TRAINING SIMULATOR FOR ANALYSIS OF ENVIRONMENTAL CONSEQUENCES OF ACCIDENTAL RADIOACTIVITY RELEASES

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Abstract

The paper presents software system HARP designed for fast assessment of radiological consequences of accidental releases of radionuclides into the living environment. Transport of activity is studied from initial atmospheric propagation, deposition of radionuclides on the ground and spreading through food consumption towards human body. Corresponding model of atmospheric dispersion and advection based on segmented Gaussian plume approach is formulated which can approximately account for release dynamics and short term meteorological forecast. Implemented numerical difference scheme enables to approximate simulations of important parent-daughter pairs formation. Subsequent deposition processes of advected admixtures and food chain activity transport are modeled. The deterministic estimation based on radiation doses resulting from external irradiation and internal activity intake is applied. The product is presented here from viewpoint of its utilization such a training tool for decision support staff. User-friendly interface for input definitions of the task is offered both for atmospheric dispersion and ingestion parts. Interactive graphical subsystem enables to present wide range of results. The algorithm is logically partitioned to time-consuming early stage analysis of accident and interactive late stage consequence estimation. The concept of alternative options and accounting for variability is implemented in the deterministic version described here. Alternative options are offered to user for testing the effect of variability of some input parameters thus providing decision-making staff to improve their perception of the problems.

Keywords: Harmful releases, model predictions, irradiation pathways, user-friendly SW

Presenting Authors' biography

Petr Pecha: Senior researcher. Experience in modeling of random temperature fields in fast reactor fuel assemblies. Development of software tool for PSA LEVEL 3 analysis. Cooperation on customization of the RODOS system. Author or coauthor about 50 reports.

Radek Hofman: Graduated in informatics on the Faculty of nuclear sciences and physical engineering in Prague (2006), now PhD student in the field of assimilation of model predictions with observations in terrain.

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1 General

Transport of radioactive harmful substances originally discharged into atmosphere and their radiological impact on population are treated. Accidental releases of passive pollutants into atmosphere are considered with duration of several hours or a few tens of hours. We are focused on radioactive discharges and their transport through the living environment towards human body. The model chain includes advection and dispersion of pollutants during its propagation in atmosphere, their deposition on terrain and subsequent transport through various food chains causing inner radioactivity activity intake into human body. The following pathways of irradiation are taken into account:

- External irradiation caused by **cloudshine** from radioactive plume drifted over the terrain according to weather characteristics.
- External irradiation from **groundshine** from radioactivity deposited on the terrain.
- Internal irradiation due to internal activity intake during **inhalation** of contaminated air.
- Internal irradiation due to internal activity intake during inhalation of air contaminated by **resuspension** of activity originally deposited on the ground.
- **Ingestion** pathway - internal irradiation due to consumption of contaminated food.

2 Atmospheric and deposition models

Complicated scenario of release dynamics have to be synchronized with available meteorological forecasts so that drifting of radioactive plume over the terrain can be satisfactorily modeled. We have used experience from various modifications of Gaussian model of admixtures dispersion in atmosphere [1,2,3,4]. For our purposes an approach of segmented Gaussian plume scheme has been adopted. We are utilizing short-term meteorological forecast being generated at point of release. Hourly changes of wind speed and direction, Pasquill class of atmospheric stability and precipitation are forecasted for the next 48 hours. Using assumption of activity conservation, the release dynamic is segmented into equivalent number of hourly segments. Each such segment is modeled in his all subsequent hourly meteo-phases when stepwise segment movement is driven by meteorological forecast for the corresponding hours. More detailed description is published in [19]. We shall mention here at least a basic approach how to determine stepwise radioactivity concentration in air, its time integral in the near-ground level and activity deposition on ground.

Radioactive release from a nuclear facility should be treated as a mixture of several tens of the most important radionuclides. Each nuclide (possibly element) has its own decay constant, dose conversion factors, physical-chemical form of admixtures in the plume (noble gas, aerosol, elemental iodine, organic form) determining their deposition ability, release dynamics or environmental transport characteristics (e.g. soil-plant transfer factors for mobile and immobile chemical elements). For simplicity of mathematical notation the index of nuclide will be omitted in the following text. Nevertheless, the HARP system accounts for 132 nuclides and contains extensive database of all necessary nuclide/elements data.

2.1 Segmented Gaussian plume approach

Basic scheme of segmented Gaussian plume approach for description of propagation of admixtures in atmosphere is shown in Fig.1. One-hour segment in its position just after the first hour motion is designated as HOUR1 position. Distribution of activity concentration has typical shape of Gaussian droplet. We describe it using Gaussian straight-line approach. In subsequent hours we shall apply hourly meteorological changes at the point of release provided the hourly changes are immediately applied in the whole vicinity around the source (more precise approach using ALADIN meteorological forecast on spatial grid is in development).

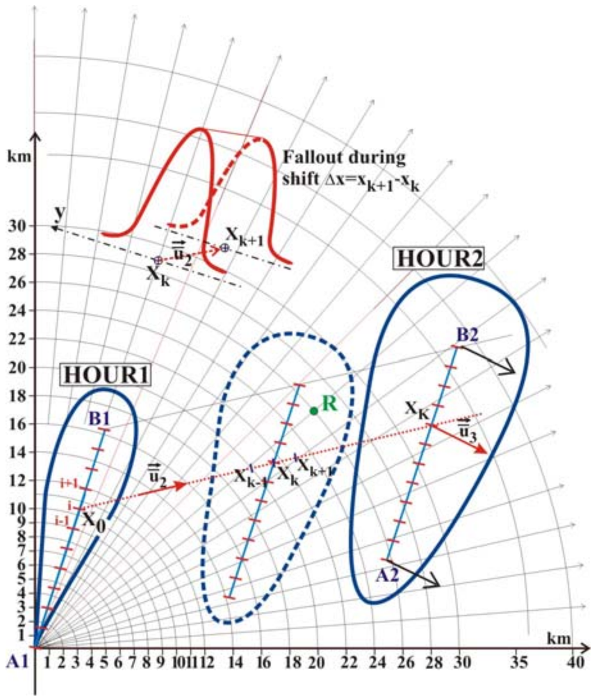

Fig. 1 Segmented Gaussian plume approach for modeling of discharges propagation in atmosphere

Let us analyze segment movement from its position HOUR1. Meteorological forecast for second hour is used and HOUR1 plume segment is drifted the whole second hour with wind direction φ_2, wind speed $\bar{u}_2$, class of atmospheric stability $class_2$ and precipitation intensity υ_2. Total movement from position HOUR1 to HOUR2 is modeled as sequence of K partial shifts starting from known initial position on the plume segment HOUR1 with axis (A_1;B_1) up to HOUR2 with axis (A_2;B_2). Near-ground activity concentrations in air C ($Bq.m^{-3}$) are calculated step by step, where corresponding time steps are 3600/K seconds (values of K ≥ 30 proved to be sufficient). Having results for partial shift *k* (see dashed contour in Fig. 1), then activity concentrations in the next step *k+1* are approximated according to the scheme (we describe development of activity only in the axis point X):

$$C(X_{k+1}) = C(X_k)\cdot\frac{\sigma_y(X_k)\cdot\sigma_z(X_k)}{\sigma_y(X_{k+1})\cdot\sigma_z(X_{k+1})}\cdot \exp\left[-\frac{H_{ef}^2}{2\cdot\sigma_z^2(X_{k+1})}\right]\Big/\exp\left[-\frac{H_{ef}^2}{2\cdot\sigma_z^2(X_k)}\right]\cdot \cdot\Delta f_R\cdot\Delta f_F^{k,k+1}\cdot\Delta f_W^{k,k+1} \tag{1}$$

σ_y , σ_z are dispersion coefficients in horizontal and vertical directions estimated differentially according to atmospheric stability. User can select alternative expressions for a certain roughness of terrain represented by Hosker, KFK-Jűlich or SCK/CEN formulae. Plume activity depletion factors during plume elemental shift k→ k+1 account for:

2.1.1 Radioactive decay:

$$\Delta f_R \;=\; \exp\left(-\lambda\cdot\Delta x/\bar{u}\right) \tag{2a}$$

2.1.2 Dry fallout:

In general:

$$\frac{\Delta Q}{\Delta x} \;\cong\; \frac{1}{\bar{u}}\int_{-\infty}^{+\infty} Depo(x,y)\cdot dy$$

and from definition: (2b)

$$\Delta f_F^{k,k+1} \;=\; Q(X_{k+1})/Q(X_k) =$$

$$1-\sqrt{2/\pi}\cdot\frac{v_g\cdot\Delta x^{k,k+1}}{\bar{u}\cdot\sigma_z(\bar{x}^{k,k+1})}\cdot\exp\left(-\frac{H_{ef}^2}{2\cdot\sigma_z^2(\bar{x}^{k,k+1})}\right)$$

Here Q is schematic expression of total activity inventory in a vertical Gaussian profile (fallout during shift in Fig. 1), $\Delta x^{k,k+1}$ is elemental shift *k→ k+1*. *Depo* is deposition rate in $Bq.m^{-2}.s^{-1}$ given by product of near-ground air activity concentration and dry deposition velocity v_g which is dependant on surface type (land use characteristics distinguishing between water, grass, agricultural fields, forest and urban areas).

2.1.3 Activity washed by atmospheric precipitation:

In general: Wet deposition can be classified (e.g. [1]) as rainout (due to cloud scavenging) and washout (below cloud). Common approach is introduction of washout model with washout constant Λ [s^{-1}]. Washing of radioactive material from the plume to water droplets is in progress during the whole falling and the precipitation induced rate of activity [$Bq.m^{-2}.s^{-1}$] to the ground is given by:

$$P_w(x,y) \;=\; \int_{z=0}^{\infty}\Lambda\cdot C(x,y,z)\,dz \tag{3a}$$

For calculation of Λ we are using expression:

$$\Lambda \;=\; a\cdot I^b \tag{3b}$$

where empirical constants a, b depend on physical chemical form of admixtures in the plume and precipitation intensity I [$mm.h^{-1}$]. Amount of activity depleted from the plume during its partial shift $\Delta x^{k,k+1}$ due to washout is described according to:

$$Q(x_{k+1}) = Q(x_k)\cdot\exp\left(-\Lambda\cdot\frac{\Delta x^{k,k+1}}{\bar{u}}\right) \tag{3c}$$

Finally, the plume activity depletion factor Δf_W from Eq. 1 has form:

$$\Delta f_W^{k,k+1} = \exp\left(-\Lambda\cdot\frac{\Delta x^{k,k+1}}{\bar{u}}\right) \tag{3d}$$

2.2 Difference technique for determination of the main driving values in early stage of accident

For each nuclide in the release there exist four main quantities on basis of which the overall estimation of radiological consequences can be put through without time consuming computing, namely:

- CAP …. near-ground activity concentration in air [$Bq.m^{-3}$] (spatial distribution around the source in polar nodes)
- TIC …. time integral of near-ground activity concentration in air (spatial distribution) [$Bq.s.m^{-3}$]
- DEP …. activity deposited on terrain (spatial distribution) [$Bq.m^{-2}$]
- TID …. time integral of activity deposited on terrain (spatial distribution) [$Bq.s.m^{-2}$]

All other output values like irradiation doses in early or late stage of accident, countermeasure estimation, long-term evolution of specific activities in agricultural products and food bans effectiveness examination, long-term doses from resuspension etc.

can be calculated directly from this four driving quantities using only additional time integration (usually can be expressed analytically).

Let us solve contribution to TIC value of the one-hour plume segment in its second hour movement at the receptor point R (see Fig. 1). As mentioned above, the movement from the position HOUR1 to HOUR2 is realized by means of *k=1, ..., K* partial shifts of the segment from axis in initial position A1B1 to the final position with axis A2B2. Determination of contribution of the segment to the TIC value in receptor point R during its movement from partial position *k* to the next partial position *k+1* is expressed as:

$$\Delta TIC(R;k) = \frac{C(R,k)+C(R,k+1)}{2}\cdot \Delta t(k) \quad (4)$$

Time difference $\Delta t(k) = (x_{k+1} - x_k)/\bar{u}_2$ is set equal for each *k*. Values of near-ground activity concentration C are calculated by means of Eq. (1).

TIC value at receptor point R from all consecutive partial shifts *k, k=1, ..., K* is given by:

$$TIC(R;K) = \sum_{k=1}^{K} \Delta TIC(R;k) \quad (5)$$

Similar considerations concerning activity deposition on terrain around receptor point R can be adopted. Deposited activity at receptor point R due to dry and wet effect during elemental shift $\Delta t(k)$ is approximated as:

$$\Delta DEP(R;k) = \Delta DEP^{dry} + \Delta DEP^{wet} \quad (6a)$$

Contribution from dry fallout:

$$\Delta DEP^{dry} = \Delta TIC(R;k)\cdot v_g \quad (6b)$$

Contribution from the wet deposition in BOX model approach (full vertical homogenization along mixing layer with height H_{mix}):

$$\Delta DEP^{wet} = \Delta TIC(R;k)\cdot \Lambda \cdot H_{mix} \quad (6c)$$

Deposited activity at receptor R just in the time of shift *k* is sum of deposited activity from all previous shifts *j* starting from position HOUR1 for *j=1* up to monitoring shift *k*. Taking into account radioactive decay, activity deposition just in time of shift *k* is given by:

$$DEP(R;k) = \sum_{j=1}^{k} \{ \Delta DEP(R;j)\cdot \exp[-\lambda(k-j)\cdot \Delta t\ ] \} \quad (7)$$

Deposited activity at R after the whole movement of segment from its position HOUR1 to HOUR2 denoted as *DEP(R,K)* is calculated according to Eq. (7) after substitution *k=K*.

Now we can determine time integral of deposited activity during the whole movement of the plume segment from HOUR1 to HOUR2 as:

$$TID(R;K) = \sum_{k=1}^{K} \{ DEP(R;k)\cdot \Delta t \} \quad (8)$$

As was mentioned above, real release is equivalently segmented into hourly segments *s, s=1,...,S*. Each segment *s* is modeled in its subsequent meteorological phases *f, f=1,...,NFAZ(s)* taking into account hourly meteorological forecast. Hourly plume segment *s* in its hourly meteorological phase *f* will be labeled as puff {s;f}. Previous numerical algorithm outlined by Eq. (1) to Eq. (8) and depicted in Fig. 1 shows treatment of the first plume segment in its second meteorological phase, hence labeled {1;2}. Initial state marked as {1;1} (position HOUR1) is described by straight-line Gaussian solution driven by the meteorological forecast for the first hour. Final total values of TIC, DEP and TID at the receptor point R are thus given by superposition of results for all plume segment and all meteo-phases according to the scheme:

$$Value_{TOTAL}(R) = \sum_{s=1}^{S} \left\{ \sum_{f=1}^{NFAZ(s)} Value^{s,f}(R) \right\} \quad (9)$$

At this step we should note:

<u>Note 1</u>: We should have on mind that deposited activity in R and its time integral are dependent on duration of the whole plume propagation. In other words, for the final processing of results in early stage of release we have to relate partial quantities for segments *s* and phases *f* to a certain fixed time T_{ref} (see below).

<u>Note 2</u>: The calculations have to be accomplished for each nuclide from the release. At the same time significant pairs of parent-daughter nuclides should be taken into account (see below).

<u>Note 3</u>: The total values have to be generated for all grid point of polar calculation grid. Individual endpoint values are then represented by background vector dimension N=(35 radial distance) × (80 angle sectors) = 2800 components.

<u>Note 4</u>: However the algorithm seems to be somewhat time consuming, the modeling appears quite applicable even for a large problem (42 nuclides in release, 10 equivalent hourly segments, each segment in 32 consecutive hourly phases). Some simplification can be introduced for nuclides with longer decay halftimes (from a few hours). The algorithm is now

elaborated for Monte Carlo calculations in probabilistic way of analysis and for application of statistical assimilation techniques for correction of model predictions with observations incoming from measuring stations (in [12,13,14]).

Numerical SGPM scheme proposed here has been verified for a certain simple scenario by comparison with COSYMA calculations [16] . The second method of verification was comparison of results of Gaussian straight-line model with presented SGPM algorithm for constant meteorological forecast. Generally very good consent has been reached for various combinations of stability categories and wind speed and precipitation intensity. A certain observable differences occurred only in short distances for extreme unstable atmosphere (Pasquill atmospheric class A). Verification results are presented in detailed in documentation [19].

2.3 Comment on buildup of important daughter products

Source term of released activities is composed from a mixture of several tens of the most important nuclides. Some of them are result of buildup daughter process of decay chains. The buildup process is not solved here in general. Several most important simple decay chains according to scheme *parent → daughter → stable* are included. The Harp code includes for example:

Kr85m → Kr89 ; Kr88 → Rb88 ;

Sr90 → Y90 ; Zr95 → Nb95 ;

Ru106 → Rh106; Te132 → I132 (aerosol) ;

Xe135m→ Xe135; Ba140 → La140 ;

Ce144 → Pr144;

Indices *p* and *d* stand for parent and daughter respectively. Balance of daughter nuclide in representation of activity concentration C^d (either for concentration in air or specific activity deposited on ground) has form:

$$\frac{dC^d}{dt} = \lambda^d \beta^p C^p - \lambda^d C^d \qquad (10a)$$

β^p is branching ratio (fraction of decays of the parent nuclide that produce daughter), λ is radioactive decay constant. Analytical forms for description of complex process of daughter buildup is known only for partial cases under limited assumptions. For example concentration of daughter in air can be expressed according to Gaussian straight-line solution under restriction, that velocity of dry fallout for parent and daughter nuclides are the same. In the HARP code we present numerical simplification which is formulated congruently with SGPM approach. For elemental shifts *k (k=1,....,K)* in Fig. 1 we use difference approximation during elemental shift $\Delta x^{k,k+1}$ = ū . Δt (Δt = 3600 / K seconds):

$$\Delta C^d(k \to k+1) = \lambda^d \beta^p C^p \Delta t - \lambda^d C^d \Delta t \qquad (10b)$$

After selection of subsequent nuclid from the release mixture for computation, identification is done if significant daughter exists. In case of positive detection selected nuclide is denoted as parent *p*. Its activity concentration is solved according to Eq. (1) and field of values $C^p(X_k)$, *k=1,....K* is stored for simultaneous processing of daughter *d* according to modified Eq.(1): (11)

$$C^d(X_{k+1}) = C^d(X_k) \cdot \frac{\sigma_y(X_k)\cdot\sigma_z(X_k)}{\sigma_y(X_{k+1})\cdot\sigma_z(X_{k+1})} \cdot \exp\left[-\frac{H_{ef}^2}{2\cdot\sigma_z^2(X_{k+1})}\right] \Big/ \exp\left[-\frac{H_{ef}^2}{2\cdot\sigma_z^2(X_k)}\right] \cdot {}^d\Delta f_R \cdot {}^d\Delta f_F^{k,k+1} \cdot {}^d\Delta f_W^{k,k+1} + \Delta C^d(k \to k+1)$$

Here depletion factors are intentionally labeled by left upper index *d*, because parent and daughter can have different physical chemical form (for example Kr88 → Rb88, where parent is noble gas, but daughter Rb88 is assumed bounded in aerosol form). Using Eq.(11) the TIC^d are modeled in analogy with Eq.(4,5).

Eq.(10a) holds true also for specific activity deposited on ground. Consequently, in analogy with Eq.(6abc) and Eq.(7) formulated for the daughter, deposited activity at receptor point R due to dry and wet effect and parent nuclide contribution during elemental shifts *j, j=1,...,k* is approximated as:

$$DEP^d(R;k) = \sum_{j=1}^{k} \left\{ \Delta DEP^d(R;j) \cdot \exp\left[-\lambda^d (k-j)\cdot\Delta t\right] \right\} + \Delta^p(R;k) \qquad (12)$$

Here $\Delta^p(R;k)$ is contribution from simultaneous parent deposition. At the end of segment shift *k→k+1* (time shift is Δt) deposited activity of parent in R was calculated in advance according to Eq. (7). Decay of the parent product represents additional source term $\Delta^p(R;k)$ into the daughter balance. It could be expressed as:

$$\Delta^p(R;k) = \lambda^d \cdot \beta^p \cdot DEP^p(R;k) \cdot \Delta t \qquad (13)$$

Here $DEP^p(R;k)$ is modeled by Eq.(7) for parent and then stored for further calculation according to Eq.(13).

Time integral of deposited activity for daughter relevant to the whole hourly shift of segment from position HOUR1 to position HOUR2 (and related to the time when segment reaches the position HOUR2) is approximated (similarly as Eq. (8)) by:

$$TID^{d}(R;K) = \sum_{k=1}^{K} \left\{ DEP^{d}(R;k) \cdot \Delta t \right\} \quad (14)$$

2.4 What is meant by early and late stage of accident?

Segmentation of release dynamic into equivalent number of hourly segments was demonstrated above. Total results are given by superposition of the results of all segments (puffs) {s;f}. Analysis in a certain segment {s;f} stands for one-hour interval starting just at *s+(f-2)* hours from the beginning of release and the whole this hour is driven by meteorological forecast for release hour *s+f-1*. It means that results generated within various segments {s;f} are related to the different times given by *s+f-1* hours after release start. In order to clarify the problem, we have introduced the concept of fixed reference time. Three definitions are introduced:

Def. 1: Let **reference time T_{ref}** is a certain selected time from the beginning of release up to the moment when radioactive cloud definitely passed away analyzed area around the source of pollution. T_{ref} can be chosen interactively in advance, usually selected value is 24 or 48 hours in dependence on S and NFAZ(s) values.

Def.2: E**arly stage** of accident analyses processes from start of release up to T_{ref} .

Def.3: **Late stage** of accident starts from T_{ref} and deal with further development of radiological situation in the impacted area.

2.5 Completion of computation of the main driving quantities in the early stage

After introduction of T_{ref} the sketchy scheme (9) should be improved. Results of all partial puffs {s;f} should be recalculated to the only value of T_{ref}. For TIC values there are no changes and at any node R of polar grid remains:

$$TIC_{TOTAL}(R;T_{ref}) = \sum_{s=1}^{S} \left\{ \sum_{f=1}^{NFAZ(s)} TIC^{s,f}(R) \right\} \quad (15a)$$

$TIC^{s,f}$ are values at any grid node R due to shift of segment *s* in its meteorological phase *f* (see Eq.(5)).

Deposition DEP should account for time delay $\Delta T^{s,f}(T_{ref})$ between end hour of puff {s;f} and T_{ref}, $\Delta T^{s,f}(T_{ref})$ = [T_{ref} – (s+f-1)] *3600.0 sec. Then deposition at any node R in time T_{ref} after release start is calculated according to:

$$DEP_{TOTAL}(R;T_{ref}) = \sum_{s=1}^{S} \left\{ \sum_{f=1}^{NFAZ(s)} \left[DEP^{s,f}(R) \cdot \exp(-\lambda \cdot \Delta T^{s,f}(T_{ref})) \right] \right\} \quad (15b)$$

$DEP^{s,f}$ are values of activity deposition at any grid node R due to shift of segment *s* in its hourly meteorological phase *f* (see Eq.(7)).

Time integral of deposited activity TID is recalculated using formula:

$$TID_{TOTAL}(R;T_{ref}) = \sum_{s=1}^{S} \left\{ \sum_{f=1}^{NFAZ(s)} \left[TID^{s,f}(R) + \int_{0}^{\Delta T^{s,f}(T_{ref})} DEP^{s,f}(R) \cdot \exp(-\lambda \cdot t) \cdot dt \right] \right\} \quad (15c)$$

$TID^{s,f}$ are values of time integral of activity deposition at any grid node R due to shift of segment *s* in its hourly meteorological phase *f* (see Eq.(8)).

3 Deterministic estimation of radiological burden of population as a consequence of radiation accident

We can conclude that time consuming calculations in the early stage of accident generate main fields of CAP, TIC, DET and TID related to selected reference time T_{ref}. Subsequent estimation of radiological impact is done in simple and straightforward way for various combinations of irradiation pathways and time horizons, age categories and organ or tissues.

Radiological consequences of accident are in system HARP estimated according to doses of irradiation calculated with the assistance of dose coefficients (factors) based on ICRP recommendations [ICRP60] and concretized by executable national regulations. Health risk estimation from exposure to radionuclides represented by mortality or morbidity risk coefficients is not so far in operation.

Evaluation accounts for 6 age human categories (from suckling to adults) so that variability in inter-individual differences is accepted. Each category has its own subset of input data (conversion coefficients, consumption baskets, breathing rates, life-style factors, …).

Effective dose on the whole human body has index *o*=1. Equivalent doses on organ or tissues are distinguished for:

o=2 … gonads

o=3 … red bone marrow

o=4 … lung

o=5 … thyroid

o=6 … gastrointestinal tract

o=7 … skin

3.1 Irradiation doses in early stage

According to pathways are distinguished external irradiation from cloudshine and groundshine and internal irradiation due to inhalation of contaminated air. The doses fields are generated in each node R of polar grid.

Cloudshine: Dose H_{cl} in Sv from γ-irradiation from the cloud spreading over the terrain in a semi-infinite cloud approach is given by sum from all nuclides *n*:

$$H_{cl}^{a,o}(R;T_{ref}) = \sum_{(n)} \left\{ TIC_{TOTAL}^{n}(R;T_{ref}) \cdot D_{cl}^{n,a,o} \right\} \quad (16)$$

TIC^{n}_{TOTAL} stands for nuclide *n* and is given by Eq.15a), D_{cl} [$Sv.m^3.Bq^{-1}.s^{-1}$] is tabulated dose conversion factor for cloudshine from semi-infinite cloud.

Groundshine: Dose H_{gr} in Sv from γ-irradiation from radioactivity deposited on terrain is given by sum from all nuclides *n*:

$$H_{gr}^{a,o}(R;T_{ref}) = \sum_{(n)} \left\{ TID_{TOTAL}^{n}(R;T_{ref}) \cdot D_{gr}^{n,a,o} \right\} \quad (17)$$

TID^{n}_{TOTAL} stands for nuclide *n* and is given by Eq.(15c), D_{gr} [$Sv.m^2.Bq^{-1}.s^{-1}$] is tabulated dose conversion factor for groundshine.

Inhalation: Committed dose H_{ih} in Sv due to inhalation of contaminated air in near-ground level is given by sum from all nuclides *n*:

$$H_{ih}^{a,o}(R;T_{ref}) = \sum_{(n)} \left\{ TIC_{TOTAL}^{n}(R;T_{ref}) \cdot D_{ih}^{n,a,o} \right\} \quad (18)$$

Once the activity enters the human organ *o*, we have to account for long-term detrimental effect. This covers dose conversion factor for inhalation D_{ih} [$Sv.Bq^{-1}$] which accounts for commitment for next 50 (70) years for adults (children).

Total dose in the early stage of accident H_{TOT} is given by summation:

$$H_{TOT}^{a,o}(R;T_{ref}) = H_{cl}^{a,o} + H_{gr}^{a,o} + H_{ih}^{a,o} \quad (19)$$

3.2 Irradiation doses in late stage of accident

Consequences of radiation accidents in late stage and possible countermeasures for mitigation of harmful effects are treated on the bases of long-term doses of irradiation from pathways of:

- Groundshine
- Resuspension – long-term inhalation of air contaminated by nuclides originally deposited on ground
- Ingestion – consumption of contaminated food

At the same time the doses in late stage comprise doses in early stage. It is clear, that cloudshine and inhalation doses are not changing after the radioactive plume leaves the terrain. In the following text we shall show how we take advantage of the main driving quantities calculated beforehand in the early stage.

3.2.1 Groundshine in late stage

Let us analyze long-term development of doses from groundshine. It can be formally expressed as:

$$H_{gr}^{a,o}(R;T_{long}) = H_{gr}^{a,o}(R;T_{ref}) + \sum_{(n)} \Delta H_{gr}^{n,a,o}(R;T_{ref} \to T_{long}) \quad (20)$$

The first term on the right side is early-stage dose given by Eq.(17). The second term belongs to contribution in late stage. Introducing principle:

$$\Delta H_{gr}^{n,a,o}(R;T_{ref} \to T_{long}) = \int_{T_{ref}}^{T_{long}} \dot{H}_{gr}^{n,a,o}(t) \cdot dt \quad (21a)$$

where the dose rate $\dot{H}$ [$Sv.s^{-1}$] can be rewritten as:

$$\dot{H}_{gr}^{n,a,o}(t) = DEP_{TOTAL}^{n}(R, T_{ref} + t) \cdot D_{gr}^{n,a,o} \quad (21b)$$

Deposition of nuclide *n* at time T_{ref} is given by Eq(15b). Deposition at time $T=T_{ref} + t$ is calculated according to: (21c)

$$DEP^{n}(R;T) = DEP_{TOTAL}^{n}(R;T_{ref}) \cdot \exp(-\lambda^{n} t)$$

More profound analysis substitutes single radioactive constant λ^n by effective constant λ^n_{eff} where effects of other environmental processes (migration out of surface ground) leading to removal of radionuclide and soil self-purification are included.

Particularly for lasting problem with Cs137 from Chernobyl accident recent experience based on fields experiments [6,7] yield more precise expressions for environmental effects leading to:

$$DEP^{n}(R;T) = DEP_{TOTAL}^{n}(R;T_{ref}) \cdot \exp(-\lambda^{n} t) \cdot E(t) \quad (21d)$$

Environmental decay factor for groundshine E(t) was studied and several semiempirical two-exponential formulas with slow and fast decay component have been recommended [6,7] as: (21e)

$$E(t) = a_{slow} \exp(-\lambda_{slow}^{Cs137} t) + a_{fast} \exp(-\lambda_{fast}^{Cs137} t)$$

The second term on right side of Eq.(20) is rewritten as:

$$\sum_{(n)} \Delta H_{gr}^{n,a,o}(R;T_{ref} \rightarrow T_{long}) = \sum_{(n)} \left\{ \begin{array}{l} DEP_{TOTAL}^{n}(R,T_{ref}) \cdot D_{gr}^{n,a,o} \cdot \\ \int_{T_{ref}}^{T_{long}} \exp(-\lambda^n t) \cdot E^n(t) \cdot dt \end{array} \right\} \quad (22)$$

Now we can conclude, that long term doses from deposition are expressed as deposition at time T_{ref} (calculated by time-consuming procedure in the early stage) multiplied by integral of rather simple function of time which can be usually expressed analytically. The principle markedly save amount of storage necessary for generation of output fields and supersede this by interactive presentation of results on user demand.

3.2.2 Comment on resuspension in late stage

Wind-driven resuspension is usually much lower than long-term doses from groundshine or ingestion. For detailed analysis we refer to user manual of system HARP [19].

3.2.3 Irradiation doses due to ingestion pathway in late stage of radiation accident

Profound analysis of ingestion pathway has primary priority during HARP code development and it should be considered as strong point of the product. Special dynamic ingestion model has been developed for quantification of risk from consumption of contaminated food for case of accidental fallout in arbitrary Julian day in a year which takes into account current vegetation state of growth due to vegetation periods. Let us mention also modification of dynamic ingestion model for analysis of situation around nuclear facility under normal routine operation when all agricultural production continues in the long-lasting submerging in contaminated environment (however low it is). Experience from international codes FARMLAND [8] and ECOSYS [9] are adopted. Important stimulus has arisen from former cooperation with skilled European experts within RODOS customization procedure for the Czech Republic [10,11].

For interactive definition of input ingestion parameters has been developed collateral interactive subsystem which was customized on the Czech condition. The subsystem has another advantage in its straightforward application as a powerful and fast user friendly tool for assessment of effects of various countermeasures introduced in food chain areas. Detailed description lies far behind scope of this article and we refer to detailed description in [17,19].

Presented food-chain transport model for the latter case of long-term releases enables more precise generation of annual activity intake. The dynamic model is adopted for the average Czech conditions taking into account local *consumption habits* (dependence on season and age), *agricultural production* scheme, average *agro-climatic conditions* and *phenological characteristics* of the plants, *feeding diets* of animals, *time delays* during processing, transport and storage of foodstuffs and feedstuffs etc. Two different mechanisms of nuclides uptake into edible parts of plants are modeled:

- *Foliar uptake of radionuclides*: In the process of deposition on leaves the initial deposited activity is decreased due to weathering effects (wind, rain), radioactive decay and tissue ageing (growth dilution effect). Furthermore, the fraction of activity translocated to other parts of the plant should be taken into account. The analysis must distinguish between plants which are used totally (e.g. leafy vegetables, grass) and plant of which only a special part is used (cereals, potatoes). Translocation from leaves to the edible parts of the plant has to be accepted. This process is strongly dependent on the physiological behaviour of the isotope considered.
- *Root uptake of radionuclides*: In general, the root uptake of activity is calculated from the concentration of activity in the soil using equilibrium transfer factors which give the ratio of activity concentration in plants (fresh or dry weight) to soil (dry soil). Decreasing of deposited activity due to radioactive decay and other environmental effects is assumed. Besides migration out of soil also fixation of nuclides should be accepted (especially is important for cesium and strontium). Nuclides bounded to immobile chemical compound are not available for root uptake transport.

Dynamic ingestion modeling accepts real Julian day of fallout T_{fall} and its relation to vegetation periods of particular plants. Corresponding total time integrated activity intake due to foliar and root transport (during time period *Δt* from start day of consumption to day *t*, normalised to the unit initial deposition of nuclide *n* on the terrain) for age category *a* due to both direct consumption of edible parts of plants and consumption of contaminated animal products is schematically written as

$$I\varepsilon_{TOT}^{a,n}(\Delta t, T_{fall}) = \sum_{(l)} I\varepsilon_{l}^{a,n}(\Delta t) + \sum_{(b)} \left\{ \sum_{(p)} I\varepsilon_{p,b}^{a,n}(\Delta t) \right\} \quad (23)$$

Here *l* denotes the plant products, *b* means the animal products (milk, meat, eggs). From the products *b* are produced various foodstuffs *p*(*b*) (for example from the milk are produced the foodstuffs *p* : fresh milk, cream, cheese, milk dry, milk condensed, curd, others

– with various specific time delays for consumption). The Czech local age-dependent consumption baskets and local dynamic parameters are implicitly included.

In the final step the ingestion doses are calculated according to: (24)

$$H_{ig}^{a,o}(R;T_{ref},\Delta t,T_{fall}) = \sum_{(n)}\left\{DEP_{TOTAL}^{n}(R;T_{ref})\cdot I\varepsilon_{TOT}^{a,n}\left(\Delta t,T_{fall}\right)D_{ig}^{n,a,o}\right\}$$

It stands for total committed ingestion dose due to consumption of contaminated foodstaffs during time consumption interval from day of fallout (respectively from starting day of consumption when time delay to consumption is assumed). Dose conversion factors for ingestion D_{ig} [Sv.Bq^{-1}] account for commitment of harm for the next 50 (70) years for adults (children). From Eq.(24) we can see again the separation of time consuming calculations in early stage (represented by main driving variable DEP(T_{ref})) and long-term much faster calculation of internal activity intakes. The fact considerably facilitates and improves the presentation of results.

Long term effect is in Eq.(24) represented by time difference *Δt*. If end time is selected as last day of the year, we are talking about annual committed dose in the first of year. Dose $H_{ig}^{a,o}$ (m) just in the *m*-th year after the year of fallout is calculated similarly to Eq.(24) but as if the day of fallout was at January 1st of the m-th year (it means winter fallout assuming only root uptake without foliar uptake of activity). For this case the values of $DEP^{n}_{TOTAL}(R;T_{ref})$ is recalculated up to the beginning of the m-th year multiplying this by exp(-λ^{n}_{eff} .$\Delta t(T_{ref};T_{beg}(m))$. .$\Delta t(T_{ref};T_{beg}(m))$ is time delay in seconds between beginning of m-th year and T_{ref}. Thereafter, for example 50-year committed ingestion dose is expressed by approximation: (25)

$$\left\{H_{ig}^{a,o}(R;T_{ref},T_{fall})\right\}_{50} = H_{ig}^{a,o}(R;T_{ref},T_{fall}\rightarrow 365) + \sum_{m=1}^{m=49}\{H_{ig}^{a,o}(m)\}$$

Dynamical ingestion model is extraordinarily complicated and data demanding. On the other hand as correct as possible estimation is desirable because ingestion pathway generally plays decisive role in health risk assessment of stochastic consequences. Many opened or half-solved problems still persist, mainly:

Problem 1: Adoption of more realistic *ingestion scheme* instead of the "*local production-local consumption*" one.

Problem 2: The equilibrium transfer factor concept should be substituted by realistic compartment metabolic models.

Problem 3: Introduction of multi-regional concept, when the whole territory is split into a certain number of so called *radioecological zones* according to differences in climate, phenological characteristics, agricultural production and feeding regimes, consumption habits, soil types (strongly influencing soil to plants transfer factors) etc. The first attempt was done in [11].

Problem 4: *Model parameters improvement*, what includes data actualisation and reconstruction of various items on fine spatial grid (site specific data, soil type, land use, elevations, agricultural production, population, more detailed meteorological statistics etc.) related to the local-specific conditions.

4 System architecture

Near-range simulation of radionuclides propagation in atmosphere up to 100 kilometres from the source of pollution is realized by implementation of SGPM model, which enables to take into account short-term meteorological forecasts (hourly changes) provided by the Czech meteorological service. Architecture of the system complies with requirements for transparent communication among particular subsystems providing user-friendly interactive environment. The system offers various alternative options of input parameters definition of the release scenarios in their atmospheric, deposition, ingestion and dose parts. For that reason the software product can serve as a training tool enabling responsible staff to improve their knowledge and preparedness in decision making during nuclear emergency situations. From general viewpoint, the system offers fast, robust and easy tool for decision support under stress emergency situations including simulation of effects of various countermeasure actions launched in early phase of release. At the same time integrated detailed dynamical food chain model FCM provides instrument for testing of various countermeasures in late stage of accident. System HARP is a result of long-running cooperation of several Czech institutions [19]. Also some experience obtained during localization of the European project RODOS on the Czech conditions (our own contribution see e.g. [10, 11]) has been learnt and incorporated into the product created in the PC-WINDOWS environment. Outline of the HARP system architecture is given in APPENDIX, Fig.2.

5 Tools for countermeasure support

5.1 Early stage of accident

From the point of view of urgent countermeasures in early stage of accident the prime significance insists in description of as correct as possible prediction of the plume spreading in consecutive hours. It enables to emergency staff to make a decision about countermeasure introduction in a certain heavily impacted areas. Decision related to urgent application of countermeasures in the early stage of accident must accounts for:

- Sheltering of inhabitants
- iodine prophylaxis (distribution of iodine tablets),
- evacuation of inhabitant

Obligatory intervention limits for respective actions are based on averted doses concept. The limits are defined in executive regulations. The process of urgent countermeasures launching is in responsibility of emergency management staff provided that the interventions levels are exceeded. The HARP system provides color differentiation in the form of isoplets or isodoses displayed on proper map background where the color levels can be interactively entered by user in correspondence with intervention levels. Interactively can be analyzed the following early stage quantities (isoplets of their 2-D distribution) related to T_{ref} :

- CAP, TIC, DEP and TID for any nuclide from release mixture or any significant daughter
- cloudshine doses,
- groundshine doses
- inhalation committed doses
- total early-stage doses (sum of cloudshine, groundshine and inhalation)

Unique feature of the architecture design offers additional valuable information related also to radiological situation at hours $t_h < T_{ref}$. Thanks to storing of partial results for each plume puff segment {s;f} for each hour $t_h \in <1; T_{ref}>$ can be displayed 2-D color picture on proper map background of:

- predicted radioactive cloud position just t_h hours after release start (superposition all puffs {s;f} where $s+f-1 = t_h$ what can be imagined as snapshot of the cloud position exactly at t_h),
- predicted TIC values, radioactive trace on terrain DEP and integrals TID exactly at t_h (superposition of all puffs {s;f} where $s+f-1 \leq t_h$ what can be imagined as "photo" with exposition lasting t_h hours from the release beginning).

Significance for decision making is evident (determination of proper evacuation routs, assessment of time delays remaining to effective introduction of interventions etc.). Furthermore, an animation of cloud movement or radiological situation development over terrain can be projected. Let us demonstrate above functions on a certain release scenario incorporating 7 nuclides and 3 significant daughters. We shall concentrate particularly on 1-hour release of total activity 1.08E+18 Bq of nuclide I131. We have used actual meteorological forecast provided by the Czech meteorological service for meteostation at place of NPP Temelin for release start on February 22, 2007, 12.00 UTM. After 8 hours transport approximately in south-east direction the wind direction changed nearly to opposite orientation. The forecast was fully confirmed by real measurements in the next days. Position of cloud of I131 activity is drawn in Fig. 3a,b,c, respectively just for 2th, 10th and 25th hour after release start.

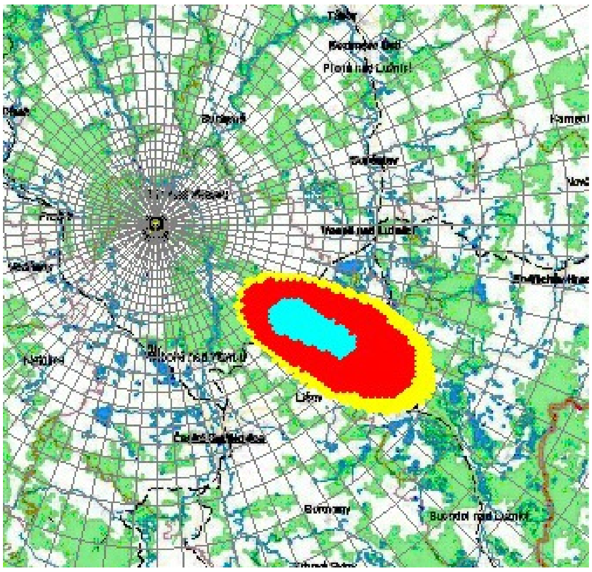

Fig. 3a Near-ground activity concentration of I131 just after 2nd hour after release start

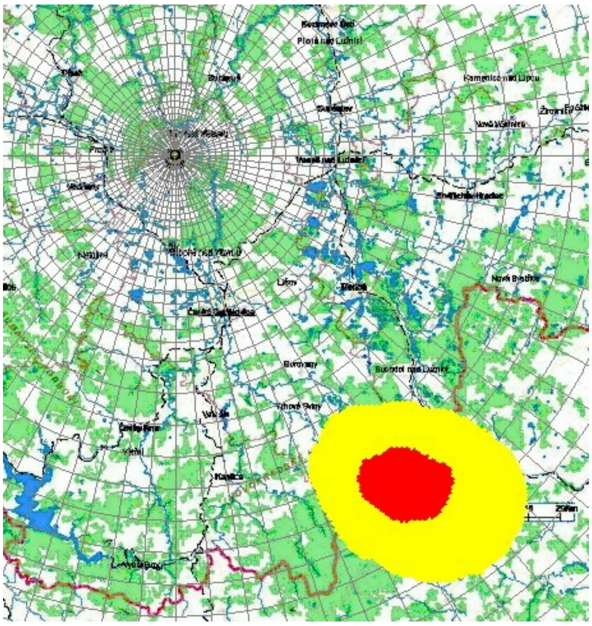

Fig. 3b Near-ground activity concentration of I131 just after 10th hour after release start (reversal movement starts).

Absolute majority of meteorological situations permits to use rather low number of successive meteorological phases NFAZ(s) (about 10÷15 when cloud leaves the analyzed area up to 100 km from the source). But from this point of view the analyzed meteorological sequence shows to be quite abnormal and we have to take into account NFAZ (1)=32 sequences so that to produce correct prediction. Seemingly ordinary meteorological situation appeared to be quiet curious and it is clear that it required to elongate reference time option Tref after 32 hours. The color levels of CAP [Bq.m^{-3}] of I131 are < 5.0E+05 ; 1.0E+06 > for yellow color, <1.0E+06 ; 5.0E+06 > for red color and < 5.0E+06 ; 8.72E+06 > for turquoise color. Depletion of the I131 activity from the plume with time is evident.

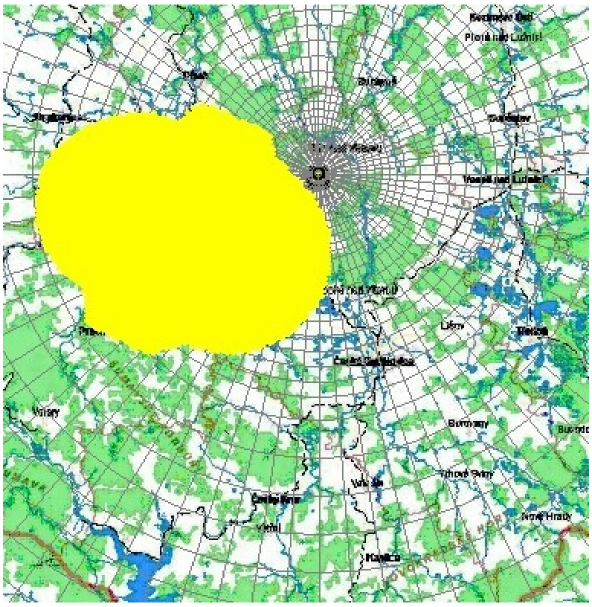

Fig. 3c Near-ground activity concentration of I131 just after 25th hour after release start (movement in opposite direction back to NPP Temelin)

Picture of I131 deposition on terrain is imaged in APPENDIX, Fig. 4 (there is used 50 % transparency display mode of results on the map background). Two "red bull" eyes are seen here near the source and at the position of reversal turn (the cloud persists here for a longer time). The color levels of deposited activity DEP [Bq.m^{-2}] of I131 are < 2.0E+07 ; 4.0E+07 > for yellow color, < 4.0E+07 ; 1.00E+08 > for turquoise color, <1.0E+08 ; 5.0E+08 > for blue color, <5.0E+08 ; 1.0E+10 > for red and <1.0E+10 ; 6.91E+10 > for violet color. Similar picture generated for TIC of I131 activity distribution can be used for highlighting of areas designated for iodine prophylaxis application.

5.2 Late stage of accident

Wide range of options is provided. There exist three ways how to utilize HARP system as a tool for countermeasure effectiveness assessment:

1. Long-term output quantities can be displayed in 2-D representation on a proper map background where color levels can be interactively entered by user in correspondence with intervention levels (for temporal or permanent relocation, checking of specific activities in agricultural products in successive years after release).
2. Comparable mode 1: After basic run of early stage calculation with default ingestion parameters is ready, the execution is waiting until the new ingestion part is recalculated. In the new ingestion run evoked by user option can be changed parameters of consumption rates for every foodstaffs.
3. Comparable mode 2: Insists in possibility of modification of parameters from the whole ingestion model by means of automatic recalling of interactive INGMODEL input subsystem. Any parameters now can be changed and dispatched for reprocessing. The basic and the new results can be now compared in the form of 1-D graphs where for example averted doses can be highlighted.

Various accident scenarios and countermeasures effectiveness has been analyzed and demonstrated within cooperation with governmental authorities supervising nuclear safety and radiation protection. The new functions of the HARP system have been verified in scenario *MELK-STEP II* which was formulated for joint Czech – Austrian negotiations STEP II b (detailed documentation see [20]) within so called "MELK PROCESS". Real dynamics for severe LOCA accident with partial fuel cladding rupture and fuel melting (from RODOS ST2 source term) is split up to 6 equivalent 1-hour segments. For prediction have been used meteorological prediction sequence "CASE2" from June 28, 2002 with release start at 00 UTM (includes fluctuating precipitation).

Spatial distribution of total annual effective dose for adults in the first year of fallout is displayed in APPENDIX, Fig.5. Many additional useful options can be generated. Fig. 6a presents circle graph for contribution of each significant nuclide to the annual effective dose from APPENDIX, Fig. 5.

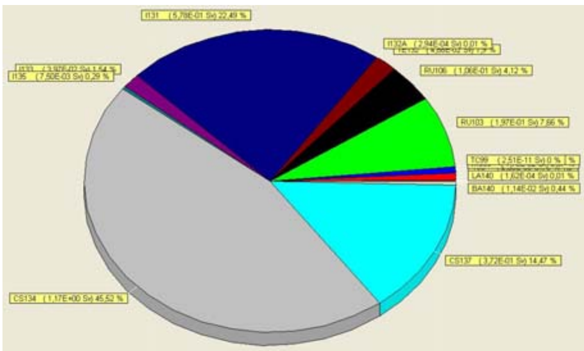

Fig. 6a Percentage nuclide contribution to annual effective dose for adults – scenario *MELK-STEP II*

The similar circle graph is given for percentile contribution of each irradiation pathway. The graphs can be automatically updated according to the position of cursor in basic Fig. 5 in APPENDIX. The figures 6a and 6b stands for 25th angular direction (from total 80) and 25th radial zone (concentric circle around source in with radius on km 47.5).

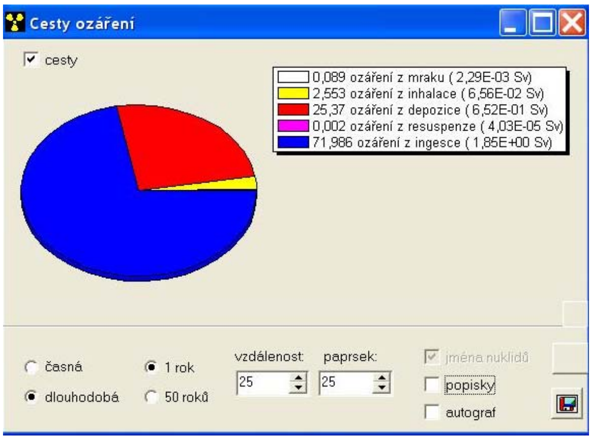

Fig. 6b Percentage contribution of particular irradiation pathway to annual effective dose for adults – scenario *MELK-STEP II.*

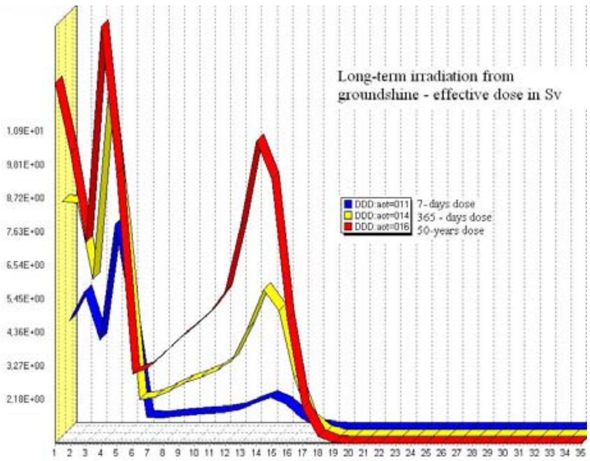

Fig. 7a Groundshine dose – time evolution - angular direction south-east (polar angle beam 20)

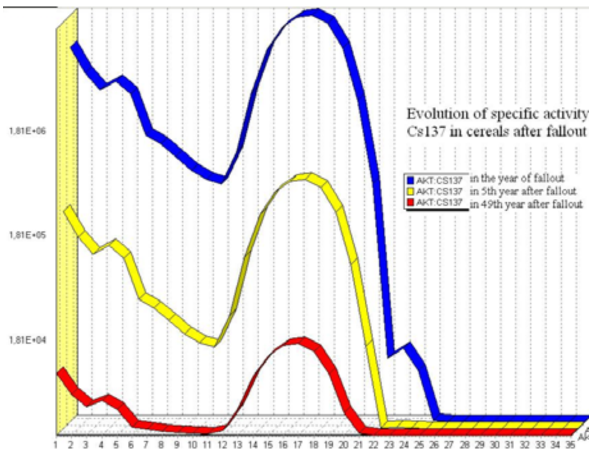

Fig. 7b Time evolution of Cs137 specific activity in cereals [Bq.kg^{-1}] (polar angle beam 21)

In the preceding Fig. 7a and 7b an example of the late stage development of groundshine irradiation doses and specific activities in harvested cereals is displayed. The information can serve as base for decision makers in sense of paragraph 5.2 point 1.

The following two Fig. 8a and Fig. 8b demonstrate comparison of interventions using "Comparable mode 2" described in paragraph 5.2. Committed doses due to consumption of contaminated food for children is compared for case of conservative ingestion scheme (red color) of local consumption ("local production ×local consumption") with reduced contaminated consumption basket (yellow) in farmers families (estimated by experts). Shaded red area represents averted ingestion dose.

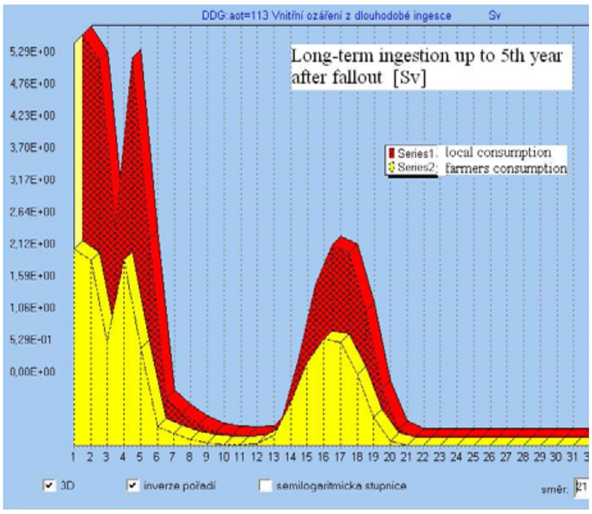

Fig. 8a Committed ingestion dose averted due to food bans in consumption (reduced contaminated consumption basket, polar angle beam 21)

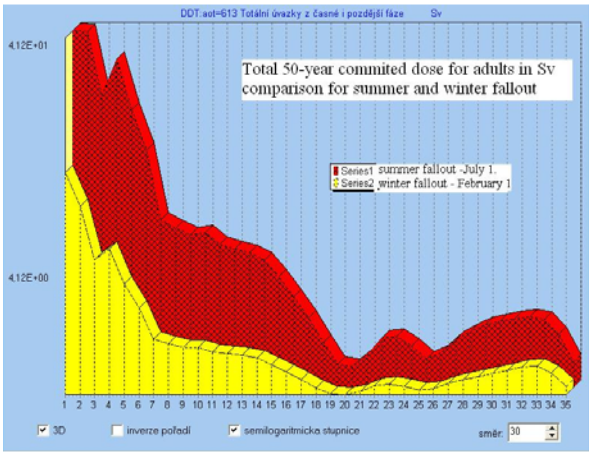

Fig. 8b 50-years total committed dose for adults for summer fallout in July 1 (in red) and winter fallout in February 1 (yellow). Shape in polar angle 30.

6 Comment on probabilistic version of the HARP code

A special emphasis in further development is laid on proper treatment of types of input parameter fluctuations in sense of differentiation between variability and uncertainty. Uncertainties arise mainly due to inherent stochastic character of some input data, partial ignorance of model description or lack of knowledge regarding the true model formulation. Relevant uncertainty groups for input parameters of ADM, FCM and dose model DOS have been formulated. Application of probabilistic concept of HARP is presented in [12,14,19]. The probability approach enables:

– Progress from deterministic simplification of consequence assessment toward probabilistic approach. Resulting endpoint fields are modeled as random and then much better informative output data is generated in addition to the deterministic "best estimate" (expected) single values. Then, the answers on consequence assessment questions can be formulated on probabilistic fundamentals.

– More detailed investigation of error structure of the model predictions can be carried out which enables to compute covariance matrices of the model error. It represents inevitable requirement for transition to the statistical assimilation techniques that can improve the posterior model predictions on the basis of optimal blending of prior model forecast with real observations incoming from terrain.

Assimilation problem is a topic of the grant approved by Grant Agency of the Czech Republic. The project is solved by authors of this paper within the period 2007-2009. In final stage the assimilation subsystem connected to Czech Early warning radiation network should be integrated into the HARP system.

7 Abbreviations and indices

ADM Atmospheric Dispersion Model
FCM Food Chain Model
SGPM Segmented Gaussian Plume Model
CAP Near-ground activity conc. in air
DEP Spec. activity deposited on ground
TIC Time integral of near-ground activity concentration in air
TID Time integral of specific activity deposited on ground
Bq Becquerel – unit of activity
Sv Sievert – unit of dose
S Total number of equivalent number of hourly release segments
NFAZ(s) Number of subsequent hourly meteorological phases of segment s
{s;f} id pair for partial hourly segment s in its meteorological phase f (plume puff {s;f})
LOCA Loss Of Coolant Accident

indices:
a … age category (6 cat from sucklings to adults)
d ... daughter nuclid
p ... parent nuclid
o … id for organ or tissue (*o=1 to 7 - whole body,* gonads, red bone marrow, lung, thyroid, gastrointestinal tract, skin)
f … hourly meteorological phase
s … partial equivalent (one-hour) plume segment
k … elemental shift of the plume segment (Fig.1)
n … nuclide

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APPENDIX

Includes Fig. 2, Fig. 4, Fig. 5

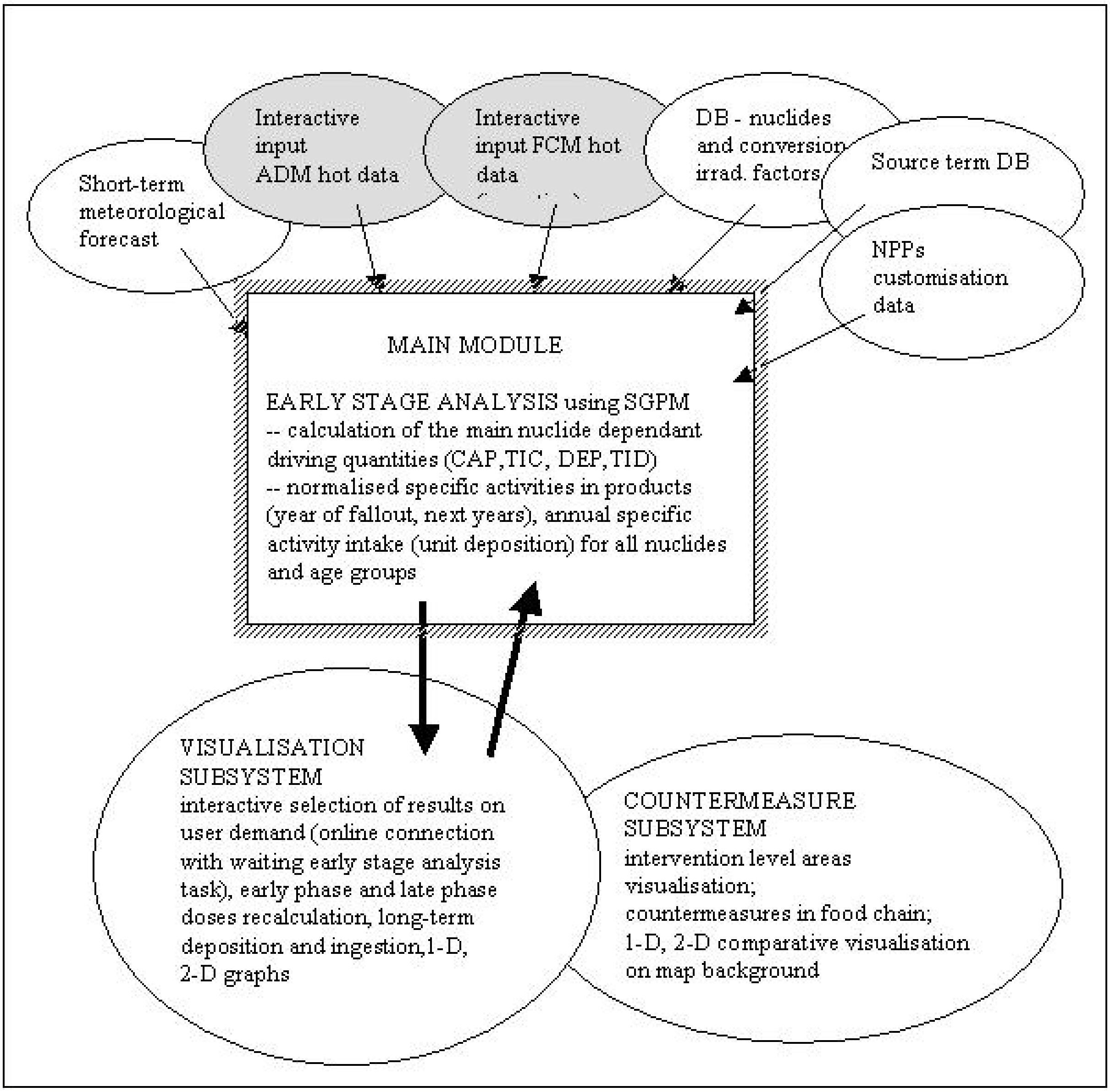

Fig. 2 Diagram of deterministic root of the HARP system

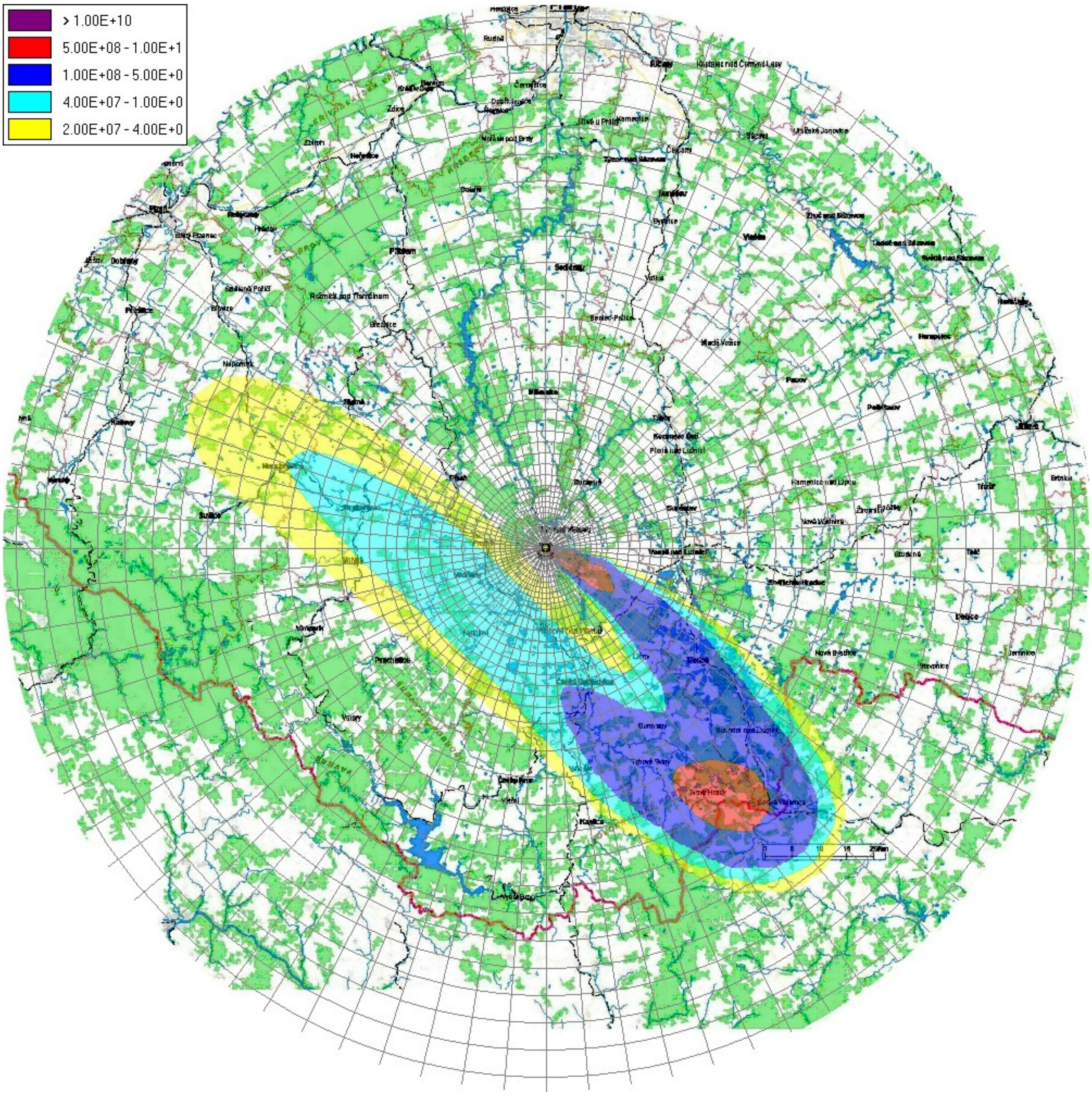

Fig. 4 Deposited activity of I131 after 32 hours after the release start at 12.00 UTM on Feb. 22, 2007. After 8 hours the wind direction changed to nearly opposite orientation (the forecast confirmed by latter measurements)

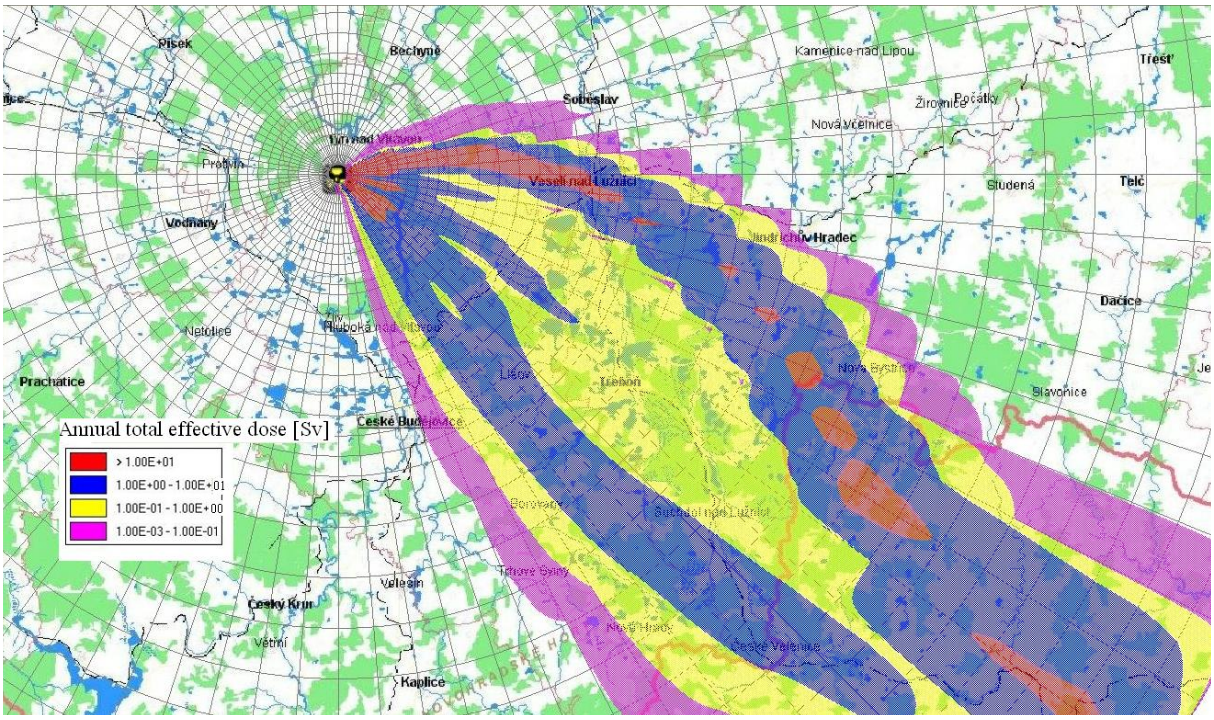

Fig. 5 Total annual effective dose for adults [Sv] in the first year of release. Source term ST2 – severe LOCA accident with fuel melting, meteorological forecast for June 28,2002, 00 UTM. Conservative "Local production × Local consumption" ingestion scheme.