi})} - \frac{h_{ef,m}^2}{2 \cdot \sigma_z^2(t_{mi})}\right) \quad (5)$$

The following approximation for dry deposition process is introduced :

$$\dot{\Omega}_{mi}^n(z = 0) = \int_0^\infty v_g \cdot C_{mi}^n(r) \cdot 2 \cdot \pi \cdot r \cdot dr \quad ; \quad \Omega_{mi}^n(z = 0) = \dot{\Omega}_{mi}^n(z = 0) \cdot \Delta t_i \quad (6)$$

and after integration  $\dot{\Omega}_{mi}^n(z = 0) = \sqrt{\frac{2}{\pi}} \frac{Q_{mi}^n \cdot v_g}{\sigma_z(t_{mi})} \cdot \exp\left(-\frac{h_{ef}^2}{\sigma_z^2(t_{mi})}\right)$

The first equation in (6) denotes dry activity deposition rate on the whole surrounding ground (average during interval  $i$ ) in Bq/s due to gravitational setting, the second one is resulting total activity deposition in Bq of radionuclide  $n$  on the whole surface around the source during time period  $\Delta t_i$ . Source depletion approach insists in construction of the depletion factor  $f_F^{mi}$  such a ratio of the original total activity contained in the puff at the starting time of the time interval  $\Delta t_i$  decreased by  $\dot{\Omega}_{mi}^n$  to the total original activity. By analogy with expression (2) we can suggest for dry deposition depletion factor the formula:

$$f_F^n(t_{mi}) = \prod_{k=m}^{k=m+i} f_F^{mi} \quad (7)$$

Further step is calculation of time integrated concentration TIC in the air, which is driving variable for derivation of irradiation doses. Time integral of activity concentration (Bq.s/m<sup>3</sup>) for the puff born at interval  $\Delta t_m$  which is spreading up to the time interval  $\Delta t_i$  is calculated as:

$$TIC_{mi}^n = \sum_{k=m}^{k=i} (C_{mk}^n \cdot \Delta t_k) \quad (8)$$

Total activity concentration  $C$  (Bq/m<sup>3</sup>) and its corresponding time integral TIC up to the time interval  $\Delta t_i$  is given as a sum of contributions from all partial puffs being born from the same beginning of release up to  $\Delta t_i$  (including) :

$$C_i^n = \sum_{m=1}^{m=i} C_{mi}^n \quad ; \quad TIC_i^n = \sum_{m=1}^{m=i} TIC_{mi}^n \quad (10)$$

The values for end of calm situation is found by substituting  $i=M$  into the previous equations.

### STANDARD GAUSSIAN PLUME MODEL MODIFIED TO THE LOW WIND SPEED

Let us assume continuous release of activity with constant source strength  $S^n$  in Bq/s during a certain basic time segment  $\Delta T$ . The propagation is assumed under strongly stable atmospheric conditions with a certain mean advection velocity  $U$  of the plume in direction  $x$ . The concentration of activity of radionuclide  $n$  in the air approximated by Gaussian straight-line solution (11) can be interpreted as a time integral of elemental time puffs extended beyond the

advection length. Whereas puff formula (3) has straightforward applicability also for calm conditions, the Gaussian plume formula (11) is generally accepted for range of mean wind speed  $1 \leq U \leq 50$  m/s. The prediction tends to infinity as the wind speed approaches zero. Unlike the dispersion coefficients in the puff model (time dependency), the dispersion for plume depends on distance  $x$  from the source of pollution and surface roughness. Alternative formulas for smooth terrain (SCK CEN) and rough terrain (KFK-Jülich) can be here used. Depletion coefficients  $f$  in (11) have usual form derived specifically for the plume model.

$$C^n(x, y, z) = \frac{S^n}{2\pi \cdot \sigma_y(x) \cdot \sigma_z(x) \cdot U} \cdot \exp\left(-\frac{1}{2} \frac{y^2}{\sigma_y^2(x)}\right) \times \left\{ \exp\left(-\frac{(z - h_{ef})^2}{2 \cdot \sigma_z^2(x)}\right) + \mathfrak{R}_{refl}^{GAUSS}(x) \right\} \cdot f_R^n(x) \cdot f_F^n(x) \cdot f_W^n(x) \quad (11)$$

The adaptation of the common Gaussian solution to the calm atmospheric conditions insists in selection of a certain low limit for wind speed (0.5 – 1.0 m/s) with further modifications of the plume rise and dispersion based on expert recommendations for calm situations. Let us outline the procedure for approximate modelling of the calm based on the plume concept.

At time  $\Delta T$  the front end of plume reaches position  $x = U \cdot \Delta T$ . Let the release stops at this moment and we shall introduce an idea of further propagation of the finite plume in additional  $K$  time stages the duration of which is  $\Delta t_k$ . The total duration  $T$  of the calm situation is covered by the particular intervals according to  $T = \Delta T + \sum_{(k)} (\Delta t_k)$ . The trick insists in assumption of periodic motion over the source when the next stage returns back in direction opposite to the propagation of the basic segment and similarly, the time stage  $k+1$  is moving always opposite to the previous stage  $k$ . From the programming point of view a special numerical method has been developed for the local code HAVAR when movement of basic segment is modelled in all further time stages taking into account stepwise changes of meteorological conditions, plume spreading and activity depletion. The final results are composed from values corresponding to the basic segment and sum of all successive time stages  $k, k=1, \dots, K$ .

## RISK ASSESSMENT AND RESULTS

Time integrated activity concentrations and activity deposition on the ground are two main driving values on basis of which the radiological burden and health detriment from all possible pathways of irradiation (cloudshine, groundshine, inhalation, ingestion) are generated. The methodology for determination of activity concentrations and its time integrals in the air is outlined in the previous chapters with respect to the worst case of calm meteorological conditions. Simultaneous calculations of the activity deposition  $\omega^n$  of radionuclide  $n$  ( $\text{Bq} \cdot \text{m}^{-2}$ ) on the ground have to follow the dynamics of the removal processes according to:

$$\frac{d\omega^n(x, y, t)}{dt} = D^n(x, y, t) - \lambda^n \cdot \omega^n(x, y, t) \quad \approx \quad \Delta\omega_k^n(x, y) = \{D_k^n(x, y) - \lambda^n \cdot \omega_k^n\} \cdot \Delta t_k \quad (12)$$

$D$  denotes the activity deposition rate ( $\text{Bq} \cdot \text{s}^{-1} \cdot \text{m}^{-2}$ ). The right side after the mark  $\approx$  symbolizes conversion into difference scheme in the time stepwise approximation used.  $D_k$  and  $\omega_k$  are activity deposition rate and deposited activity, both averaged on the time interval  $\Delta t_k$ . More precise solution based on the differential equation has to be applied for the short-term nuclides. Let us notice that the source term  $D^n$  in the differential equation expresses contributions from dry deposition rate and the precipitation-induced flux on the ground. Variable  $D^n$  is linked to the concentration calculations according to the scheme:

$$D^n(x, y, t) = v_g^n \cdot C^n(x, y, z=0, t) + \int_0^\infty \Lambda^n(t) \cdot C^n(x, y, z, t) \cdot dz \quad (13)$$

Presented results are linked to one of the situation occurred in October 2003 when the calm conditions lasted more then 2 hours. The scenario of radioactive release is taken from simulation of potential Large Break LOCA accident for WWER 1000 reactor. The results based on the puff model are shown on Figure 1. Continuous 2 hours activity release of radionuclide Kr88 ( $8.80 \cdot 10^{11}$  Bq in total) is split into 12 discrete puffs (10 minutes of duration) and methodology described here in the second chapter is applied. Partial results according to segmented Gaussian plume model are demonstrated on Figure 2 where a certain recommendations on low-wind speed situations are adopted.

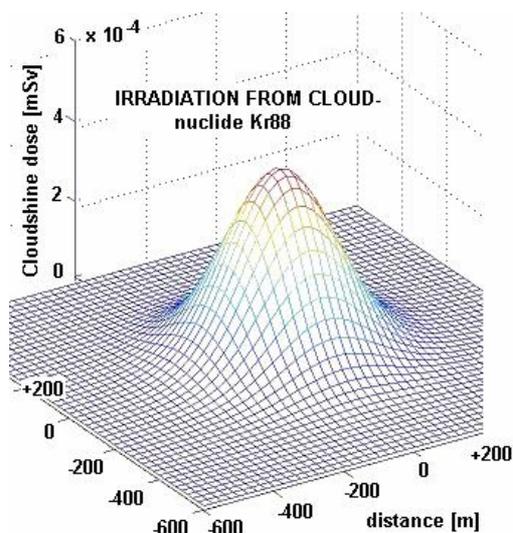


Figure 1. Multiple puff simulations: cloudshine dose (adults) in miliSieverts [mSv] from Kr88 ( $\lambda^{Kr88} = 6.88 \cdot 10^{-05} \text{ s}^{-1}$ , conversion factor for semi-infinite cloud =  $1.02 \cdot 10^{-13} [\text{Sv} \cdot \text{s}^{-1} \cdot \text{Bq}^{-1} \cdot \text{m}^3]$ , stable atm. stratification, constant conditions in all time subintervals

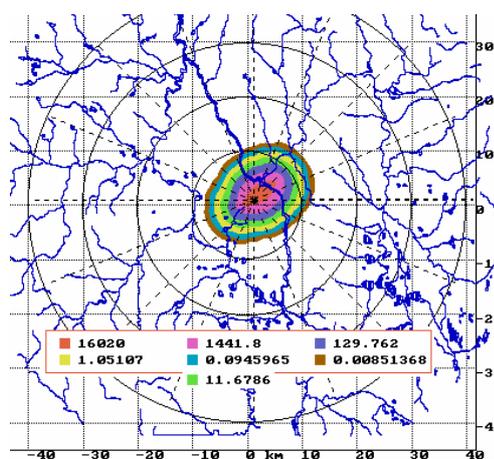


Figure 2. Segmented plume simulations: Time Integr. Conc. isolines [ $\text{Bq} \cdot \text{s} \cdot \text{m}^{-3}$ ]: 1 hour release of Cs137 ( $1.85 \cdot 10^{10}$  Bq in total) in direction NE, stable atmosf. stratification,  $U_{10} = 1 \text{ m/s}$ ; the plume returns 8-times alternately over source

The results of the puff model are expected to be more conservative and then applicable in the field of the „worst case“ analysis. More detailed results and comparisons are given in the poster presentation associated with this paper.

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