APPLICATION OF MULTI-PATHWAY TRANSPORT MODEL FOR REGULATION OF NORMAL ATMOSPHERIC RADIOACTIVE DISCHARGES FROM NUCLEAR FACILITIES

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INTRODUCTION

Radiological impact of routine radioactive atmospheric releases on population has to be minimised and rigorous evidence of the compliance with governmental limits and regulations has to be brought. The functional relationship is modelled between the annual routine releases of radionuclides to atmosphere from nuclear power plant (NPP) and corresponding irradiation of a person from critical group of inhabitants. All specific features of activity transport have to be taken into account starting from the same beginning of incorporation of airborne admixtures into the plume, their dispersion and depletion from the plume due to various removal mechanisms. Further movement over the terrain according to the current wind field results to the propagation of radioactivity into the living environment. Because of long-term character of the releases the annual weather statistics is used for averaging the particular atmospheric situations. Consecutive determination of the expected annual values provides for estimation of resulting irradiation burden.

The main expected annual values are represented by resulting spatial distributions of the activity concentration of radionuclides in the air, their deposition on the ground due to dry and wet deposition processes and activity deposition rates. The values implicitly incorporate effects of all parameters entering into the previous atmospheric modelling (spatial distribution of the *surface type* and *elevation profile*, selected formulas for determination of dispersion parameters and vertical *wind profile*, *site-specific characteristics* of the release including the release height, initial plume rise, *near-standing building effects* and long-term site-specific weather statistics, etc.) - see more detailed description in *Pechova, E. (1999), Pecha, P.(1999)*. On the basis of the main expected annual values the further multi-pathway activity transport in direction to the human body is modelled. Finally, the external and internal irradiation expressed in terms of annual doses due to pathways of cloudshine, groundshine, inhalation (including resuspension) and ingestion of contaminated foodstaffs are determined.

Significant contribution to the total doses is caused by the ingestion pathway. The new improved dynamic algorithm of the NORMAL code accepts the real situation of the ecosystem being submerged into the continuously contaminated environment where the customary agricultural practices are applied - *Pecha, P. (2000).* Instead of deposited activity on the surface the new driving variable of instantaneous activity deposition rate is introduced. It enables more precise modelling of the time dependency of the activity deposition on soil and plants due to the vegetation periods.

As a result of radionuclide transport analysis around the source of pollution a set of site-specific conversion coefficients in Sievert/Becquerel is provided for each nuclide which represents the effect of normalised annual release of 1 Bq/year. Then, the quick estimation of the real annual dose can be found by multiplying the real annual activity release by the conversion coefficients. A certain trend can be introduced for time-dependence of the deposition rate during the year and then an optimisation of the annual discharges distribution can be modelled. Specifically, the effect of shift in the long-term maintenance shutdown with regards to vegetation periods on the averted dose due to ingestion is quantified.

PROGRESS IN ATMOSPHERIC DISPERSION MODELLING

The methodology used for atmospheric dispersion modelling for both normal and accidental releases of radionuclides is described in *Pecha, P. (1999*), where a choice of proper atmospheric dispersion model for the particular cases is discussed. For short-term accidental scenarios the segmented Gaussian plume model (and more precise algorithm ATSTEP for hybrid plume –puff model originally developed for the RODOS product) is adopted for purpose of taking into account dynamics of the release and changes in current weather situation (step-wise approach). As for normal routine operation the procedure for determination of the time-averaged annual values (spatial distribution of near-ground activity concentration in air, activity deposited on the ground and averaged deposition rate up to 100 km from the source of pollution) is based on procedure of weighting the real particular situations (described by a certain atmospheric stability category, wind speed and direction, precipitation intensity, occurrence of inversion situation) by the annual weather statistics. For such averaging procedure the Gaussian straight-line solution is generally applicable and justified. Let us notice that several options for dispersion calculations are offered (semiempirical dispersion formulas for rough or smooth terrain, box-model homogenisation) for purposes of uncertainties analysis or "worst case" scenario studies.

The further development has established close connection of inputs with the existing external fine gridded geographical data. The newly developed **data preprocessor** transforms for each NPP site the detailed available spatial information related to elevation, roughness and land use type (in absolute geographical coordinates) to the required calculating polar grid with variable cells (relatively to the NPP position). For example the more detailed information relating to the land use (5 categories: water, grass, agricultural, forest, urban) enables to generate the occurrence (%) of each category and then to calculate the mean weighted value of the dry deposition velocity v_g on each polar cell (on the basis of the maximum v_g for fully developed plant canopy recommended in the RODOS product for each physical-chemical form of the radionuclide – aerosol, elemental, organic, noble gas – see Kuca, P. (2001)). For each polar grid *cell (I,K), radial distance interval I, windrose direction K* , the value of the long-term coefficient of dry deposition is expressed as sum of partial dry depositions weighted by the annual weather statistics. For each partial situation characterised by the Pasquill-Gifford weather category *j*, wind direction *K* and wind velocity category *m*, the corresponding partial plume depletion correction factor, which represents the total activity depletion due to dry deposition from the source up to the radial distance x_{I+1}, is expressed as:

$$F^{n}_{dry}(K,I,j,m) = \exp\left\{ -\sqrt{\frac{2}{\pi}} \cdot \frac{1}{u_0^{K,j,m}} \cdot \sum_{i=1}^{i=I} \left[v_g^n(K,i) \cdot \int_{xi}^{xi+1} \frac{\exp(-Hef^2(j)/2\cdot\sigma^2_{z,j}(K,i))}{\sigma_{z,j}(K,i)} \cdot dx \right] \right\} \qquad (1)$$

H_{ef} is effective plume axis height, u_0 is reference wind speed at measurement height 10 m, σ_z is vertical diffusion coefficient at position (K,i) expressed by Karlsruhe-Jűlich exponential set. This represents an improvement in comparison with the former access when v_g^n was assumed to be constant in all radial distances in a certain windrose direction. The similar procedure has been implemented for case of accidental scenarios and then both algorithms are consistent and its meaning increases for rough terrain with extensive forest areas. It is just case of the NPP Temelin, for which generated spatial distribution of conversion factors $K_{eff,tot}$ is displayed in the form of isopleths on Figure 1. Let us notice, that the factors K are strictly assigned to the NNP site of interest and has clear physical meaning as annual effective dose normalised to the unit annual release 1 Bq/year of nuclide I131 due to corresponding external annual irradiation (cloudshine , groundshine) and internal annual activity intake (inhalation, ingestion). Doses from internal activity intake mean the 50-years (adults) or 70-years (children) committed doses. The results enable **quick estimation of the real annual doses** by multiplying the real annual activity release by the conversion coefficients and then represent useful tool for national regulatory bodies. The conversion coefficients are generated also for other nuclides, different critical age categories or various other endpoint values (equivalent doses, for individual pathways). Different types of quantities (normalised annual values of the near-ground activity concentration in the air, normalised annual deposition rates) were calculated and delivered to successive environmental impact assessment (EIA) analysis for NPP Temelin – see *Pecha, P. (2001).*

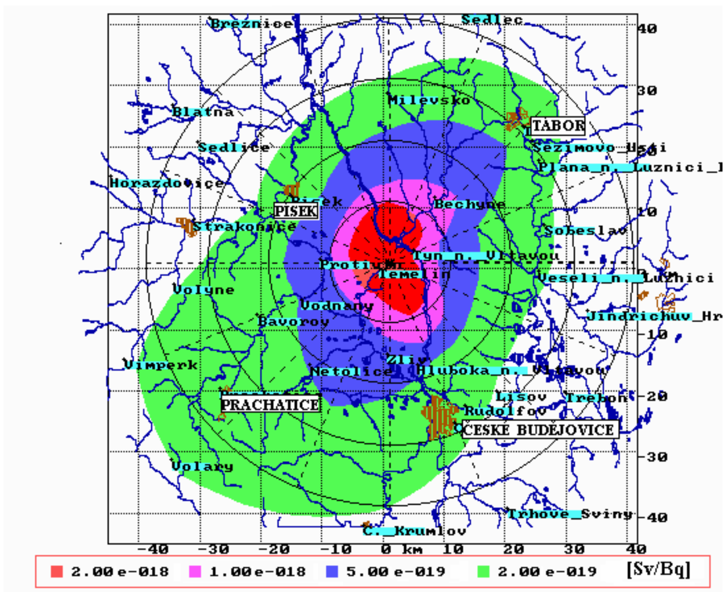

Figure 1. Spatial distribution of factor $K_{eff,tot}$ (Sv/Bq) for conversion of normalised annual release 1 Bq/year of the nuclide I131 to the corresponding annual effective dose (Sv/year) for age category of adults; vicinity of NPP Temelin; multi-pathway transport included (cloudshine, groundshine, inhalation + inhal. from wind-driven resuspension, ingestion).

DYNAMIC FOOD-CHAIN MODELLING

On the basis of current knowledge from early 90's (mainly based on the European ECOSYS code) the local dynamic model ENCONAN (author V. Kliment) for transport of radionuclides through food chains was developed and adopted for average Czech conditions taking into account local *consumption habits* (dependence on season and age), *agricultural production* scheme, average *agro-climatic conditions* and *phenologic characteristics* of the plants, *feeding diets* of animals, *time delays* during processing, transport and storage of foodstuffs and feedstuffs etc. The model was originally developed for incidental radioactive fallout in a certain Julian day of a year. For normal operation of NPP an approach of equivalent number of discrete radioactive fallouts is usually used. The approach was revised and an attempt for more detailed modelling for case of long-termed continuous routine releases is presented in *Pecha, P. (2000)*.

The ecosystem surrounding the NPP is assumed to be continuously submerged into the contaminated environment where customary agricultural practices are applied. Root and foliar uptakes of activity into plants are modelled day by day and contamination of foodstuffs and feedstuffs is predicted on the basis of *equilibrium* soil-plant *transfer factors* and equilibrium transfer factors from feedstuffs into animal products. Annual activity intakes are estimated for both direct consumption of plant products and consumption of contaminated animal products. Conservative ingestion scheme of "*local production-local consumption*" is still used (products produced at place x,y are here also consumed). For more details we refer to *Pecha, P. 2000* where specific features of foliar and root transport of nuclides into the plants are analysed (weathering effects, leaf area indexes during vegetation periods, growth dilution, translocation to edible parts of plants, nuclide mobility etc.). Let us mention only the latest extensions being developed for purposes of more detailed optimum regulation of annual radioactive discharges. It relates mainly to possibility to accept a certain trend in time dependence of release intensity during a year instead of homogenous release.

In the following text the specific activities are normalised to the homogenous unit deposition rate 1 Bq/(s.m^2). As for foliar transport, the specific activity ε^n_l of nuclide *n* [m^2.s.kg^{-1}] at time t' after harvest (normalised to unit deposition rate) that was cumulated in 1 kg of the plant *l* during the whole vegetation period < t^l_{veg} ; t^l_{har} > is expressed as

$$\varepsilon^n_l\,(t^l_{har}+t') = \left\langle\ \frac{1}{V^l_c}\cdot\sum_{ti=tveg}^{ti=thar} SP^n_i\cdot R^l(ti)\cdot Z^l(ti)\cdot\exp\left[-(\lambda_w+\lambda^n)\cdot(t^l_{har}-ti)\right]\ \right\rangle\cdot\exp(-\lambda^n\cdot t') \qquad (2)$$

$V_c^{\,l}$ ….. *yield of fresh product l at harvest time [kg.m^{-2}]*

SP^n_i ….. *coefficient for total daily deposition at day ti ; for unit dep. rate SP = 86 400 [s]*

$R^l(ti)$ ….. *interception factor – fraction of deposition onto plant l in day ti;*
ti ∈< t^l_{veg} ; t^l_{har}>; in dependence on the stage of development of plant canopy;

$Z^l(ti)$ ….. *simple correction factor (empirical formulas) for approximation of the case of translocation of activity from leaves to other considered (edible) parts of the plant in dependence on the vegetation phases;*

λ_w …... *loss activity rate due to weathering [d^{-1}] – a value equivalent to half-life of 25 days is here assumed;* λ^n ….. *radioactive decay rate [d^{-1}].*

The similar detailed modelling is done for root uptake of radionuclides into plants when activity deposition on the ground takes into account also contribution from previous M years of NPP operation. Specific deposition Ω_l^n(M; thar^l) in (s) of radionuclide *n* during vegetation period up to harvest of plant *l* (normalised to the continuous unit deposition rate) represents resulting activity deposition on the ground at harvest time *thar^l*. Furthermore, when using the idea of equilibrium transfer factors, then the specific activity $^R\varepsilon^n_l$ of nuclide *n* [m^2.s.kg^{-1}] (normalised to unit deposition rate) cumulated in 1 kg of the plant *l* during the whole vegetation period due to root transport has form

$$^R\varepsilon^n_l(M;\,t^l_{harl}) = \ \Omega^n_l(M\,;\,t^l_{har})\cdot BV^n_l\ /\ PH_l \qquad (3)$$

BV^n_l .... *soil to plant transfer factor of nuclide n for plant type l [Bq.kg^{-1}plant / Bq.kg^{-1}soil];*

PH_l .... *effective root zone (surface weight of contaminated soil) in [kg/m^2] - depends on ploughing practices (depth of 0.25 m and 0.1 m are assumed for arable soil or pasture soil, respectively; different values are applied for different cuts of forage);*

Modelling of the total activity intake into human body due to ingestion accepts all dynamics parameters of the food chain specific features associated with mechanisms of direct consumption of plants products and consumption of contaminated animal products.

Comment on the specific transport of isotopes H3 and C14: The transfer of tritium and carbon-14 between atmosphere and terrestrial environment is more complex and different from the previous scheme. Its simplified evaluation is based on assumption that living environment components come into rapid equilibrium with the C14 or H3 in the atmosphere. For plants the important role plays foliar uptake during the photosynthesis process. According to the US NRC Reg. Guide 1.109 the concentration of the isotope X in vegetation (X=C14, H3) is calculated by assuming that there is known its equilibrium ratio f^X to the natural component. Concentrations of the nucleus in the plant *l* is in relation to the corresponding value in the near-ground layer of air derived from the annual near-ground activity concentration of X. In the model are used recommended values f^{C14}=1.0 and F^{H3}=0.5.

ONE SPECIAL APPLICATION FOR REGULATORY PURPOSES

Following our intentions in the ingestion pathway analysis, the new access enables to introduce a certain time dependence for daily deposition coefficient in the form SP_i^n = 86 400 * RATE(ti), where the RATE(ti) is relative deviation from unit homogenous deposition rate 1 Bq/(s.m^2). Let us introduce a scenario of the planned reactor maintenance shutdown during a period of 40 days and try to find optimum decision of its realisation in order to minimise the irradiation of population. The "40 days shutdown window" is shifted within a year and corresponding sensitivity on changes of conversion factors (or normalised doses) is calculated. For *ti* inside the window we assume RATE(ti)=0, otherwise RATE(ti)=1. As for ingestion pathway, the largest decrease occurs for shutdown period covering July. The results for nuclide Cs137 is displayed on Figure 2. The shaded area can be interpreted as averted annual normalised dose related to the annual internal intake of Cs137 due to activity release 1 Bq/year of Cs137. Multiplying the values by actual annual Cs137 activity release, the real annual averted dose is determined. Let us notice significant angular variability introduced by real spatial distribution of the surface characteristics which is displayed on Figure 3. The angular distribution of the conversion coefficient K_{eff} without and with shutdown maintenance period is demonstrated in the polar image.

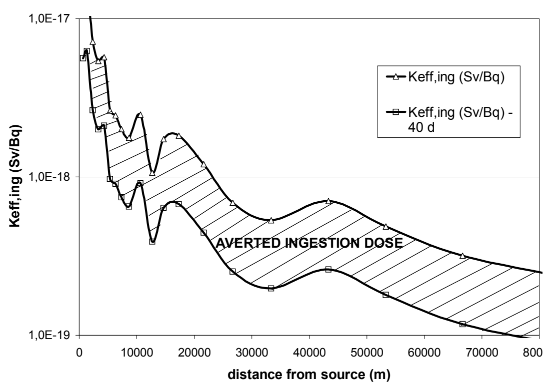

Figure 2. Radial distribution of factors for conversion of normalised annual release 1 Bq/year of the nuclide Cs137 to the corresponding annual effective dose (Sv/year) from ingestion pathway for age category of adults; in North-East direction of windrose of NPP Temelin ; $K_{eff,ing}$ (Sv/Bq) : uninterrupted annual reactor operation; $K_{eff,ing}$ –40d : 40 days regular maintenance shutdown in the period June 25 ÷ Aug. 5 (fully developed vegetation).

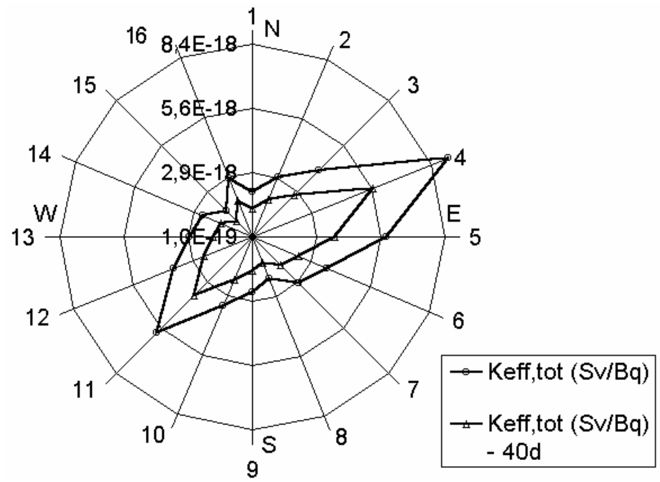

Figure 3. Angular distribution (at radial distance 2,3 km from the source of NPP Temelin) of factors for conversion of normalised annual release 1 Bq/year of the nuclide Cs137 to the corresponding annual effective dose (Sv/year) from all pathways (cloudshine, groundshine, inhalation, ingestion) for age category of children 1-2 years; $K_{eff,tot}$ (Sv/Bq) : uninterrupted annual reactor operation; $K_{eff,tot}$ –40d : 40 days regular maintenance reactor shutdown in the period June 25 ÷ Aug. 5 (fully developed vegetation canopy).

COMMENT ON RESULTS

The described model chain follows the propagation of airborn nuclides on their passage through the living environment in direction to human body. It provides tool for generation of radiological inputs for further EIA analysis. Another application of the results described here can be used for regulatory purposes for optimum schedule of regular reactor maintenance shutdown. The calculations have demonstrated obvious fact, that doses from cloudshine, groundshine and inhalation practically don't depend on season of the year. The annual doses are then decreased proportionally to the reduction of the annual NPP operation. On the other hand the considerable seasonal effect of the shutdown was found for doses from the ingestion pathway as is documented on the previous figures and the following Table 1. The results have been generated for the local food-chain model customised on the average Czech conditions which consists of the following basic plants (beginning of growth and mean harvest dates are in parenthesis):

leafy vegetables - spring (1.5.÷15.6.), *leafy vegetables - autumn* (1.6.÷30.9.),
root vegetables (1.5.÷30.9.), *fruit vegetables* (1.5.÷31.7.), *cereals - wheat* (20.4.÷31.7.),
potatoes (10.5.÷30.9.), *fruit (only root transport)* (1.5.÷30.9.),
barley spring (20.4.÷31.7.), *maize (sillage)* (1.6.÷20.9.), *sugar beet* (10.5.÷20.10.),
forage 1st cut (15.4.÷10.6.), *forage 2nd* cut (11.6.÷31.7.), *forage 3rd* cut (1.8.÷15.10.)

The animal products include: milk (fresh, dry + condensed, cream, cheese, curd + others), meat (beef, pork, poultry), eggs. The corresponding basic dynamical parameters for feeding scenarios and feeding diets were collected, but all should be brought up to date in order to reflect the latest changes in agricultural production practices.

Table 1. Influence of shutdown period on factors for conversion of annual release 1 Bq/year to the total annual effective dose (Sv/Bq) - partial results for ingestion pathway are in parenthesis. The values belong to one point at NE angular dir. and radial distance 5,3 km.

40 days maintenance shutdown interval:	*Annual normalised effective dose (factor K_{eff}) for nuclides:* $H3^{(f)}$	$C14^{(f)}$	$Kr88^{(n)}$	$I131^{(e)}$	$Cs137^{(a)}$
25.2.-5.4. (March)	1.13E-21 (7.33E-23)	6.61E-20 (4.26E-20)	2.94E-21 (0.0)	1.22E-18 (1.04E-18)	3.16E-18 (2.63E-18)
25.5.-5.7. (June)	1.12E-21 (6.38E-23)	6.03E-20 (3.68E-20)	2.94E-21 (0.0)	1.10E-18 (9.22E-19)	2.25E-18 (1.72E-18)
25.6.-5.8. (July)	1.10E-21 (4.63E-23)	5.04E-20 (2.70E-20)	2.94E-21 (0.0)	9.12E-19 (7.32E-19)	1.50E-18 (9.68E-19)
no - uninterrupted whole year operation	1.21E-21 (7.33E-23)	6.90E-20 (4.26E-20)	3.30E-21 (0.0)	1.24E-18 (1.04E-18)	3.23E-18 (2.63E-18)
% of pathway -cloudshine, groundshine, inhal.,ingest.	0; 0; 94.0; 6.0	0; 0; 38.3; 61.7	100; 0; 0; 0	0.1; 9.6; 6.5; 83.8	0.1; 13.4; 3.7; 82.8

(n)....noble gas; (e)....elemental iodine; (a)....aerosol form; (f)....only foliar photosynth. uptake

The reason of the negligible effect of realisation of shutdown on March is connected with the fact of dominant effect of foliar activity uptake in comparison with the root uptake. Moreover the presented calculations relate to the first year of NPP operation when deposition on the ground for long-term nuclides is low. The maximum decrease in the ingestion dose for the 40 days shutdown occurs for period of fully developed vegetation canopy (July in Table 1). The scenario generates significant averted ingestion doses an then decreases the irradiation burden of population.

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