SOFTWARE TOOL FOR ASSESSMENT OF FOOD CONTAMINATION AND FOOD BANS REGULATIONS

Petr Pecha
Radek Hofman
Institute of Information Theory and Automation of ASCR
Pod Vodarenskou vezi 4
182 08 Prague 8, Czech Republic
E-mail: pecha@utia.cas.cz

Emilie Pechova
Nuclear Research Institute Řež, Division EGP
Vyskočilova 3/741
140 21 Prague 4
E-mail: pechova@egp.cz

KEYWORDS
Irradiation, ingestion pathway, countermeasures, food bans.

ABSTRACT

Dynamic food chain model INGMODEL of radioactivity transport inside a human body is briefly described. Proposed methodology and corresponding user-friendly software enable estimating the consequences arising from ingestion of contaminated foodstuffs. The model is connected with interactive subsystems for entering of input data and graphical presentation of results. An effectiveness of some protective actions introduced in the ingestion pathway on population protection can be tested. The areas contaminated above the permissible limits can be presented directly on the map backgrounds and immediately used for decisions related to launching of the food bans regulations. Simulation of time and space evolution of committed doses from ingestion pathway enables estimate the risk for persons living for a long time in the polluted areas. Architecture of the INGMODEL subsystem was designed with the intention to facilitate examinations of influence of variability of input data. The sensitivity analysis and worst-case assessment can be accomplished as well. An example related to the variability of soil-plant transfer factors is given in the conclusion.

PROPAGATION OF RADIOACTIVITY THROUGH THE LIVING ENVIRONMENT

After the radioactive material is released from a source the admixtures are incorporated into the plume and drift in the downwind direction. The polluted plume expands horizontally and vertically due to turbulent diffusion in the atmosphere. The radionuclides in the plume are bound in a certain physical-chemical forms (aerosols, elemental form, organically bound) and during dispersion are removed from the plume due to several removal mechanisms. The most important are radioactive decay (including daughter products build-up process), dry deposition (gravitational setting and deposition due to contact of the contaminated plume with the ground, vegetation or urban structures) and wet deposition – removal by rainout (precipitation formation process inside of the plume) or by washout (interaction between falling drops and admixtures).

Advection and diffusion transport of pollution are based on the standard Gaussian solution. Further segmentation of the plume into consecutive one-hour segments ensures an accounting for the real situation. A basic idea insists in synchronization of available short-term meteorological forecast (hourly forecast for the next 48 hours provided by the Czech meteorological service) with the time evolution of radioactivity discharges released into the atmosphere. The real dynamics of the accidental release is transformed into an equivalent number G of consecutive homogeneous segments with 1 hour duration. The movement of each segment of pollution is driven by a short-term meteorological forecast for the corresponding hours (phases) of further propagation. SGPM (Segmented Gaussian Plume Model) acronym is used for these approach (more detailed description in (Pecha et al. 2007)). Many effects have to be taken into account approximately such as the thermal structure of the atmosphere (here Pasquill-Gifford notation), surface roughness and other land cover characteristics, orography of the terrain, reflection from the ground and top of the mixing layer or inversion layers, the effect of initial plume rise due to vertical momentum and buoyancy, recirculation in the wake region of the near standing buildings. The effects are usually expressed by semi-empirical expressions derived from experimental results. In the final stage the activity dispersed in the air and deposited on the ground enters into food chains causing a certain contamination of the foodstuffs and fodder. The following radiological consequences from possible pathways of radionuclide transport through the living environment are estimated:

- Exposure to external irradiation from the passing cloud (photons and electrons).
- Exposure to external irradiation from deposited radionuclides (photons and electrons).
- Internal irradiation caused by inhalation of radionuclides from the passing cloud.
- Internal irradiation from inhalation of resuspended radionuclides originally deposited on the ground.
- Internal irradiation resulted from activity intake from the contaminated foodstuffs.

Effective and equivalent doses and/or corresponding committed doses on organs or tissues (gonads, red bone marrow, lung, thyroid, upper large intestine, skin) are evaluated for each of six human age groups.

INTERNAL INTAKE OF RADIOACTIVITY FROM THE INGESTION PATHWAY

Transport of radionuclides through the food chains is treated in relationship to the exposure scenarios. Methodology for chronic long-term releases occurring during normal operation of a nuclear power plant were adopted from the fundamental code PC-CREAM (Simmonds et al.2010). A new algorithm is proposed in (Pecha et al. 2002). The ecosystem surrounding the NPP is assumed to be continuously submerged into the contaminated environment where customary agricultural practices are applied. An evolution of root and foliar transport of radioactivity into the plants is modelled day by day. Each partial pollution in a day is taken as an adequate portion from the given total annual routine emission. The final consequences are weighted by annual weather statistics.

Short-term accidental releases attended by the radioactive fallout can occur unexpectedly in an arbitrary day in a year. An experience from significant European ingestion models ECOSYS (Müller et al. 1993) and FARMLAND (Brown and Simmonds 1995) has been utilised. Valuable knowledge has been obtained by our participation on customisation of the RODOS project (final report see Müller et al. 2003) for the Czech territory (Raskob et al. 2000), our own contribution is summarized in (Pecha et al. 1999).

In this report we shall concentrate in brevity on description of the ingestion pathway model. Its applications will be presented in more detail. Two different mechanisms of the nuclides uptake into edible parts of the plants are considered:

Foliar uptake of radionuclides: Radioactivity is deposited on leaves and other aerial parts of plants. It depends on the stage of development of the plant canopy which is usually characterized by the actual leaf area index (LAI). Growing functions for each plant during its vegetation period should be determined. 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 infiltrating into other parts of the plant should be taken into account. This translocation from leaves to the edible parts of the plant is approximately simulated. Proposed dynamical model 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).

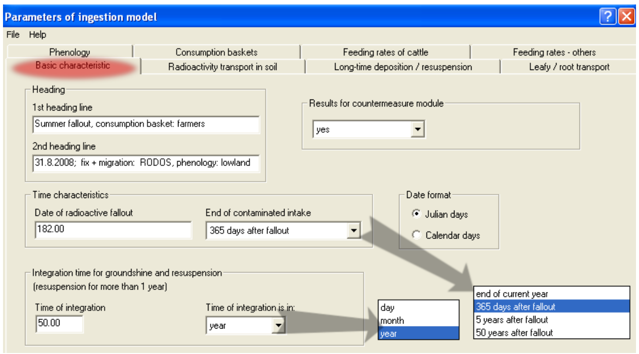
Root uptake of radionuclides: In general, the root uptake of activity is calculated from the concentration of activity in soil using equilibrium transfer factors which give the ratio of activity concentration in plants (fresh or dry weight) to soil (dry soil). Vertical migration of elements and their fixation in root zone depend on physical-chemical form of an element and on various soil properties. Accumulation of activity in crops is strongly dependent on type of the soil. For example the differences in transfer factors for sand and clay soil types are two orders of magnitude (these variability will be estimated here in the further chapters). The time evolution of activity deposited on the ground is important for consequence assessment in the late stages of an radiation accident. Various magnitudes for migration and fixation recommended for strontium and caesium by a particular expert could be entered into the calculations directly through the subpanel “Radioactivity transport in soil” (see Figure 1). Total time integrated intake of activity $I\mathcal{E}^{a,n}_{TOT}(t)$ (in Bq during the time period $\underline{t}$, normalised to the unit deposition of nuclide $\underline{n}$) for age category $\underline{a}$ due to both direct consumption of edible parts of plants and consumption of contaminated animal products is schematically written as:

$$I\mathcal{E}^{a,n}_{TOT}(t) = \sum_{(l)} I\mathcal{E}^{a,n}_{l}(t) + \sum_{(b)} \left\{ \sum_{p(b)} I\mathcal{E}^{a,n}_{p(b)}(t) \right\} \qquad (1)$$

Here $\underline{l}$ denotes the plant products, $\underline{b}$ means the animal products (milk, meat, eggs). From the products $\underline{b}$ are produced various foodstuffs $\underline{p}(\underline{b})$ (for example from commodity milk are produced the foodstuffs $\underline{p}$: fresh milk, cream, cheese, milk dry, milk condensed, curd, others – with various specific time delays for consumption). The Czech local age-dependent consumption basket and local dynamic parameters are implicitly included. Substituting $t=1$ *year* into Equation (1), the terms on the right side represent the total annual activity intake of radionuclide $\underline{n}$ (normalised to the unit deposition rate 1 Bq.m^{-2}) from direct consumption and from consumption of contaminated animal products. Resulting activity intake $I_{ing}(Drate^{n}_{gr}\ (x,y))$ is found by multiplying the normalised values from Equation (1) by the real distribution of radioactivity deposited on the ground $Drate^{n}_{gr}\ (x,y)$ related to the day of fallout. The distribution of $Drate^{n}_{gr}\ (x,y)$ values on terrain with coordinates (x,y) are determined by the dispersion and deposition calculations. The final committed ingestion doses are assessed as a product of the I_{ing} and tabulated conversion factors.

INTERACTIVE INPUT SUBSYSTEM INGMODEL

We have proposed a user friendly subsystem INGMODEL which enables interactive input of the basic parameters of the ingestion calculations. Structure of ingestion panel consists of sequence of separate subpanels that can be called from the basic menu illustrated in Figure 1. A dynamic model is customized for the average Czech conditions using experience from significant European codes ECOSYS (Müller et al. 1993), FARMLAND (Brown and Simmonds 1995) and PC-CREAM (Smith and Simmonds 2008). The dynamical models take into account local consumption habits in dependence on season and human age categories. Agricultural production scheme, average agro-climatic conditions and phenologic characteristics of the plants are determined in direct relation to the specific day of fallout in a year. Many other food chain specific features can be selected interactively such as feeding diets of animals, time delays during processing, transport and storage of foodstuffs and feedstuffs.



1st heading line: Summer fallout, consumption basket: farmers

2nd heading line: 31.8.2008; fix + migration: RODOS, phenology: lowland

Results for countermeasure module: yes

Date of radioactive fallout: 182.00

End of contaminated intake: 365 days after fallout

● Julian days

○ Calendar days

Time of integration: 50.00

Time of integration is in: year

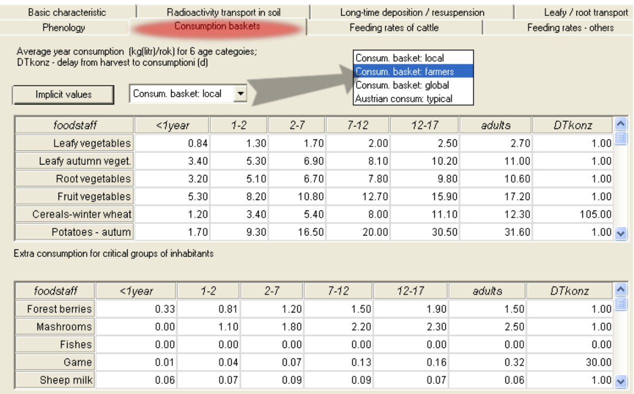
day
month
year

end of current year
365 days after fallout
5 years after fallout
50 years after fallout

Figure 1: Basic input panel of the INGMODEL subsystem

An attempt for partial differentiation according to so called “radioecological regions” is included in several options from Figure 1: *“Consumption habits”* (see in Figure

2), “*Feeding practices”* or “*Phenology”* (implicit subsets for lowland or highland are offered for selection and, possibly, for additional modifications). The architecture of the module ensures fast examination of influence of variability of the input parameters. It enables to perform effectively the sensitivity analysis and the worst-case assessment. Furthermore, a user can select options for alternative semi-empirical formulae used for particular transport effects. These options can be activated through the entries “*Leafy/root transport*”, “*Radioactivity transport in soil*” or “*Long-time deposition/resuspension*” (see Figure 1). It facilitates markedly the variability examinations and sensitivity analysis of the crucial resulting quantities mentioned above.



Average year consumption (kg(litr)/rok) for 6 age categoies;
DTkonz - delay from harvest to consumptioni (d)

foodstaff	*<1year*	*1-2*	*2-7*	*7-12*	*12-17*	*adults*	*DTkonz*
Leafy vegetables	0.84	1.30	1.70	2.00	2.50	2.70	1.00
Leafy autumn veget.	3.40	5.30	6.90	8.10	10.20	11.00	1.00
Root vegetables	3.20	5.10	6.70	7.80	9.80	10.60	1.00
Fruit vegetables	5.30	8.20	10.80	12.70	15.90	17.20	1.00
Cereals-winter wheat	1.20	3.40	5.40	8.00	11.10	12.30	105.00
Potatoes - autum	1.70	9.30	16.50	20.00	30.50	31.60	1.00

Extra consumption for critical groups of inhabitants

foodstaff	*<1year*	*1-2*	*2-7*	*7-12*	*12-17*	*adults*	*DTkonz*
Forest berries	0.33	0.81	1.20	1.50	1.90	1.50	1.00
Mashrooms	0.00	1.10	1.80	2.20	2.30	2.50	1.00
Fishes	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Game	0.01	0.04	0.07	0.13	0.16	0.32	30.00
Sheep milk	0.06	0.07	0.09	0.09	0.07	0.06	1.00

Figure 2: Consumption baskets selection. Predetermined options: Czech Local, Global and Farmers, Austrian typical

ILLUSTRATION OF CAPABILITY FOR RISK ASSESSMENT IN INGESTION PATHWAY

Proposed INGMODEL code is demonstrated here for two cases of hypothetical accidental releases of radioactivity. A more complex scenario labeled in Table 1 as *case 1* accounts for the real meteorological data archived for March 5, 2009. The hypothetical release was assumed to start at 20.00 CET. Just after two hours the release was assumed to finish.

Table 1: Parameters of examined hypothetical scenarios

	Basic characteristics of hypotetical release
case 1	Real meteorological conditions: from archive for March 5, 2009, 20.00 CET , local rain, stability class D, discharge (Bq per 2 hours): ^{90}Sr:1.00E+14, ^{131}I:1.00E+14Bq, ^{137}Cs: 1.00E+15; Segmented Gaussian Plume Model (SGPM) used; the day of fallout for ingestion calculations: summer, July 1st.
case 2	Discharge of radioactivity (Bq per 6 hours): ^{90}Sr:5.00E+12, ^{131}I$_{organic}$:5.00E+13, ^{131}I$_{elemental}$:9.00E+14, ^{131}I$_{aerosol}$:5.00E+13, ^{137}Cs:3.00E+13, ^{140}Ba:1.00E+14; Model of straight-line Gaussian propagation used in direction South-East, stability class D, wind speed 3m.s^{-1}, intensive rain 10 mm.h^{-1}, with modification of wet interception on leaves, summer day of fallout: July 1st.

Each of these two one-hour consecutive segments of the plume was driven in the successive 24 hours by meteorological conditions given for each particular hour of the propagation. The real meteorological situation from March 5, 2009 was rather unusual. The radioactivity release with two hours duration was subjected to this atypical (but real) meteorological sequence. At 20.00 CET the wind blew around direction WNW and speed about 2.5 m.s^{-1}. Prevalent category D of the atmospheric stability according to Pasquill classification with rain was observed. The drifting continued with small changes of wind direction and speed until hour 12 of the propagation. Then the meteo-situation started to change. Situation with low wind speed arouse and during the next 6 hours the plume turned nearly to the opposite direction and local atmospheric precipitation again occurred. Each of the 3 nuclides escaping during 2 hours interval from the source were drifting in subsequent 24-hours around the source. The trace of radioactivity was disseminated on terrain. The deposition distributions have entered the ingestion calculations.

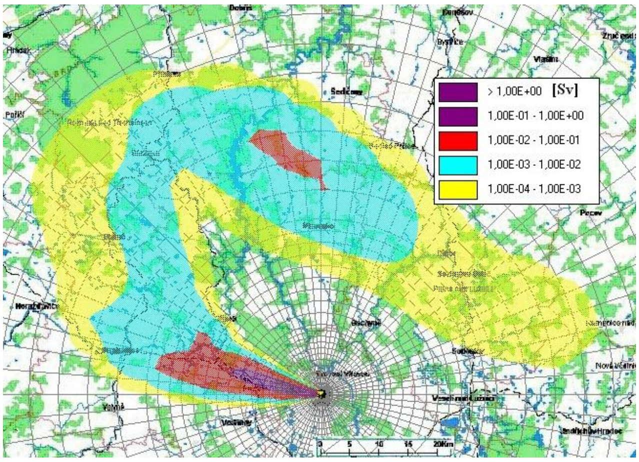


Figure 3: Total effective committed doses for adults – scenario “case 1” from Table 1.

The total annual effective committed doses for adults illustrated in 2-D representation in Figure 3 include the pathways of cloudshine, groundshine, inhalation and ingestion. The ingestion is assumed to be caused by annual radioactivity intake in the first year (year of fallout, summer fallout in July 1 is considered). The effect of local rain caused intensive wet removal of radioactivity and higher deposition on the ground (see Figure 3 - red “rain eye” to the north). More detailed results for scenario “case 1” are in Figure 4. The progression is drown for the West-North-West straight line according to Figure 3. A person permanently living here and consuming here contaminated foodstuffs will suffer these expected doses after the first year, after the 5th year in total and after the 50th year in total.

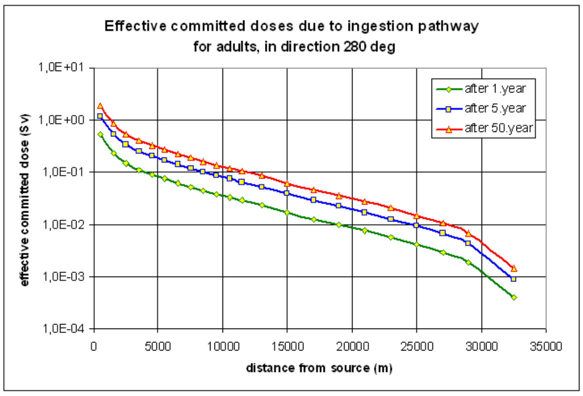
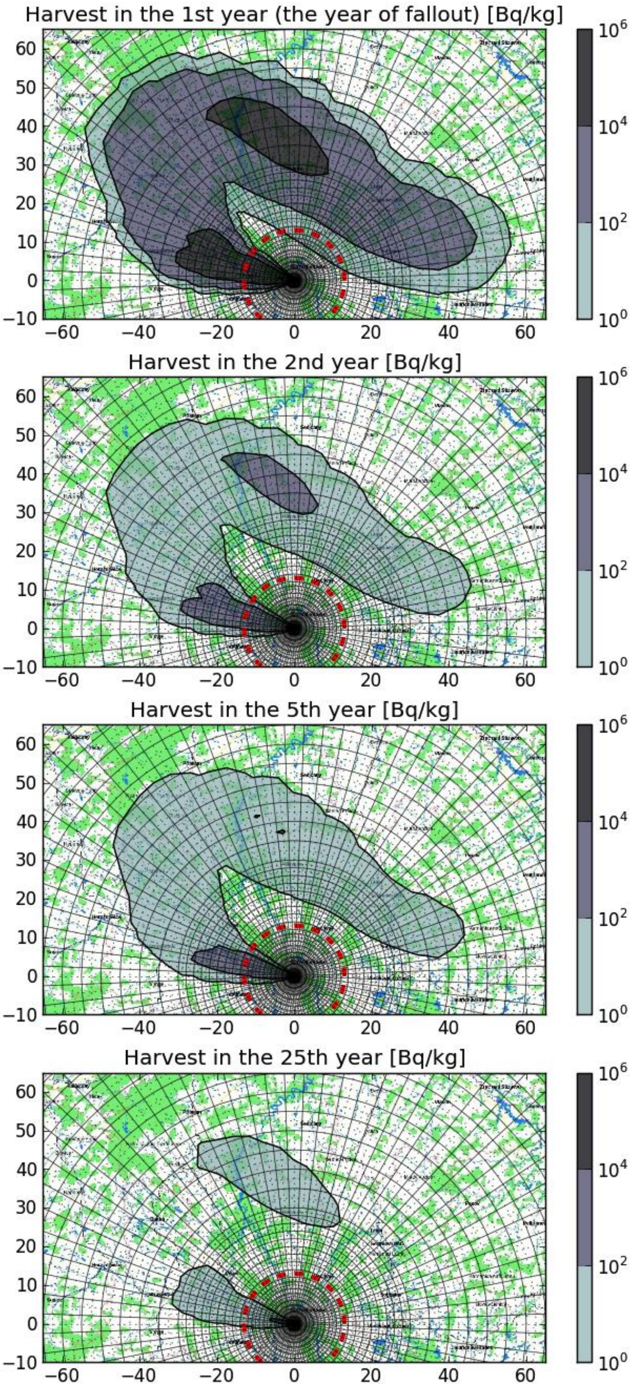


Figure 4: Effective ingestion doses for adults from long term activity intake during 1, 5, 50 years - “case 1”.

Capability to estimate 2-D distribution of the specific activity concentration of ^{137}Cs in the cereals grains is drawn in Figure 5. Depletion of specific activity in the grains at harvest time in the future years is anticipated taking into account effects of Cs migration and fixation in the soil.


Harvest in the 1st year (the year of fallout) [Bq/kg]

Harvest in the 2nd year [Bq/kg]

Harvest in the 5th year [Bq/kg]

Harvest in the 25th year [Bq/kg]

Figure 5: Depletion of specific activity of ^{137}Cs (Bq.kg^{-1}) in grains of harvested cereals in horizon of 25 years after the fallout - scenario “case 1” from Table 1.

Another illustration of the miscellaneous functions of the countermeasure subsystem associated with the INGMODEL product is given in Figure 6. We consider the harvest in the 2nd year (1 year after the fallout). Limit for cereal grains contamination by ^{137}Cs according to (SONS 2002) is 1250 Bq/kg. Considering the limit for consequences of the scenario “case 1” from Table 1, the restricted area with specific concentrations above the limit has red colour. The crop harvested in these areas should not be distributed.

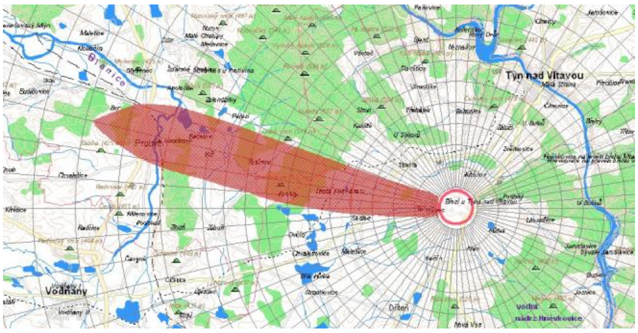


Figure 6: Restricted area for harvest of cereals in the 2nd year after the fallout, given limit of ^{137}Cs in grains is 1250 Bq/kg - scenario “case 1” from Table 1.

PRELIMINARY STUDY OF SENSITIVITY OF INGESTION DOSES ON VARIABILITY OF TRANSFER FACTORS

We should make a distinction between the variability and uncertainty concepts in a risk management. *Variability* reflects changes of a certain quantity over time, over space or across individuals in a population. Variability represents diversity or heterogeneity in a well characterized population. The true variability does not disappear with better measurement. The term *uncertainty* covers stochastic uncertainties, structural uncertainties representing partial ignorance or incomplete knowledge associated with poorly-characterized phenomena and uncertainties of input data. We can only reduce the uncertainties by obtaining the better information.

Let mention the influence of variability of soil types on root uptake of radionuclides in agricultural ecosystems. Root uptake of activity normalized to the unit deposition of radionuclide n [m^2 kg^{-1}] into the plant l and related to the harvest day t_{skl} can be expressed as:

$$ {}^{Root}\varepsilon_l^n(t_{skl}) = \left(1-f^l\right)\cdot \exp\left[-\left(\lambda_2+\lambda^n\right)\cdot\left(t_{skl}-t_{spd}\right)\right]\cdot BV_l^n \Big/ PH_l \tag{2}$$

f^l is interception fraction of foliar deposition, t_{spd} is a day of fallout, λ^n , λ_2 represent radioactive decay and removing by environmental effects, PH is density of root zone [kg m^{-2}]. BV_l^n is equilibrium soil to plant transfer factor [Bq.kg^{-1} plant / Bq.kg^{-1} soil]. Thorough search was accomplished in (IAEA Technical Report Series 2010) which represents an extensive long-lasting study following the consequences of the nuclear weapons testing. Several selected values are recorded in Table 2.

Table 2: Soil to plant transfer factors for pasture [Bq.kg^{-1} plant / Bq.kg^{-1} soil] (all soil types), (IAEA TRS2010).

element	*mean value*	*minimum*	*maximum*
Cs	2.50E-01	1.00E-02	5.00
I	3.70E-03	9.00E-04	5.00E-01
Sr	1.3	5.60E-02	7.3

At the same time the activity transfer to animals due to ingestion of contaminated feedstuffs were selected and recorded in Tables 3 and 4. This equilibrium factors express the rate of daily activity intake which remains in one kilogram or liter of the animal product.

Table 3: Equilibrium transfer factor to cow milk $[\mathrm{d.L^{-1}}]$.

element	*mean value*	*minimum*	*maximum*
Cs	4.6E-03	6.0E-04	6.8E-02
I	5.4E-03	4.0E-04	2.5E-02
Sr	1.3E-03	3.4E-04	4.3E-03

Table 4: Equilibrium transfer factor to beef $[\mathrm{d.kg^{-1}}]$.

element	*mean value*	*minimum*	*maximum*
Cs	2.2E-02	4.7E-03	9.6E-02
I	6.7E-03	2.0E-03	3.8E-02
Sr	1.3E-03	2.0E-04	9.2E-03

Geometric mean is given in the tables. Statistical analysis depends on number of observed values. In some cases only limited data are available and reported data should be used with caution. The values in Table 2 are recommended for a certain representative mixture of soil types. More precise treatment should include the discrimination by soil type categories *sand, loam, clay* and *organic*. The maximum values in Table 2 are close to the sand category, whereas minimum values come near to the clay items. The results in Figure 7 can be perceived as a sensitivity examination of the ingestion pathway on the variability in soil types.

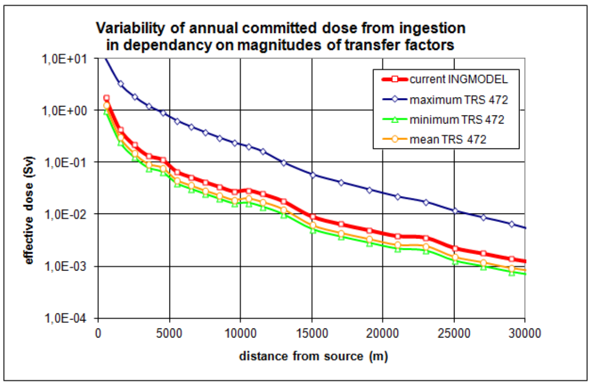


Figure 7: Sensitivity of ingestion doses on variability of transfer factors (TRS 2010)- scenario “case 2” in Table 1.

CONCLUSION

The proposed dynamic ingestion system is briefly described and various capabilities are demonstrated using graphical output subsystem. This article summarizes a wide range of deterministic calculations of the radiological consequences of a hypothetical accidental release of radionuclides into the living environment. A step towards sensitivity examinations is finally mentioned. The INGMODEL development continues in direction of probabilistic risk evaluation when more informative answers can be generated on assessment questions. Our first results covering the late stage of radiation accident were published in (Pecha and Pechova 2005). From that time onwards an effort for advancing a proper software tool for assimilating of model predictions with the field measurements is in a systematic progress.

ACKNOWLEDGEMENTS

This activities are supported by the project No. VG20102013018 provided by the Ministry of the Interior of the Czech republic.

REFERENCES

Brown, J. and J.R. Simmonds. 1995. “FARMLAND-A Dynamic Model for the Transfer of Radionuclides through Terrestrial Foodchains.” Research Report NRPB-R273, Chilton, Didcot,UK.

International Agency for Atomic Energy. 2010. Handbook of Parameter Values for Predictions of Radionuclide Transfer in terrestrial and Freshwater Environments. IAEA Technical Report Series TRS No. 472, Vienna.

Müller, H. and G. Pröhl. 1993. “ECOSYS’87: A Dynamic Model for Assessing Radiological Consequences of Nuclear Accidents.” *Health Physics*, Vol. 64, No. 3, March 1993.

Müller, H., F. Gering and G. Pröhl. 2003. “Model Description of the Foodchain and Dose Module Terrestial in RODOS PV6.0”. Technical report RODOS(RA3)-TN(03)-06.

Pecha, P., P. Kuca and P. Nedoma. 1999. “Foodchain and Dose Module Terrestial Customization for the Czech Republic”. Technical report RODOS(WG3)-TN(98)-14 – final version 1999.

Pecha, P. and E. Pechova. 2002. "Application of Multi-Pathway Transport Model for Regulation of Normal Atmospheric Radioactive Discharges from Nuclear Facilities”. In *Proc. of the 8-th Int. Conf.. on Harmonisation within Atmospheric Dispersion Modelling* (Sofia, Bulgaria), paper No. A94rep.

Pecha, P. and E. Pechova. 2005. “Modeling of random activity concentration fields in air for purposes of probabilistic estimation “. In *Proc. of the 10-th Int. Conf.. on Harmonisation within Atmospheric Dispersion Modelling* (Sissi, Greece,), paper No. H11-069.

Pecha, P., R. Hofman and E. Pechova. 2007. “Training simulator for analysis of environmental consequences of accidental radioactivity releases”. In *Proc. of the 6th EUROSIM Congress on Modelling and Simulation* (Ljubljana, Slovenia, Sept. 9-13, 2007), 18 pp., Conference CD– ISBN 978-3-901608-32-2.

Raskob, W. ed., A. Kerekes, A. Dvorzak, O. Slavik and P. Pecha. 2000. "Documentation on the Two INCO Working Programs: Review of the Adequacy of the Present Foodchain and Dose Calculations and Collection of the Data Required for Each Radioecological Region and their Integration into RODOS”. Technical report RODOS (WG3) – TN(99)-40, 180 pages.

Smith, J.G. and J. R. Simmonds. 2008. The Methodology for Assessing the Radiological Consequences of Routine Releases of Radionuclides to the Environment Used in PC-CREAM 08. Research Report HPA-RPD-058, Health Protection Agency, Chilton, Didcot,UK.

State Office for Nuclear Safety (SONS). 2002. *Regulation No. 307/2002 on Radiation Protection: Annex No. 8: Maximum Permissible Levels of Radioactive Contamination of Foodstuffs.* SONS Governmental Document of the Czech Republic No. 307/2002, Prague.