MODELLING OF RADIONUCLIDES TRANSPORT DUE TO ATMOSPHERIC RELEASES USED IN THE VARIOUS STAGES OF NUCLEAR POWER PLANT DESIGN

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ABSTRACT
Two program products have been developed for purposes of assessment of radiological consequences of radionuclide releases from nuclear facilities to atmosphere. Routine atmospheric releases during normal operation of nuclear power plant are treated by program product NORMAL. Accidental releases are analysed in the system HAVAR. The basic driving variables of time integrated near ground activity concentration of radionuclides in air and deposited activity on surface are estimated under several model options. In the final stage the various endpoints of radiological consequences assessment are calculated. Both systems offer a user-friendly interactive support in the stages of entering of input data and presentation of results.

KEYWORDS:
ROUTINE AND ACCIDENTAL RELEASES FROM NPP; ATMOSPHERIC DISPERSION AND DEPOSITION MODELLING; FLOW MODELS; GAUSSIAN STRAIGHT-LINE MODEL; SEGMENTED MODELS; DOSES DUE TO IRRADIATION; FOOD CHAIN MODEL; CODE COMPARISON

INTRODUCTION

Substantial part of the radiological consequences assessment insists in realistic modelling of radionuclide transport in the atmosphere and penetration into the living environment. Processes of the advection and diffusion result in dilution of admixtures in the plume and special removal mechanisms lead to their deposition on surface.

The second stage follows when further transport of radionuclides in direction to human body continues. Various possible pathways of the transport are taken into account which result in:

- Exposure to external irradiation from the passing cloud
- Exposure to external irradiation from deposited radionuclides
- Internal irradiation due to inhalation of radionuclides from the passing cloud
- Inhalation of resuspended radionuclides originally deposited on the ground
- Internal irradiation from radionuclides contained in contaminated foodstaffs (ingestion)

The final endpoints of the assessment are various short-term or long-term organ doses of irradiation referring to conditions either at particular points or summed over the population. All the endpoints are calculated on the basis of driving values of radionuclides concentration and deposition or their time integrated values. Then, sufficiently fine and precise spatial distribution of the two main driving variables have to be determined in advance in order to obtain reliable final assessment.

The description of radionuclide transport brings more complications than case of common admixtures. Radioactive decay and daughter build-up during the period of the plume travel have to be taken into account for concentration of activity in air and during the period of persistence on the ground for activity deposition. Furthermore, the governmental regulations for nuclear safety assessment direct the designers to bring evidence related to radiation situation up to 100 kilometres from the source of releases. Consequently, the atmospheric dispersion and radionuclide deposition modelling should take into account the effects occurring at areas of near region and at far distances as well.

Two main kinds of atmospheric releases are analysed here:

1. Continuous releases of radionuclides during normal operation of a nuclear power plant having character of routine releases. In this case the mean annual average values are determined on the

basis of annual frequency of a certain meteorological conditions. The intensity of radioactive material discharges from the source (usually at height about 100 m of the venting stack) is assumed to be more or less constant over a year. Such situation is treated by the code NORMAL

2. Incidental short-term releases from sources at various heights and generally with strong time dependency of their intensity. The period of duration is assumed to be within the range from several hours to several tens of hours and then the possible changes of the meteorological situation should be taken into account. The code HAVAR presents a certain simplified solution of the irregular situations developed for purposes of NPP designers support.

CHOICE OF ATMOSPHERIC DISPERSION AND DEPOSITION MODELS

Atmospheric dispersion of airborne nuclides is determined by mechanisms of advection and diffusion transport. The processes are realised in the turbulent layer near the ground with upper boundary H_{mix}, where wind shear and surface heating/cooling represents source of the turbulence. Atmospheric transport is described by wind field which generally determine the trajectory along which the radioactive plume travels. The diffusion processes are initiated by turbulent motion of atmosphere and cause the spread of admixtures vertical to transport direction. According to the two processes of advection and diffusion, atmospheric dispersion model consists of the two separate models of flow and diffusion, which are analysed independently.

Flow models in general generate meteorological fields of wind and precipitation and many important factors have to be taken into account such thermal structure of the atmosphere, land cover characteristics and orography of the terrain. Various models have been derived with various complexity of their algorithms and ability to describe the real situation, such as:

- Single-point model: The wind speed and direction is assumed to be constant over the entire analysed area resulting from the measurement at the site of the nuclear facility. It holds true during simple condition of the flat and homogenous terrain and stationary conditions.
- Multiple-point model: The wind field is calculated on the basis of interpolation from measurements at two or more meteorological stations. The situation can be simulated in the case of adaptation of the Gaussian segmented model.
- Complex sophisticated models: Various techniques starting from mass-consistent type of interpolation schemes to 3-D calculations of flow and turbulence over complex terrain during non-stationary conditions.

As for diffusion models the surface roughness of terrain and thermal stability of the atmosphere have to be taken into account. The following methods ranked with respect to complexity were derived:

- Gaussian plume model: Radioactive material is assumed to disperse perpendicularly to a straight-line transport direction to the Gaussian probability distribution.
- Segmented Gaussian plume models: The real time interval of the total release is subdivided into stepwise intervals, where meteorological conditions and release intensity are assumed to be constant. Then, the changes in wind directions, wind velocity and category of atmospheric stability can be taken into account. At the same time a stepwise approximation of the real dynamics of release intensity can be adopted as well.
- More sophisticated complex models : Lagrangian puff models, Lagrangian particle and Eulerian grid models, which are able to consider complex 3-D solution.

In principle any diffusion model can be combined with any flow model. However for achievement of the endpoints stated above the corresponding optimum levels of the both compartments should be adjusted. Well-balanced solution with respect to complexity, accuracy, availability of the algorithm and its computing time should be found.

The choice of the dispersion models for continuous releases treated in the code NORMAL, where mainly mean annual average values are determined on the basis of many times repeated calculations, leads to selection of a simple flow and diffusion models represented by the single point flow model and basic Gaussian plume model. It leads to Gaussian straight-line solution and its applicability is in general increased in such analysis where averaging procedures take place (weighting by annual weather statistics, meteorological sampling procedure used within extensive probabilistic PCA studies).

DEPOSITION MODELS AND DEPLETION OF THE PLUME

Several mechanisms act to further reduce the concentrations of the initially discharged activity. The radioactive plume is depleted by dry and wet deposition as well as radioactive decay. On the contrary the radioactive decay for some nuclides may lead to creation of daughter products which have to be taken into account. Daughter products will grow into the plume with the decay of the parent radionuclide.

Source depletion model accounts for reduction of concentration downwind due to the removal mechanisms. It insists in substitution of the original values of source intensity A^n of radionuclide *n* in $Bq.s^{-1}$ by modified source intensity $A^n(x)$ related to loses from source up to downwind location *x* . Original intensity A^n in the Gaussian straight-line solution for activity concentration is substituted by $A^n(x)$ according to relation:

$$A^n (x) = A^n \cdot F_R^n (x) \cdot F_F^n (x) \cdot F_W^n (x) \qquad (1)$$

The correction factors F represents influence of the removal mechanisms. The following removal processes are considered:

Radioactive decay: Modified source strength of radionuclide *n* for location *x* due to decay can be written as:

$$A^n (x) = A^n \cdot \exp (- \lambda^n \cdot x / u_m) \qquad (2)$$

λ^n is radioactive decay constant and u_m represents mean wind speed

Dry deposition (fallout): The contamination of a surface is characterised by the deposition velocity v_d. It is defined as a ratio of the contamination rate of the surface and the nuclide near-ground activity concentration in the air C in $Bq.m^{-3}$. The deposition velocities depend on surface properties. The dry deposition rate D in $Bq.s^{-1}.m^{-2}$ is given by:

$$D = v_d \cdot C \qquad (3)$$

Total deposition can be calculated using the same expression where concentration C is substituted by its time-integrated value. The corresponding correction factor $F_F^n (x)$ from eq. (1) is calculated on the basis of balance of depleted activity from the plume and deposited activity. The correction factor of fallout F_F is calculated from expression for near-ground activity concentration. Then, the correction factor depends on implemented diffusion model (Gaussian, BOX model etc.).

Wet deposition: There are two basic precipitation mechanisms by which the removal of radioactive particles and gases from the plume occurs:

- washout, when rain is falling through the plume and removes the material throughout the whole of the plume volume
- rainout, when incorporated activity in the rain cloud is removed in dependence on condensation processes within the cloud

Wet deposition rate during rainfall can be calculated using the washout coefficient (wet removal coefficient) Λ [s^{-1}] defined as a fraction of material within the plume removed by rain in unit time. Washout is affected by the size distribution of the rain drops as well as the properties of the diffusing materials (its physical-chemical form). Washout coefficient usually incorporates both processes of washout and rainout. The washout coefficient is expressed as:

$$\Lambda = a \cdot \upsilon^b \qquad (4)$$

where υ is rainfall rate [mm/hour] . Constant coefficient *a* and exponential coefficient *b* are distinguished according to the following physical-chemical forms:

- aerosols
- elemental iodine
- organically bound iodine

As for noble gases they are assumed not to be affected by fallout and washout. Some modifications are given also for case of snow or hail types of precipitation. The resulting source depletion for radionuclide *n* due to washing mechanisms is assumed in the form:

$$F_W^n(x) = \exp(-\Lambda_n \cdot x / u_m) \quad (5)$$

ATMOSPHERIC DISPERSION MODEL OPTIONS IN *NORMAL* AND *HAVAR* PRODUCTS

Single point flow model and Gaussian model for diffusion of the plume are used in both products. The original well-known Gaussian straight-line solution is used which results from the diffusion / advection equation. Empirically determined horizontal and vertical σ parameters derived from the statistical theory of turbulence are dependent on turbulence in the boundary layer, it means on category of atmospheric stability. Pasquill-Gifford notation is used where stability conditions are divided into six classes A (extremely unstable) to F (moderately stable). The σ dispersion parameters are experimentally defined and can be obtained from semiempirical formulas or graphs as a functions of the downwind distance for each stability class.

The straight-line Gaussian plume model was originally derived for idealised conditions of flat terrain, uniform surface roughness and constant atmospheric conditions and it is strictly applicable in only a limited range of atmospheric and environmental conditions. The Gaussian model is not applicable neither in calm or near calm conditions nor for non-stationary conditions. On the other hand the model is semiempirical in nature and many other phenomena could be more or less successfully considered, such as:

- Effect of plume rise on the effective height of emission, which may occur mainly for two reasons: (1) a certain vertical escape velocity due to initial vertical momentum, and (2) influence of upward buoyancy force due to the original heat capacity of releases.
- Near-standing building wake effect, when admixtures released through the venting stacks or leaks in the building will be mixed in the turbulent wake created by the ambient air flow around these buildings.
- Orographic effect and criteria for its incorporation or neglect.
- Occurrence of inversion atmospheric situation, where multiple reflection on the inversion layer should be taken into account. Moreover, for correct calculation of the mean annual values the probability of occurrence of inversion at a height of given category should be available on the basis of annual weather statistics.

Special attention in both products NORMAL and HAVAR has been directed to determination of the diffusion parameters σ_y (x) and σ_z (x) and their dependence on downwind direction x , stability category, surface roughness and effective release height. Several options are offered from the input menu and user can select the proper one according to his consideration. The diffusion parameter options are:

1) Parameters σ_y (x) and σ_z (x) for urban locations (in principle for rough terrain including built-up areas and forests). A set of diffusion coefficients has been derived on the basis of tracer dispersion measurements for higher surface roughness (1 - 1.5 m) and is expressed in the exponential form:

$$\sigma_y = p_y \cdot x^{qy} \quad (6)$$

$$\sigma_z = p_z \cdot x^{qz}$$

The data is called Karlsruhe-Jűlich set and is additionally defined for three different release heights of 50 m, 100 m, 180 m. These calculation formulas are valid up to about 10 km distance from the release point.

2) Diffusion parameters σ_y (x) and σ_z (x) for rural areas including flat open terrain with small roughness. Two alternative options are available:

- Hosker-Smith formulas derived for smooth terrain with further discrimination for roughness ≥ 0.1 m and < 0.1 m . The results are presented up to distances of 100 km.
- Mol - parameters derived at SCK/CEN, Mol, Belgium on the basis of the tracer experiments over a rather smooth terrain (roughness from 0.1m to 1m) which have the same form such expression (6). The results have been checked for hourly values at a height of 69 m above surface.

The above options are offered to NORMAL/HAVAR user with additional modifications (multiple reflection on inversion layer and upper boundary of mixing layer). Separate BOX model is incorporated such a proper tool for treatment of non-standard conditions and for purposes of marginal estimations.

The computer codes automatically apply correction of the diffusion coefficient for far fields. In accordance with (Modelle, 1992) the maximum value of the σ_z (x) can extend to value of 0.8 * H_{mix} and then the turbulent vertical mixing finally generates an uniform profile of the vertical contamination. For σ_y (x) calculated according to (6) is used the correction (ATSTEP approach) for distances x > 10 km in the form:

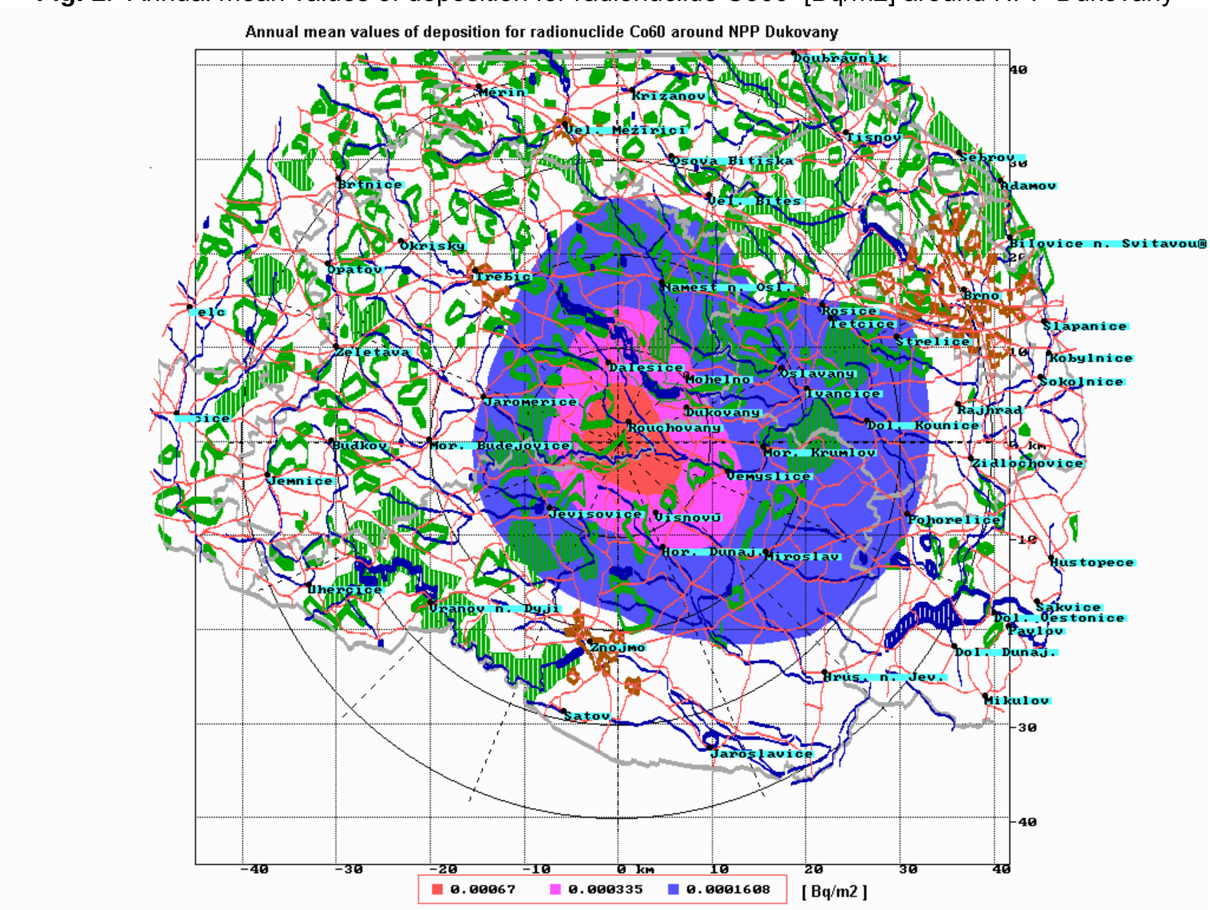
$$\sigma_y \,(x > 10 \text{ km}) = B \,.\, \sqrt{x} \qquad (7)$$

where constant B is determined from the assumption of smooth change of the variable σ_y (x) at distance of 10 km. Combinations of the above diffusion formulas for near range areas with homogenous BOX model for far fields are incorporated as well.

A PROCEDURE FOR DETERMINATION OF THE TIME-AVERAGED ANNUAL VALUES

Basic endpoint of the code NORMAL is to determine time-averaged mean annual values of activity concentration and deposited activity in the whole area of a nuclear power plant up to distance of 100 km (for all 16 angular sectors of the windrose). Let us consider one real situation with category of atmospheric stability *j* , when wind blows in direction *k* of windrose with speed from wind category *m* . Moreover, atmospheric precipitation occurs with intensity from category *s*, inversion situation occurs with inversion height from category *g* (s = 1, g = 1 => no precipitation, no inversion occur). The mean values over the sector *k* of windrose for the activity concentration C_k^n (x; j,m,s,g) of radionuclide *n* in air is given by the Gaussian straight-line solution.

Fig. 1: Annual mean values of deposition for radionuclide Co60 [Bq/m2] around NPP Dukovany



The calculations are repeated for all possible values of the indexes j,m,s,g and the resulting mean annual values are computed by weighting the particular values by annual weather statistics QW(k,j,m,s,g) given by the National Meteorological Service. In practice, only QW(k,j,m) and separate probabilities PS(s) of atmospheric precipitation and PIN(g) of inversion situation occurrence are so far available. Final annual mean activity concentration MC_k^n (x) of radionuclide _n_ in the direction _k_ and radial distance _x_ from the source can be schematically expressed as:

$$MC_k^n\,(x) \;=\; \sum_{(j)} \sum_{(m)} \sum_{(s)} \sum_{(g)} C_k^n(x;j,m,s,g)\cdot \mathrm{QW(k,j,m,s,g)} \qquad (8)$$

The similar scheme is used for calculation of other annual values. Such an example is given on fig. 1 the 2-D plot of annual mean values of deposited activity of radionuclide Co60 on the ground. Prevalent annual wind directions can be recognised from here. The results are displayed over a real map background of the locality of NPP Dukovany. The picture was generated on the screen by the interactive presentation module of the system NORMAL.

We can conclude, that for purposes of analysis of the routine releases the semiempirical Gaussian plume model is reasonable approximation. The model is still widely adopted not only for its simple form, but also for its close connection to the experiments when the parameters values are related to readily measurable quantities. It is also considered suitable where the endpoints of the calculations are long-term average or time integrated variables. The same conclusions were confirmed during extensive PSA studies in the case of probabilistic calculations. It was found that the choice of atmospheric model was not a major contributor to the differences observed.

ANALYSIS OF ACCIDENTAL RELEASES

We can hardly rely on the basic Gaussian plume model to be able to describe realistically the current radiological situation during an accidental release. Only the simplest cases having the character of marginal studies or estimation for the „worst case“ of hypothetical situation can give the reasonable results (anyway, the special worst situations have to be verified during the design stage of a nuclear facility, too). The accidental release is characterised in general by variable release intensity of the radioactive products and strong dependence on changes of meteorological conditions in the site vicinity.

An attempt to adopt the situation is done by introduction of the segmented Gaussian plume model. The real process is divided into several time segments during which the weather characteristics and release intensity is assumed to be constant. Each segment is treated separately and the resulting values are given by superposition of the partial results. Then, the solution can take into account time changes. The question is, how the time changes are reflected in the whole area of NPP.

The first simplest approach of the segmented model included into HAVAR assumes each segment to <u>travel in its original direction all the time</u> without any dependence on the original directions of the other successive segments. Then, each segment is treated separately and it is fully described by Gaussian straight-line model.

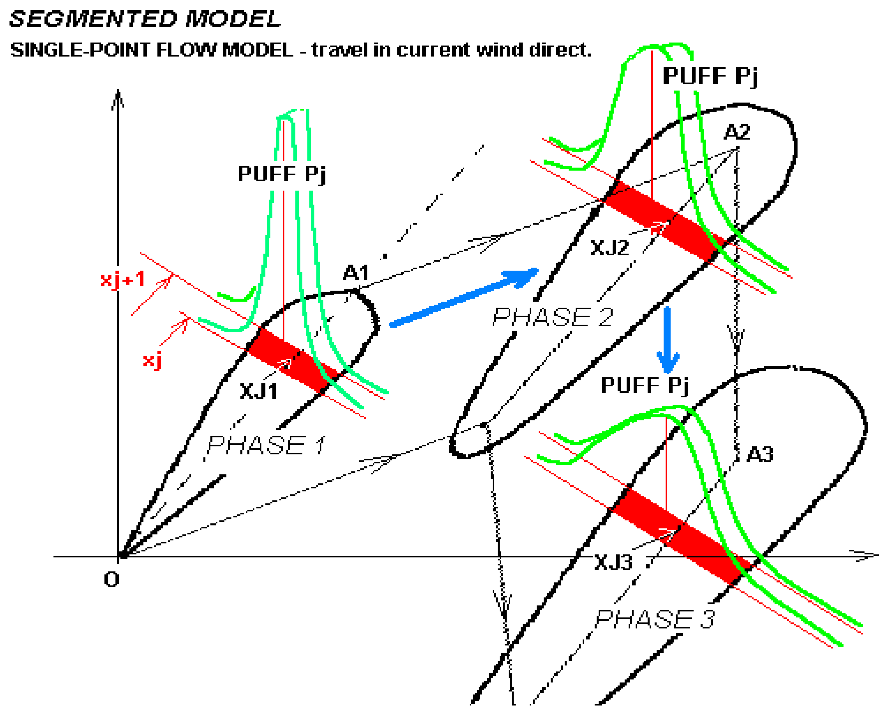
The second approach: More realistic modelling was introduced on the basis of algorithms of model ATSTEP (Päsler-Sauer, 1997). <u>All material travels in the current wind direction</u>. The stepwise changes of the meteorological conditions and release intensity are applied in the whole area (single point flow model under stepwise changes). The whole situation is described on fig. 2. The phase 2 of a segment is shifted from its original direction according to the direction of the new successive segment and the lateral transport is no longer directed along the segment axis.

The segment is assumed to be created from a certain number NJ of Gaussian puffs. Length OA1 is divided into elemental puffs _j_ having width xj+1 - xj = Δx = u_m . 1 sec (modification for larger puffs of _n_ seconds is clear). Longitudinal diffusion in the phase 1 is now taken into account when assumption about longitudinal diffusion coefficient is done on the basis of some proportionality σ_x (x) ~ σ_y (x). During its transport from the source O to XJ1 the puff Pj spreads horizontally and vertically according to Gaussian formula which enables to calculate original concentration C_{orig} (XJ1,y,z) at distance XJ1 = xj + (xj+1-xj)/2 (without effect of longitudinal transport). According to ATSTEP approach the longitudinal diffusion is now modelled by the error-function with parameter σ_x (x). Taking into account the contribution of the neighbouring puffs from interval OA1 the modified activity concentration C_{mod}(XJ1,y,z) at distance XJ1 incorporating effect of the longitudinal diffusion can be expressed as:

$$C_{\mathrm{mod}}(XJ1,y,z) = \sum_{j=1}^{j=NJ} \frac{1}{\sqrt{2\pi}\cdot\sigma_x(x_j)} \cdot \exp(-\frac{(XJ1-x_j)^2}{2\sigma_x{}^2(x_j)}) \cdot C_{orig}(x_j,y,z) \qquad (9)$$

where x_j = (xj+1 + xj)/2;

Fig. 2: Segmented scheme – material travels in the current wind direction



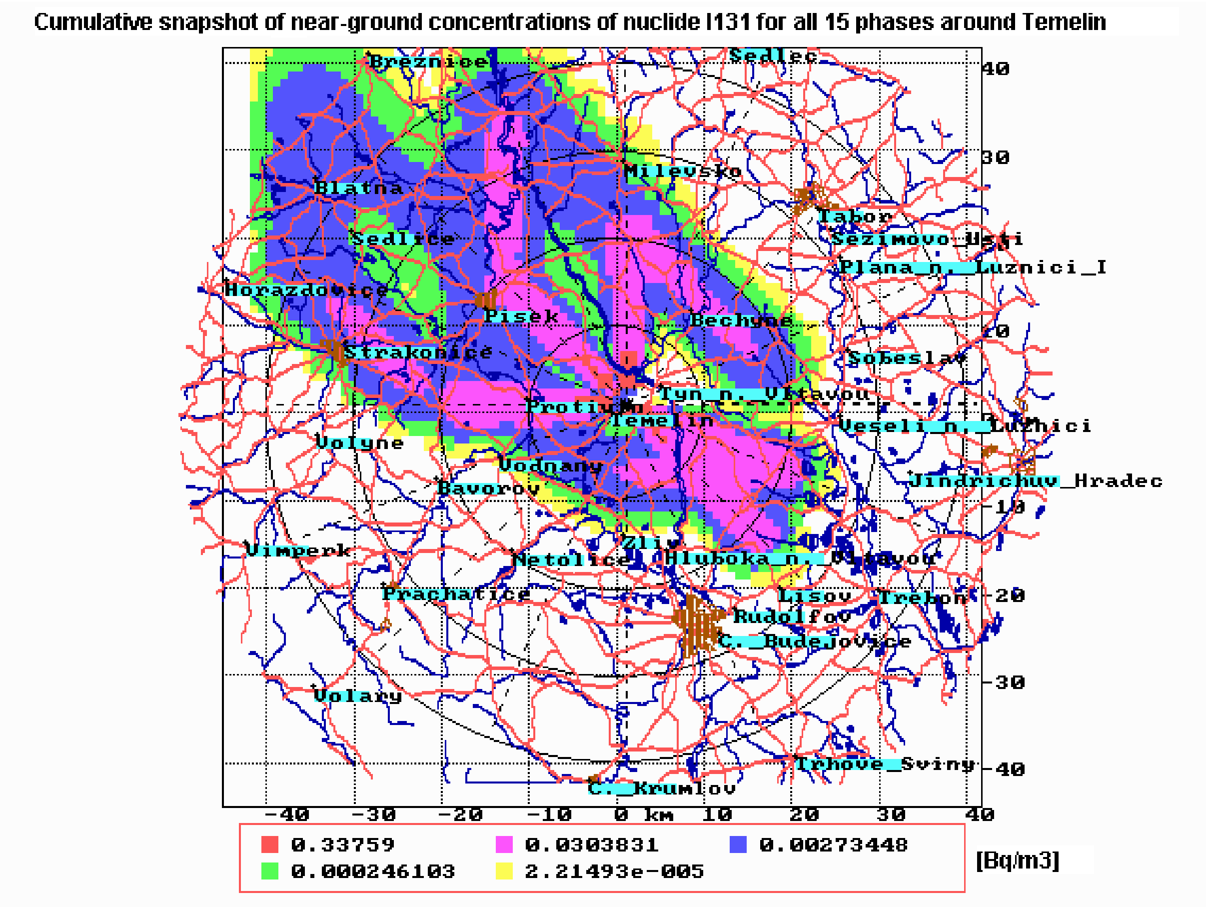
During further transport of puff P1 the trajectory O-> XJ1-> XJ2-> XJ3 .... is modelled. At the same time the depletion of the puff together with deposition on the surface is calculated ensuring the balance of the activity depleted and deposited. The resulting values of time integrated concentrations are determined using some simplifications but respecting the real time scale in all phases. Final superposition from all puffs is performed. For case of dose of irradiation, the resulting values are summed over all radionuclides contained in the release. An example of the segmentation is given in table 1 and fig. 3.

Tab. 1 : An example of segmentation of the total release to 5 consecutive time segments

segment no.	*release direction*	*release duration within segment*	*Pasquill stability category*	*relative release rate*
1	7 (SE)	7 780 s	D	0.2
2	1 (N)	7 200 s	D	0.2
3	15(NW)	7 200 s	D	0.2
4	13 (W)	7 200 s	D	0.2
5	6 (SEE)	7 200 s	D	0.2

Corresponding results for ground-level activity concentration in air for radionuclide I131 are displayed on fig. 3. Cumulative snapshot of the results of all segments in all phases (It means 15 plumes in total) are presented here. The same weather categories were selected because of better discrimination on the screen. The results are displayed over a real map background of the NPP Temelin locality. The picture was generated on the screen by the interactive presentation module of the system HAVAR.

Fig. 3: Segmented release according to tab. 1 – near ground activity concentration of I131 in air, all phases in their particular final stages – cumulative snapshot



The third approach of the segmented Gaussian plume model, which is just under implementation in the code HAVAR, can adopt the multiple-point flow model where the wind field is calculated on the basis of interpolation from measurements at more meteorological stations. The situation is schematically drawn on fig. 4. In common, the segment is in its successive phase submitted to shift, rotation and dilatation.

The following options for subdivision of the total release into the partial segments is adopted in the system HAVAR:

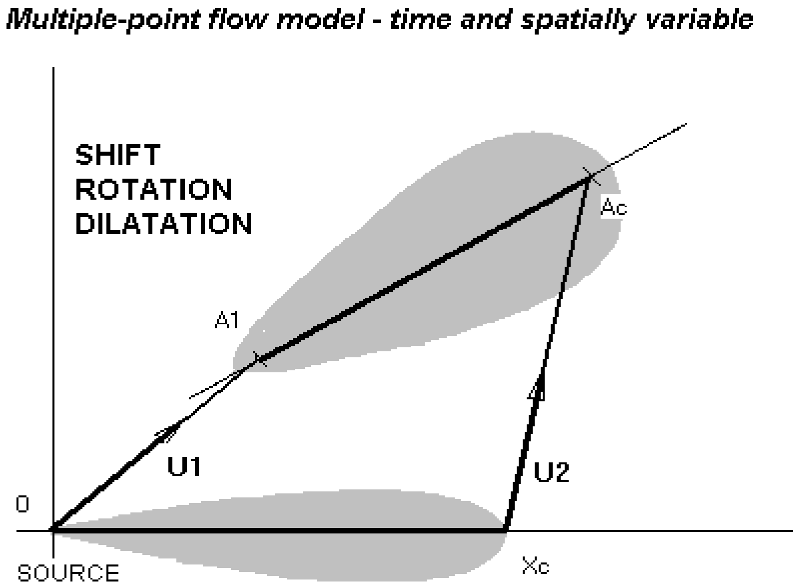
1. Batch option: The whole subdivision is done interactively in advance from the input panels. So far maximum 5 segments is allowed.
2. Interactive option: The successive segment is determined interactively and the calculation starts from the current state. The results are superimposed to the initial values calculated in the previous step and the new situation is displayed according to user option from the output interactive presentation panel. The system waits for entering of the new data for the successive segment. The calculations could have character of diagnosis or prognosis according to the incoming data nature (real-time meteorological measurements or meteorological forecast). The option is in stage of tuning and testing.

CONCLUSION

Both products NORMAL and HAVAR are “alive” products with continuous development and maintenance under sponsorship of ENERGOPROJEKT Prague. Then, any changes initiated either by the new requirements of users during their activities related to NPP design or by the new regulations issued by the national authorities for areas of the nuclear safety can be easily implemented with short response time. Particular models of the systems are customised for the territory of the Czech Republic and particularly for localities of both NPP Dukovany and Temelin. Extensive customisation on the national and regional scale was performed for dynamic model ENCONAN describing the successive transport of radionuclides in the food chains.

The products were submitted for process of standardisation according to the rules following the new Czech Atomic Law. The process is obligatory for any software used for calculations in the field of nuclear safety. Important part of the standardisation process is running of given obligatory validation tasks.

Fig. 4: Consideration of time and spatially variable conditions within the segmented model



Extensive comparative studies with commonly accepted international codes were done. For case of accidental releases the results according to HAVAR were compared with partial deterministic runs of the COSYMA code. The same validation tasks had to be prepared during the RODOS accreditation procedure for its use in the Czech Republic (Pecha, 1998) and then the results were compared to the corresponding HAVAR results, too (Pecha, 1999 – Part III). Annual-average values of all main variables (ground level concentration of radionuclides, deposited activity, gamma doses) were compared between products NORMAL and PC CREAM (Pechova, 1998).

The process of customisation of various modules and an attempt to adopt local data for its use in the other foreign program products during the comparative studies have brought a good evidence why to simultaneously develop own local codes.

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