Description of the Atmospheric Dispersion Model
ATSTEP

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Management Summary

This report describes the atmospheric dispersion model ATSTEP.

The basic mathematical formulae used in the model are given and their physical meaning and model approximations are explained and illustrated.

The use of additional models in ATSTEP like plume rise, deposition and depletion, and gamma radiation is described.

Furthermore the internal structure of the ATSTEP code and the use of the SUBROUTINE ATSTEP in RODOS diagnosis- and prognosis calculations is shown.
Abstract

ATSTEP is a Gaussian puff model for distances up to 50 km. It was developed especially for quick simulation calculations in the case of accidental releases of airborne radioactive contaminants. ATSTEP can calculate real-time diagnoses of the radiological situation during or after a release and dispersion prognoses for 24 hours. The radiological situation is described by the following results calculated with ATSTEP: the concentration in the air near ground (instantaneous and time-integrated), the contamination of ground surface (dry and wet), and the gamma radiation from ground and from the radioactive cloud. These results are presented as time dependent, nuclide specific fields in the whole calculation area in the environment of the source of the release. The following phenomena are considered in the modelling of atmospheric dispersion and the radiological situation in ATSTEP: time dependent meteorology (meteorological tower- or SODAR data, forecast data, inhomogeneous wind fields), time dependent nuclide-group specific release rates, thermal energy and rise of the puffs released, dry and wet deposition and corresponding depletion of the cloud, gamma radiation from cloud and from ground, radioactive decay, and potential doses.

Different to classic puff models (RIMPUFF [1], ...) in ATSTEP no instantaneous puffs but time-integrated elongated puffs are released, similar to the plume sections of a segmented Gaussian plume model. Different to a segmented plume model in ATSTEP the transport of each elongated puff is achieved by two trajectories, which are fixed at both ends of the puff. As these pairs of trajectories follow the inhomogeneous and variable 2D-wind fields step by step, also the elongated puffs perform all the necessary changes in position, shape, and orientation, like stretching, rotations, shrinking, and sideways drift.

Because of the elongated puffs the plume can be covered by a substantially smaller number of puffs. Correspondingly the number of time steps needed for the simulation of the release and the transport is smaller. The elongated puff approximation reduces the computing time of the model code, so that during less than 10 minutes real-time a complete dispersion and contamination prognosis can be performed with releases over several hours. In comparison with the classic puff model the elongated puff approximation causes also a reduction of resolution in space and time (the minimum time interval is 10 minutes in the diagnosis mode, and 30 minutes in the prognosis mode), but a higher resolution is only needed during extremely variable and inhomogeneous dispersion conditions.
1 Model description

1.1 Advection and Diffusion in ATSTEP

1.1.1 Time steps and puffs

In ATSTEP the duration T of a release step equals the duration of the advection step. The release rate QR at the source and the wind velocity and direction u and θ are assumed to be constant during the time step. After each time step of duration T a puff is released from the source with a puff length uT and an puff axis direction θ-180°.

Fig.1: Geometry for a puff release

The cross wind diffusion is modelled using horizontal and vertical Gaussian distributions normal to the puff axis; the corresponding sigma-parameters are σ_y and σ_z. They depend on the length co-ordinate x as in the Gaussian plume model. The longitudinal diffusion is modelled by error-functions with the parameter σ_x. Therefore the puff extends beyond the advection length uT (Fig. 2). The resulting concentration distribution of the puff equals the time-integral TIC(x,y,z) of a 3-dimensional Gaussian distribution χ_0 (ellipsoidal puff), that has been advected from the source to the distance uT and that has grown corresponding to the increase of the σ-parameters (equations 1 and 2).

\[
TIC(x, y, z) = \int_0^T \chi_0(x - ut, y, z - h) dt \quad \text{(Eq. 1)}
\]
\[
\chi_a(x,y,z) = \frac{QR}{(2\pi)^{3/2} \sigma_x \sigma_y \sigma_z} \exp \left( -\frac{1}{2} \left( \frac{x}{\sigma_x} \right)^2 \right) \exp \left( -\frac{1}{2} \left( \frac{y}{\sigma_y} \right)^2 \right) \exp \left( -\frac{1}{2} \left( \frac{z}{\sigma_z} \right)^2 \right) \quad \text{(Eq. 2)}
\]

The computation of the time-integral TIC leads to the function \( F(x) \), which is a superposition of error functions and models the length and the \( \sigma_x \)-diffusion of the puff.

\[
\frac{1}{\sqrt{2\pi\sigma_x}} \int_0^T \exp \left( -\frac{1}{2} \left( \frac{x - ut}{\sigma_x} \right)^2 \right) dt = \frac{1}{2u} \left( \text{erf} \left( \frac{x}{\sqrt{2} \sigma_x} \right) - \text{erf} \left( \frac{x - uT}{\sqrt{2} \sigma_x} \right) \right) = \frac{F(x)}{u} \quad \text{(Eq. 3)}
\]

The complete concentration distribution of a puff (without ground surface and top of mixing layer reflection) is then given by:

\[
\chi(x,y,z) = \frac{Q}{2\pi \sigma_x \sigma_y \sigma_z} \cdot F(x) \cdot \exp \left( -\frac{1}{2} \left( \frac{y}{\sigma_y} \right)^2 \right) \cdot \exp \left( -\frac{1}{2} \left( \frac{z - h}{\sigma_z} \right)^2 \right) \quad \text{(Eq. 4)}
\]

A typical concentration distribution along the puff axis is shown in Fig. 2 a. The square with length \( uT \) corresponds to the puff’s length without diffusion in x-direction, i.e. the plume segment’s length. The slope of the curve in the middle of the picture results from the increasing dilution of the concentration due to the \( \sigma \)-parameters \( \sigma_y \) and \( \sigma_z \). The tails of the curve result from the error-functions (Eq. 3) and represent physically the downwind and upwind diffusion along the puff axis. In this way the puff’s concentration field is calculated from a plume segment’s field by smearing it out along its axis in a mass conserving manner. Fig. 2 b shows the cross axis Gaussian distribution.

![Concentration curves on the puff axis and on the lateral y axis](image)

**Fig. 2: Concentration curves on the puff axis and on the lateral y axis**

### 1.1.2 puff trajectories

For determining the location, the orientation, and the spread of a puff during the transport in a variable wind field, **two trajectories are calculated for each puff**. They start at the source location and follow the movements of the start- and end-points of the puff axes in each time step during the atmospheric dispersion calculation. After each time step the change of orientation and length of the puff axis is determined corresponding to the local transport vectors \( u_A(t) \) and \( u_E(t) \) at the starting point A and the end point E of the puff i (see 2.1.7). The construction of the puff trajectories is carried out like shown in Fig.3 and results in 2n polygon curves in a plain layer at release height if n puffs were released. Because ATSTEP does not use
3-dimensional wind fields, but height layer dependent 2-dimensional wind fields, the trajectories are 2-dimensional curves in the height layer, except for the case of thermal puff rise (see 2.1.8).

![Fig.3: puff transport by a pair of trajectories](image)

1.1.3 puff time-integral calculation with sideways drift

If wind fields depend on time generally the puff’s transport direction will not be parallel to the puff’s axis (sideways drift, Fig.3). Figure 4 shows the approximation that is used in ATSTEP to calculate time-integral of the air concentration if puff transport is sideways. The time-integral of the puff i during the step from t to t+T is shown by the grey shaded area. Because of the diffusion it is more extended than the area covered by the puff axis (the trapeze with wave pattern), and is mathematically described by a two-dimensional function F(x,y) like in Eq. 3.
1.1.4 Transport in inhomogeneous, variable windfields

The most general case is a spatially inhomogeneous, time dependent windfield. In this case the orientations and the lengths of the puffs change during the time step from $t$ to $t+T$. The growth of the puffs by diffusion is taken into account by increasing the size of their $\sigma$-parameters corresponding to the increase of their total travelled distances.

Fig. 5: Transport in inhomogeneous, variable windfield

1.1.5 Dispersion parameters

The modelling of turbulent diffusion in ATSTEP is parameterised by using diffusion parameters either depending on travelled distance (Eq. 5) or on travelled time (Eq. 6):

$$\sigma_y = p_y \cdot x^{q_y}, \quad \sigma_z = p_z \cdot x^{q_z}, \quad \sigma_x \propto \sigma_\text{oder} = \sigma_y \quad \text{(Eq. 5)}$$

$$\sigma_y = \sigma_y(t), \quad \sigma_z = \sigma_z(t) \quad \text{(Eq. 6)}$$

$\sigma$-parameters depending on travelled distance

In the case of dispersion parameters depending on travelled distance (Eq. 5) there are 2 classes of roughness length ($z_0 = 0.5 - 1 \text{ m}$ and $z_0 = 1 - 1.5 \text{ m}$). The dispersion parameters are defined by sets of dispersion coefficients $p_y$, $q_y$ and $p_z$, $q_z$ for $\sigma_y$ and $\sigma_z$ which are derived from tracer dispersion measurements. The Mol parameters set [2] corresponds to lower roughness length (rural, small houses, open or with trees), the Karlsruhe-Jülich set [3] corresponds to higher roughness (urban, with high buildings or forest). Both sets have 6 Pasquill-Gifford diffusion categories. The Karlsruhe-Jülich set is additionally defined for 3 different release heights: 50m, 100m und 180m.
These diffusion parameters are valid up to about 10 km travelled distance from the release point, i.e. trajectory length. Beyond 10 km therefore the following $\sigma_y$ parameters are used in ATSTEP corresponding to Briggs[4]:

$$\sigma_y^* (x \geq 10000 \text{ m}) = a \cdot \sqrt{x} \quad \text{(Eq.7)}$$

Here $a$ is defined such that $\sigma_y(x)$ changes smoothly into $\sigma_y^*(x)$ at $x=10$ km.

The problem of larger distances does not arise in the case of $\sigma_z(x)$, the parameter of the vertical diffusion, because vertical diffusion is limited by the thickness of the mixing layer (see 2.1.4).

Diffusion along the axis of the puff is described by $\sigma_x(x)$. At small distances $\sigma_x$ is determined from the horizontal wind direction fluctuation $\sigma_\theta$ corresponding to the dominating small scale turbulence. At larger distances $\sigma_x$ is derived from $\sigma_y$.

The variable $x$ used in this paragraph means the straight line way travelled like in the Gaussian plume model. Instead of this the trajectory length $s$ taken in ATSTEP.

In ATSTEP the $\sigma(x)$ parameters are calculated by adding their differential increase during each time step, so that in each time step from $t_1$ to $t_2$ a change of the diffusion category is possible:

$$\sigma (x(t_2)) = \sigma (x(t_1)) + p \cdot (x(t_2)^y - x(t_1)^y) \quad \text{(Eq.8)}$$

The $\sigma$-parameters $\sigma(x(t_2))$ at the trajectory point $x$ at time $t_2$ are calculated from the parameters at the point $x(t_1)$ during the step from $t_1$ to $t_2$, by adding the difference term in Eq. 8, and choosing the dispersion coefficients $p$ and $q$ corresponding to the actual diffusion category. Eq. 8 shows that growth of the $\sigma(x)$ parameters only can be achieved by a variation of $x$ in time: ($x(t_2) \neq x(t_1)$). Therefore no turbulent broadening of the puffs is possible during zero wind speed.

In the case of zero wind speed ATSTEP assumes a very small non-zero wind speed of 0.1 m/s moving the puffs to and fro with the time steps. So the puffs can grow though they are effectively not moving. In the case of a wind speed between 0 and 0.1 m/s the speed 0.1 m/s is used.

$\sigma$-parameters depending on travelled time

The time dependent dispersion parameters (Eq.6) are the sigma parameters $\sigma_S$ [2] of the spectral turbulence model which was chosen as a suitable common German-French model by the German French Commission (GFC) [3]. The variable $t$ means the travelled time of each respective puff. Therefore a turbulent broadening of the puff is also possible during zero wind speed without change of puff location. The GFC-$\sigma_S$ parameters continuously consider wind speed, height of the puffs, roughness length, Monin Obuchov length, and the friction velocity. The $\sigma_S$ parameters are calculated outside ATSTEP with the new meteorological data during each time step and are stored in a table with travelling times of 0-10000 seconds. During the dispersion calculation step in ATSTEP the sigma parameter values $\sigma_{xyz}(t)$ and $\sigma_{xyz}(t)$ at both puff ends are taken from the table and interpolated corresponding to their travel times for all released puffs.
1.1.6 Reflection at ground surface and lid on top of mixing layer

In the Gaussian modelling of the vertical concentration profile total reflection of the concentration at the ground surface and the top of the mixing layer are assumed. The reflection at ground surface enhances the air concentration close to the surface by a factor of 2. The additional reflection at the top of the mixing layer causes the air contamination to get trapped in the mixing layer. Turbulent vertical mixing finally generates a uniform profile of the vertical contamination that is inversely proportional to the mixing height $h_{mix}$. In the model this is approximated by replacing $s_z(x)$ by $0.8 \cdot h_{mix}$ in Eq. 5, if $\sigma_z(x)$ exceeds 80% of the mixing height (Eq. 8):

$$\sigma_z(x) \geq \sqrt{\frac{2}{\pi}} \cdot h_{mix} = 0.8 \cdot h_{mix} \quad \text{(Eq. 9)}$$

$$\chi(x, y; 0) = \frac{Q}{\pi \sigma_y(x) \cdot 0.8 \cdot h_{mix} \cdot u} \cdot F(x) \cdot \exp \left( -\frac{1}{2} \left( \frac{y}{\sigma_y} \right)^2 \right) \quad \text{(Eq. 10)}$$

1.1.7 Vertical wind profile and mass weighted transport velocity

Wind speed and direction generally depend on height. The wind profile is generated in the meteorological pre-processor from wind data measured at various heights. If there is only one measurement height a power law profile is used for defining the wind at other heights. In this case no directional shear with height is assumed. The power law profile parameter (wind profile exponent WP) depends on diffusion category and roughness length $z_0$:

$$u(z) = u(z_m) \cdot \left( \frac{z}{z_m} \right)^{WP} \quad \text{(Eq. 11)}$$

The transport velocity vectors at the head and the end of each puff are derived using the vertical wind profile and weighting it with the vertical mass profile of the puff at 9 heights.

1.1.8 Thermal rise

If thermal energy is released with a puff the rising phase and the final rise is considered in the form of a rising trajectory of this puff. First the rise phase of a thermal release is calculated taking into account neutral, stable, and unstable atmospheric stabilities, and the corresponding wind profile following the plume rise model of Briggs [5]. From this the final rise of the puff $\Delta h_{fin}$ and the corresponding distance $x_{fin}$ is derived. The rising puff trajectory is then calculated as a linear approximation like in Fig. 6:
1.2 Deposition to surfaces and depletion of the cloud

In ATSTEP 4 groups of radioactive materials are distinguished according to their dry and wet deposition properties. These (deposition-) groups are:

- noble gases (neither dry nor wet deposition)
- elementary iodine, i.e. airborne I\(_2\)-vapor (dry and wet deposition)
- organically bound iodine, e.g. Methyl Iodide CH\(_3\)I (dry and wet deposition)
- aerosols, i.e. radionuclides in aerosol form or bound to aerosols, e.g. aerosol iodine, metal oxides (dry and wet deposition)

1.2.1 Dry deposition: deposition velocities

The contamination of a surface in contaminated air can be characterised by the deposition velocity \( v_d \). It is defined as the ratio of the contamination rate \( \frac{dC_d}{dt} \) of the surface and the nuclide concentration in the ambient air \( \chi \):

\[
v_d \left[ \frac{m}{s} \right] = \frac{dC_d}{dt} \left[ \frac{Bq}{m^2 s} \right] / \chi \left[ \frac{Bq}{m^3} \right] = C_d / \int \chi dt = C_d / TIC \quad \text{(Eq. 12)}
\]

[6] Correspondingly the ground contamination is calculated in ATSTEP during each time step from the time-integrated concentration in the air near ground and the deposition velocity. The deposition velocities of the deposition groups depend on the degree of vertical turbulent mixing of the air (atmospheric resistance) and on local surface properties (surface resistance), which can be derived in a simplified manner from the land use. The RODOS database contains land use information containing 5 classes:

- 1. settlements, urban or industrial areas
- 2. pasture
- 3. Agricultural areas
• 4. Mixed forest
• 5. Water

**Attention:** The standard surface type used in RODOS and ATSTEP is lawn. In ATSTEP ground contaminations are calculated exclusively assuming this surface type. This holds also for the calculation of ground gamma radiation and local gamma dose rates, i.e., location factors = 1 are assumed. This does not imply that the plume is depleted corresponding to the surface type lawn. For depletion calculations the land use pattern under each puff is considered. An effective depletion is derived for each puff during each time step from the local deposition velocities in the area of the puff (2.2.3).

Table 1 contains the deposition velocities for the standard surface lawn in [m/s]:

<table>
<thead>
<tr>
<th>Surface type</th>
<th>elemental Iodine</th>
<th>organically b. Iodine</th>
<th>Aerosols</th>
</tr>
</thead>
<tbody>
<tr>
<td>lawn</td>
<td>5 E-3</td>
<td>0.05 E-3</td>
<td>0.5 E-3</td>
</tr>
</tbody>
</table>

**Depletion, dry**

Due to mass conservation the material $\Delta Q$ taken from a puff during deposition corresponds to the surface contamination under the puff times the area $\Delta F$ crossed:

$$\Delta Q \left[ Bq \right] = -C_d \left[ \frac{Bq}{m^2} \right] \cdot \Delta F \left[ m^2 \right] = -v_d \cdot TIC(x, y, l, m) \cdot \Delta x \Delta y \quad (Eq. 13)$$

Integration of Eq. 12 gives the amount of material reduced by depletion of a vertically Gaussian puff during transport in x direction:

$$Q(x) = Q_0 \cdot \exp \left( -\sqrt{\frac{2}{\pi}} \cdot \frac{v_d}{u} \int_{x_0}^{x} \frac{1}{\sigma_z(x')} \cdot \exp \left( -\frac{h^2}{2\sigma_z(x')^2} \right) dx' \right) \quad (Eq. 14)$$

The integral over the variable $x'$ is solved numerically, as long $\sigma_z$ is still growing and depends on x, i.e. if there is no homogeneous vertical mixing of the puff.

**1.2.2 Wet deposition: Washout**

Wet deposition is calculated using a washout model with the parameter $\Lambda$[1/s]. The contamination $C_w[Bq/m^2]$ is the product of the washout constant $\Lambda$, the precipitation duration $\Delta t$, and the integral of the vertical profile $\chi$ of the Gaussian puff:

$$C_w = \Lambda \cdot \Delta t \cdot \int \chi \cdot dz \quad (Eq. 15)$$

The washout constant depends on the deposition group and the precipitation intensity I in [mm / h]:
\[
\Lambda^{\frac{1}{s}} = a \cdot \left( \frac{I}{1[mm/h]} \right)^b
\]  
(Eq. 16)

In table 2 the values of a and b for different deposition groups are given:

<table>
<thead>
<tr>
<th>deposition group</th>
<th>a</th>
<th>b</th>
</tr>
</thead>
<tbody>
<tr>
<td>noble gases</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>aerosols</td>
<td>8.0E-5</td>
<td>0.8</td>
</tr>
<tr>
<td>elementary iodine</td>
<td>8.0E-5</td>
<td>0.6</td>
</tr>
<tr>
<td>org. bound iodine</td>
<td>8.0E-7</td>
<td>0.6</td>
</tr>
</tbody>
</table>

**Depletion, wet**

The amount of material still in the puff after being washed out during transport in x direction is:

\[
Q(x) = Q_0 \cdot \exp \left( -\Lambda \cdot \frac{x}{u} \right)
\]  
(Eq. 17)

It is assumed that the cloud is washed out homogeneously over its full depth.

### 1.2.3 Deposition depending on location and puff depletion

Generally deposition processes depend on local conditions. Local land use defines the kind of surfaces (agricultural use, canopy, etc.) and by this influences the dry deposition velocities (surface resistance). Additionally the local state of turbulence of the atmosphere influences the resistance against vertical transport (atmospheric resistance). In the case of wet deposition the local precipitation intensity a local value of the washout parameter \( \Lambda \). The local values of the deposition parameters \( v_D \) and \( \Lambda \) are defined as fields on the calculation grid, so that each grid cell has its own set of deposition parameters. Because the state of turbulence and precipitation can change this set is time dependent.

The concentration of the material staying in the depleted cloud after deposition is calculated assuming „source depletion“, i.e., the amount of material deposited from a puff onto a surface is taken from the puff as a whole, not only from the near to the surface parts of the puff’s volume. Because a puff generally covers more than one grid cell with locally different deposition parameters during the advection step, but the puff can only be depleted as a whole, its depletion can only be calculated with effective, puff-averaged deposition parameters. The exact way to determine these effective parameters is to calculate the concentration weighted average of the \( v_D \)- and \( \Lambda \)-values in all the grid cells under the puff.
Instead of this in ATSTEP the simple average over the grid cells with the highest concentrations of the puff, i.e. the grid cells within the $\sigma_y$-surrounding of the puff axis, is calculated. For this purpose rectangles with $2\sigma_y$ width are constructed around the puff axes before and after the transport step (at times $t_1$ and $t_2$). Then the grid cells situated inside these rectangles are determined, and the averages of the deposition parameters in these cells are calculated. These averages are used as effective deposition parameters for determining the depletion of the puff in the step from $t_1$ to $t_2$.

### 1.3 Radioactive decay

Radioactive decay is calculated at each time step for all nuclides during dispersion and deposition and is considered in the output fields concentration in air, ground contamination, potential doses and dose rates.

### 1.4 Gamma radiation fields

In ATSTEP nuclide specific and total gamma radiation fields are calculated. The fields are the gamma dose rates in [mSv/h] and doses in [mSv] from the contaminated air (cloud gamma radiation) and from the contaminated ground surface (ground gamma radiation). Furtheron the total local gamma dose rate (local dose rate) is calculated. All dose rates and doses are calculated at a height of 1m.

#### 1.4.1 Cloud gamma radiation

The gamma radiation field of the cloud is the sum of the fields of each puff released. The puff fields are calculated separately during each time step of the dispersion calculation. Two methods of cloud gamma radiation calculation are used: the cloud gamma correction factor method and the gamma submersion method.

The cloud gamma correction factor method is used at distances below 10 km. It was originally developed for saving computer time when calculating the plume gamma radiation for the straight line Gaussian plume model. In ATSTEP it is applied as a quick approximation for the long puff gamma radiation. A cloud gamma correction factor gives the ratio between the gamma radiation of a Gaussian plume concentration distribution and the radiation of a semi-infinite cloud with the same axis concentration. The correction factor is 1 for submersion in a homogeneous semi-infinite cloud. It is always $< 1$ for inhomogeneous Gaussian clouds, where the maximum concentration is on the axis. For the calculations in ATSTEP a pre-calculated matrix of cloud gamma correction factors for different types of sigma-parameters (differing in roughness
length, plume height, and stability class) and for a grid of polar co-ordinates is used. The correction factor data are from Monte-Carlo gamma calculations of the GSF[9]. Suitable interpolation allows the calculation of the nuclide specific cloud gamma dose rate at any location \((x, y)\) relative to the plume:

\[
\frac{d}{dt} D_{\gamma C}^{\text{nuc}} (x, y, 1m) \left(\frac{S_{\gamma}}{s} \right) = DRF_{C}^{\text{nuc}} \left(\frac{S_{\gamma}}{s} \cdot \frac{m^2}{Bq}\right) \cdot C_{\text{axis}}^{\text{nuc}} (x, y, 1m) \left(\frac{Bq}{m^3}\right) \cdot f_{\text{corr}} (x, y, z) \quad \text{(Eq. 18)}
\]

Here \(DRF_{C}\) is the nuclide specific cloud gamma dose rate factor for a semi-infinite cloud, \(C_{\text{axis}}(x)\) is the plume axis concentration, and \(f_{\text{corr}} (x,y,z)\) is the interpolated correction factor. The plume axis is directed along the x-co-ordinate axis at the height \(z\). In ATSTEP instead of a plume gamma field the gamma field of long puffs have to be calculated. For this purpose the long puffs are interpreted as a plume segments with rounded ends (see Fig. 2). The corresponding gamma field is approximated by multiplying the plume axis concentration \(C_{\text{axis}}(x)\) in Eq.18 with the error function difference \(F(x)\) from Eq.3, now using an additional \(\sigma_x=100m\) for the average range of gamma radiation in air.

The submersion method is used at distances beyond 10 km. It is assumed that the puff cloud gamma radiation is just proportional to the local air contamination \(C_{\text{C}}(x, y, 1m)\) in the puff and that the radiation is given by the semi-infinite cloud approximation.

\[
\frac{d}{dt} D_{\gamma C}^{\text{nuc}} (x, y, 1m) \left(\frac{S_{\gamma}}{s} \right) = DRF_{C}^{\text{nuc}} \left(\frac{S_{\gamma}}{s} \cdot \frac{m^2}{Bq}\right) \cdot C_{\text{nuc}}^{\text{axis}} (x, y, 1m) \left(\frac{Bq}{m^3}\right) \cdot F(x) \quad \text{(Eq. 19)}
\]

### 1.4.2 Ground gamma radiation

The gamma radiation from the ground is proportional to the nuclide contamination \(C_{\text{G}}\) of the ground surface layer and is calculated by dose and dose rate conversion factors \(DRF_{G}\) for ground gamma radiation. The nuclide specific gamma dose rate is:

\[
\frac{d}{dt} D_{\gamma G}^{\text{nuc}} (x, y, 1m) \left(\frac{S_{\gamma}}{s} \right) = DRF_{G}^{\text{nuc}} \left(\frac{S_{\gamma}}{s} \cdot \frac{m^2}{Bq}\right) \cdot C_{\text{nuc}}^{\text{G}} (x, y) \left(\frac{Bq}{m^2}\right) \quad \text{(Eq. 20)}
\]

A simplifying assumption is that the local gamma radiation comes from an infinite plane which has the local contamination everywhere. This approximation is not valid in the case of high gradients of the contamination over distances below 100 m. The vertical distribution of the contamination is not considered in the case of deposition to canopies (e.g. forest). Independent of local land use deposition to lawn is assumed everywhere and according to this the ground gamma radiation is calculated.
2 The ATSTEP-Code

The ATSTEP code (programming language: FORTRAN) is integrated in RODOS/RESY as a subroutine of the prognosis-(Fig. 8) and diagnosis-modules (Fig. 9) in the subsystem ASY. ATSTEP is called in each step of a loop corresponding to the time steps of a dispersion prognosis or diagnosis calculation. The prognosis time step is 30 minutes, the diagnosis time step is 10 minutes.

Fig. 8: Environment of ATSTEP
Prognosis module

- Initializing of the prognosis run
  Input
  coordinates, grid, RODOS fix data

- Preprocessing a series of meteorological prognosis data

- Preparation of forecasted or measured and extrapolated source term data

- Subroutine FINRISE
  Precalculation of thermal rise

- Subroutine ATSTEP
  Calculation of an atmospheric dispersion and deposition prognosis for 24 hours, including gamma radiation.
  Archiving of contamination and radiation fields

- Subroutines ADORAT and ADOPOT
  Calculation of gamma dose rates and potential doses for each half hour step of the prognosis

- Subroutine DOSBAU
  Calculation and Archiving of 24 hours potential dose histories for each grid location;
  (dose bricks for ECM-EMERSIM)
Initializing of the diagnosis run
Input coordinates, grid, RODOS fix data

Preprocessing measured meteorological data
Preparation of measured or assessed actually released source term fraction

Subroutine AURED: Read in of stored trajectory and puff data of the last time step
Subroutine AUCYC: Re-numbering of all puffs indices if the oldest puff leaves the grid

Subroutine FINRISE
Precalculation of thermal rise for the puff currently released

Subroutine ATSTEP
Calculation of atmospheric dispersion and deposition for the puffs released, including gamma radiation.
Archiving of contamination and radiation fields

Subroutines ADORAT and ADOPOT
Calculation of actual gamma dose rates and potential doses for each 10 minutes step of the diagnosis

Subroutine AUSTORE: Store trajectory and puff data of the actual time step

Fig. 9: Environment of ATSTEP
Diagnosis module
2.1 Inner structure of the ATSTEP code

The inner loop structure of ATSTEP, the sequence and contents of subtasks is shown in the diagram in Fig. 10.

The initialisation is carried out during the first time step, at M=1. All concentration and dose arrays are set to zero, other variables get their initial values. During all later time steps with M >1 this part is skipped.

The slowest loop is the loop over the released puffs. These puffs have been emitted from the source from the start of the release at time step M=1 until the time step M (inclusively). The number of these puffs is equal to M or less, because, if there are intervals with no releases, the corresponding puffs are omitted and not counted. In the puff loop the geometrical properties like location, orientation, and size are calculated. This includes the calculation of the height of the puff in the case of thermal rise and its local dispersion parameters. Furthermore each puff's remaining relative source term contents, which decreases due to depletion, is calculated for each of the 4 deposition groups (noble gases, elementary iodine, organically bound iodine, and aerosols).

The next loop (nested in the puff loop) is the loop over all relevant grid cell locations on the calculation grid. It serves to calculate each puff's normalised concentration distributions and map them to the calculation grid. To avoid zero calculations there are frames for calculation around each puff. In this loop the Gaussian formulae, the error functions, the dispersion parameters, the time integrations, and the cloud gamma radiation fields are calculated.

The next loop (nested in the locations loop) is the loop over the deposition groups. Here the deposition and depletion, and the resulting concentration and radiation fields of the noble gases, elementary and organically bound iodines, and aerosols are calculated.

The inner loop (nested in the deposition groups loop) is the loop over the nuclides contained in the source term. Here the nuclide specific concentration and radiation fields are calculated by connecting the nuclide and time specific source term information with the corresponding normalised puffs of the deposition groups. The final fields are the sums over all contributing puffs with corrections for radioactive decay.

The program ends with the closing of all loops. It is ready for calculating the next time step in the M+1 cycle of a prognosis or diagnosis calculation (Figs. 8 and 9). At the beginning of the next time step ATSTEP needs all local variables to have their last values, i.e. the values of the past time step. In the prognosis mode this is done with the option „save locals on“, so the locals are saved and not set to zero automatically.

In the diagnosis mode this is not possible because the execution of the diagnosis module is finished after each calculation step and memory is closed down. Therefore a stop and restart mechanism is used: At the end of each diagnosis step all geometrical information containing position and orientation of trajectories and puffs, and all time integrated fields are stored in files (Subroutine AUSTORE). At the beginning of each new diagnosis step these files are read in again (Subroutine AUREAD). In this way the diagnosis can be continued without forgetting the past (see Fig. 9).
Initializing at time step $M=1$

- met. data, transport vectors, geometry

Loop over the puffs released during time step $M$

- Puff trajectories up to time step $M$
  - Thermal rise
  - Vertical wind- and mass profile
  - Travelled distance and times, calculation frame

- Sigma-parameters at front and end points and relative depletion of puffs during time step $M$
  - in all deposition groups

Loop over the grid points and monitoring locations in the calculation frame

- Transformation of coordinates:
  - Translation and rotation to location and axis orientation of the current puff in time step $M$

- Preparation of calculation of concentrations:
  - local sigma-parameters, time integral error functions, Gaussian formulae incl. reflections, cloud gamma.

Loop over the deposition groups

- Local depletion of puffs,
  - calculation of normalized concentration-, contamination-, and gamma radiation fields
  - of all puffs in time step $M$

Loop over the nuclides in the deposition groups

- Connecting the puff fields to the source term:
  - calculation of nuclide specific concentration-, contamination-, and gamma radiation fields
  - in time step $M$

End of loops over the nuclides, deposition groups, grid points and monitors, puffs

Fig. 9: Program structure of ATSTEP
References


[9] Jacob, P., Müller,H.M., Gamma Exposure from Bi-Gaussian Clouds, GSF.