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A dynamic food-chain model and program for predicting the consequences of nuclear accident

Hu Er-bang, Gao Zhan-rong, Zhang He-yuan, Wei Wei-qiang

Institute of Environmental Science, CIRP, Taiyuan 030006, China

Abstract—A dynamic food-chain model and program, DYFOM-95, for predicting the radiological consequences of nuclear accident has been developed, which is not only suitable to the West food-chain but also to Chinese food chain. The following processes, caused by accident release which will make an impact on radionuclide concentration in the edible parts of vegetable were considered: dry and wet deposition interception and initial retention, translocation, percolation, root uptake and tillage. Activity intake rate of animals, effects of processing and activity intake of human through ingestion pathway ware also considered in calculations. The effects of leaf area index LAI of vegetable were considered in dry deposition model. A method for calculating the contribution of rain with different period and different intensity to total wet deposition was established. The program contains 1 main code and 5 sub-codes to calculate dry and wet deposition on surface of vegetable and soil, translocation of nuclides in vegetable, nuclide concentration in the edible parts of vegetable and in animal products and activity intake of human and so on.

Keywords: dynamic food-chain; model and program; consequences of nuclear accident.

1 Introduction

A dynamic food-chain model and program for predicting the radiological consequences of nuclear accident has been developed which is not only suitable to West food-chain but also Chinese food-chain (Koch, 1986; Whieker, 1987). Fig. 1 shows the concept scheme of this dynamic food-chain model.

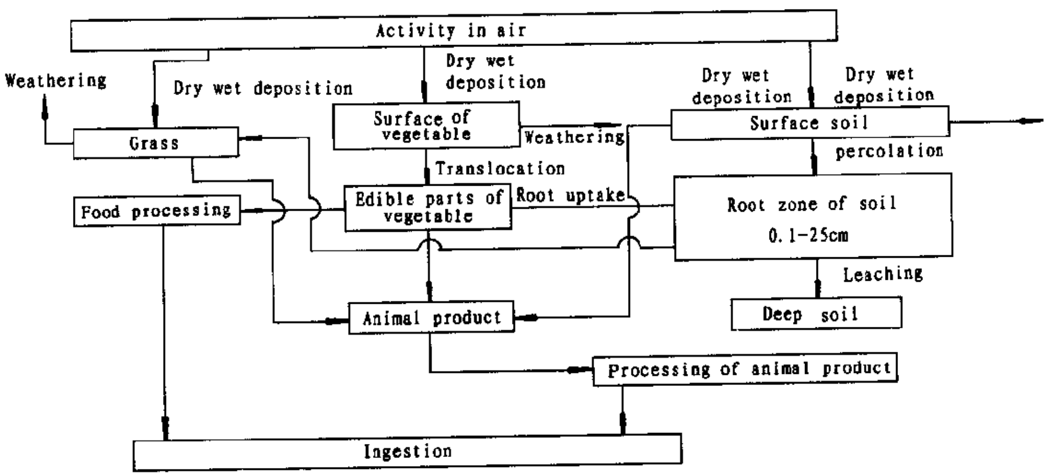

Fig. 1 Concept scheme

2 Dry and wet deposition and initial retention (Brenk, 1980; Prochl, 1993; Simmonds, 1982)

2.1 Dry deposition on the vegetable surface

When the duration of an accident is so long that the decay must be considered, the amount of dry deposition of i-nuclide on j-vegetable surface at the end of accident $A_{dij}(t_e)$ (Bqm^{-2}) could be given by the following formula:

$$A_{dij}(t_e) = V_{dij}\chi_i \frac{(1 - e^{-\lambda_i \Delta t})}{\lambda_i}, \quad (1)$$

where, χ_i is concentration of i-nuclide (Bq·m^{-3}); V_{dij} is deposition velocity of i-nuclide on j-vegetable (ms^{-1}); λ_i is decay constant of i-nuclide (s^{-1}); t_e is the time at end of accident (s); Δt is time needed for plume through the calculation areas.

V_{dij} is relative to leaf area of vegetable and is given as follows:

$$V_{dij} = V_{dij,\max} \frac{LAI_j(t_e)}{LAI_{j,\max}}, \quad (2)$$

where, $V_{dij,\max}$ is maximum deposition velocity of i-nuclide for j-vegetable (i.e. for full developed foliage); $LAI_j(t_e)$ is leaf area index of j-vegetable at time of end of deposition (t_e); $LAI_{j,\max}$ is leaf area index of j-vegetable at time of fully developed foliage. Table 1 shows the result of experiment measuring in Taiyuan.

Table 1 Leaf area index of plant in Taiyuan, m^2/m^2

Vegetable	Date	Leaf area index (LAI)
Winter wheat	4.13	1.19
	4.22	2.33
	4.29	2.66
	5.6	2.92
	5.13	3.69
Rice	7.18	1.92
	8.1	3.48
	8.15	4.58
	8.24	4.83
Potato	6.27	0.87
	7.2	1.48
	7.18	1.50
	8.1	2.13
Carrot	9.5	0.48
	9.12	0.52
	9.19	0.81
	9.26	1.30
	10.3	1.77

2.2 Wet deposition

The amount of wet deposition at the time t_e, $A_{wi}(t_e)$ (Bq. m^{-2}), could be expressed as follows:

$$A_{wi}(t_e) = \sum_K \frac{8\Lambda_{ik}Q_i}{\pi u x}\left(\frac{1 - e^{-\lambda_i \Delta t_k}}{\lambda_i}\right) \times e^{-\lambda_i(t_e - t_k)}. \quad (3)$$

where, Λ_{ik} is washout coefficient of i-nuclide for k-rainfall event (s^{-1}); Q_i is source intensity of i-nuclide (Bq·s^{-1}); u is wind speed (m·s^{-1}); x is wind-down distance (m); Δt_k is duration of k-rainfall event (s); k is number of rainfall event during the accident plume through the calculation area. Fig. 2 shows the time after arriving of plume at calculation area.

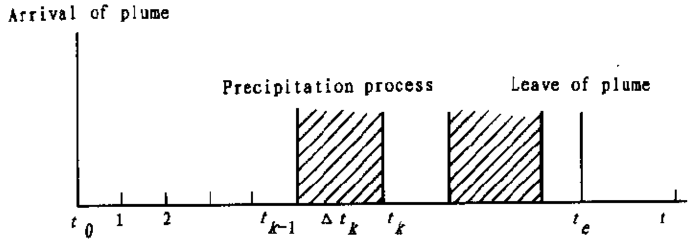

Fig. 2 Time after arriving of plume at calculation area(s)

2.3 Interception and initial retention by vegetable of wet deposited radionuclides

The amount of wet deposition of i-nuclide on j-vegetable during accident $A_{wij}(t_e)$ (Bqm^{-2}) is shown by the following equation:

$$A_{wij}(t_e) = f_{wj}A_{wi}(t_e), \tag{4}$$

where f_{wj} is interception fraction of j-vegetable and could be given as follows:

$$f_{wi} = \frac{LAI_jS_j}{R}\left[1 - \exp\left(\frac{-\ln 2}{3S_j}R\right)\right], \tag{5}$$

where, S_j is effective water storage capacity of j-vegetable (mm); R is total amount of rainfall during accident (mm).

2.4 Total deposition on soil

The total deposition of i-nuclide on the soil with j-vegetable at the end of accident $A_{sij}(t_e)$ ($Bq.m^{-2}$) could be estimated by the following equation:

$$A_{sij}(t_e) = A_{dijs}(t_e) + A_{wijs}(t_e), \tag{6}$$

$$A_{sij}(t_e) = \chi_i V_{dij,\max}\left(1 - f_a\frac{LAI_j}{LAI_{j,\max}}\right)\frac{1 - e^{-\lambda_i\Delta t}}{\lambda_i} + (1 - f_{wi}),$$
$$\times\sum_K\left\{\frac{8\,\Lambda_{ik}Q_i}{\pi ux}\left(\frac{1 - e^{-\lambda_i\Delta t}}{\lambda_i}\right)\exp[-\lambda_i(t_e - t_k)]\right\}, \tag{7}$$

where, f_a is fraction of deposited nuclide which is not intercepted by vegetable and arrives to soil.

3 Translocation (IAEA, 1993)

Translocation factor $Tr(a)$ ($Bq\cdot m^{-2}/Bq\cdot m^{-2}$) is defined as a ratio of activity in the edible parts of vegetable of 1 m^2 at harvest to activity retained on the foliage of 1 m^2 at deposition.

The translocation factor for Cs at time δt can be described as:

$$T_r(\delta t) = T_{r,\max}\exp[-b(\delta t - t_{\max})], \tag{8}$$

where, δt is time distance before harvest (d). $T_{r,\max}$ is maximum value of translocation factor, b is a parameter for experimental measure curve, $T_{\max}$ is time distance before harvest at which the maximum translocation factor occurs. Table 2 gives the measuring value of Cs translocation factor $T_r(a)$ ($Bq\cdot m^{-2}/Bq\cdot m^{-2}$).

4 Activity concentration due to dry, wet deposition and translocation at harvest time

The concentration of i-nuclide in the edible parts of j-vegetable at harvest time $A_{ij}(T_p)$ (Bq·kg^{-1}) could be given as:

$$A_{ij}(t_p) = \frac{[A_{dij}(t_e) + A_{wij}(t_e)]}{Y_j} Tr(\delta t) \exp[-(\lambda_w + \lambda_i)\delta t], \quad (9)$$

where, λ_w is loss rate due to environment (d^{-1}), Y_j is output of j-vegetable (kg·m^{-2}).

5 Percolation and radionuclide concentration in the soil surface layer

In our work, soil is divided into 3 layers: surface layer (0—0.1 cm), root zone of soil (0.1—25 cm) and deep soil (>25 cm). The deposition occurs only in surface soil and root uptake occurs only in root zone of soil.

Table 2 Measuring value of Cs translocation factor T_r(a), m^2/m^2

Vegetable	Time to harvest, d	Translocation factor, m^2/m^2
Winter wheat	63	0.0067
	54	0.0303
	47	0.0244
	40	0.0215
	33	0.0200
Rice	79	0.016
	66	0.010
	52	0.096
	43	0.068
Potato	106	0.0014
	101	0.0028
	85	0.0107
	71	0.0059
Carrot	49	0.059
	42	0.070
	35	0.147
	28	0.066
	21	0.048

5.1 Percolation

The phenomenon that moves radioactivity from 0—0.1 cm surface soil layer to the underlying soil is referred to as percolation. Percolation constant λ_{per} is taken as $1.98 \times 10^{-2}\ d^{-1}$, here, it is correspondence with a half time of 35d.

5.2 Radionuclide concentration in the soil surface layer $A_{sij}(t)$ (Bq·m^{-2})

The concentration of i-nuclide in the surface soil with j-vegetable at t time is expressed as:

$$A_{sij}(t) = A_{sij}(t_e) \times \exp[-(\lambda_{per} + \lambda_i)(t - t_e)], \quad (10)$$

where, t is time after end of deposition event.

6 Root uptake

6.1 Radionuclide concentration in the root zone of soil

After deposition event the nuclides deposited on the surface soil will go into root zone of soil through percolation process. Suppose nuclides entered into root zone is distributed evenly in total root zone of soil, the concentration of i-nuclide in the root zone of soil with j-vegetable at t time could be given as follows:

$$A_{rij}(t) = \frac{A_{sij}(t_e)[1 - \exp(-\lambda_{per}(t - t_e))]}{L\rho}\exp[-(\lambda_s + \lambda_f + \lambda_i)(t - t_e)], \qquad (11)$$

where, L is depth of root zone, L is 0.1m for grass soil and 0.25m for other soil; ρ is density of soil, ρ is 1.4 $kg \cdot m^{-3}$ here; λ_s is rate of activity decrease due to migration out of the root zone (d^{-1}); λ_f is rate of fixation of the radionuclides in the soil (d^{-1}); λ_f is $2.2 \times 10^{-4} d^{-1}$ for Cs and $9 \times 10^{-5} d^{-1}$ for Sr.

6.2 Root uptake

A transfer factor is commonly used to express the uptake of nuclides by vegetable from soil. The transfer factor B_V is defined as a ratio between the concentration of nuclides in vegetable and in soil ($Bq \cdot kg^{-1}$ dry vegetable /$Bq \cdot kg^{-1}$ dry soil). Hence the concentration of i-nuclide in vegetable at time t after deposition contributed from root uptake $A_{srij}(t)$ ($Bq \cdot kg^{-1}$) is given by following equation:

$$A_{srij}(t) = B_{vij}A_{rij}(t)f_{gi}, \qquad (12)$$

where, f_{gj} is a time reduction factor

$$f_{gj} = \frac{\text{Time span from deposition to harvest}}{\text{Length of the whole growing period}}$$

$$f_{gj} = \begin{cases} f_{gi} & \text{if the deposition occurs during the growing period} \\ 1 & \text{if not} \end{cases}$$

7 Influence of the tillage on radionuclide concentration in the soil surface layer and root zone of soil

Suppose the ratio of activity between surface layer and root zone is proportional to their mass and their soil density is 1.0 g cm^{-3} and 1.46 g cm^{-3} respectively. And so the retention fraction by surface layer f_s and root zone f_r are respectively 0.0027 and 0.9973.

7.1 Deposition occurrence before tillage

7.1.1 For the period from end of deposition to tillage time

The radionuclide concentration in the soil surface layer and in the root zone of soil could be estimated by Equation (10) and (11). The activity concentration of i-nuclide in the edible of j-vegetable due to root uptake is given by Equation (12)

7.1.2 For the period from tillage to harvest

The radionuclide concentration in the soil surface layer $A'_{sij}(t)$ ($Bq \cdot m^{-2}$) and in the root zone of soil $A'_{rij}(t)$ could be estimated by following two formula:

$$A'_{sij}(t) = \{A_{sij}(t_e)\exp[-(\lambda_{per} + \lambda_i)(t_d - t_e)] + A_{sij}(t_e)[1 - \exp(-\lambda_{per})(t_d - t_e)] \times \exp[-(\lambda_s + \lambda_f + \lambda_t)(t_d - t_e)]\} f_s \times \exp[-(\lambda_{per} + \lambda_i)(t - t_d)]. \qquad (13)$$

$$A'_{rij}(t) = \{A_{sij}(t_e)\exp[-(\lambda_{per} + \lambda_i)(t_d - t_e)] + A_{sij}(t_e)[1 - \exp(-\lambda_{per})(t_d - t_e)] \times \exp[-(\lambda_s + \lambda_f + \lambda_t)(t_d - t_e)]\} f_r \times \frac{\exp[-(\lambda_s + \lambda_f + \lambda_i)(t - t_d)]}{L\rho}. \qquad (14)$$

7.1.3 Radionuclide concentration in the edible part of vegetable contributed from root uptake

The following formula could be used to estimate the concentration of i-nuclide in the edible part of j-vegetable contributed from root uptake at t_p harvest time $A'_{sij}(t_p)$ (Bq·kg^{-1}).

$$A'_{srij}(t_p) = B_{Vij} A'_{rij}(t_p) f_{gi} f_{rf}, \tag{15}$$

where, f_{rf} shows a ratio of dry and wet weight of vegetable.

7.2 Deposition occurrence after tillage

In this case there is no influence from tillage.

8 Radionuclide concentration in the edible parts of vegetable

8.1 Deposition occurrence before tillage

In this case the influence of tillage should be into considered. The total i-nuclide concentration caused by leaf deposition and root uptake in j-vegetable at harvest time $A_{ijT}(t_p)$ (Bq·kg^{-1}) is given as follows:

$$A_{ijT}(t_p) = A_{ij}(t_p) + A'_{srij}(t_p), \tag{16}$$

where, $A_{ij}(t_p)$ and $A'_{srij}(t_p)$ represent the contribution from two pathway: leaf deposition and root uptake respectively. $A_{ij}(t_p)$ is given be Equation (9). $A'_{arij}(t_p)$ is as follows:

$$\begin{aligned} A'_{srij}(t_p) &= B_{vij} A'_{rij}(t_p) f_{gi}/f_{rf} = \frac{B_{Vij} f_{gi} f_r}{f_{rf} L \rho} \{ A_{sij}(t_e) \exp[-(\lambda_{per} + \lambda_i)(t_d - t_e)] \\ &+ A_{sij}(t_e)[-\exp(-\lambda_{per}(t_d - t_e))] \times \exp[-(\lambda_s + \lambda_f + \lambda_i)(t_d - t_e)] \} \\ &\exp[-(\lambda_s + \lambda_f + \lambda_i)(t_p - t_d)]. \end{aligned} \tag{17}$$

8.2 Deposition occurrence after tillage

In this case there is no influence of tillage on the activity concentration of vegetable.

$$A_{ijT}(t_p) = A_{ij}(t_p) + A_{srij}(t_p). \tag{18}$$

9 Activity intake of man through ingestion pathway

The rate of activity intake of man through ingestion pathway could be estimated by following equation:

$$\begin{aligned} A_{Hi}(t) &= \left\{ \sum_j A_{ijT}(t_p) \exp[-\lambda_i(t - t_p)] V_j(t) F_{rj}/P_{ej} \right\} \\ &+ \left\{ \sum_k C_{mki}(t_s) \exp[-\lambda_i(t - t_s)] V_k(t) F_{rk}/P_{ek} \right\}, \end{aligned} \tag{19}$$

where, $A_{Hi}(t)$ is human activity intake rate of i-nuclide at time t (Bq, d^{-1}); $A_{ijT}(t_p)$ is activity concentration of i-nuclide in j-vegetable at harvest time (t_p) (Bq. kg^{-1}); $C_{mkj}(t_s)$ is activity concentration of i-nuclide in k-product of m-animal at butcher time (Bqkg^{-1} or BqL^{-1}) (Vokt, 1989); P_{ej}, P_{ek} are processing efficiency for j-vegetable and for k-product of animal respectively (kg prepared product/kg raw material) (IAEA, 1992); $V_j(t)$, $V_k(t)$ are consumption rate for prepared product of j-vegetable and for k-product of animal respectively (kgd^{-1}); F_{rj}, F_{rk} are processing retention factor for j-vegetable and for k-product of animal respectively. Table 3 shows the average annual consumption rates of towns people near Qinshan NPP site. It could be used to estimate the activity intake rate for Chinese people.

Table 3 Average annual consumption rates of towns people nearby site

Foodstuff, kg/a	Adult	Teen-agers	Children	Infant
Cereals	204.71	204.71	102.36	40.94
Leafy veg.	137.41	137.41	68.70	27.48
Root veg.	5.15	5.15	2.58	1.03
Fruit veg.	22.33	22.33	11.16	4.47
Aquatic veg.	6.78	6.78	3.44	1.37
Poultry	7.75	7.75	3.87	1.55
Pork	23.14	23.14	11.57	4.63
Beef and lamb	1.07	1.04	0.53	0.21
Eggs	9.79	9.79	4.90	1.96
Milk	5.07	5.07	12.67	15.20
Aquatic product	21.66	21.66	10.83	4.33
Fruits	55.78	55.78	27.89	11.16

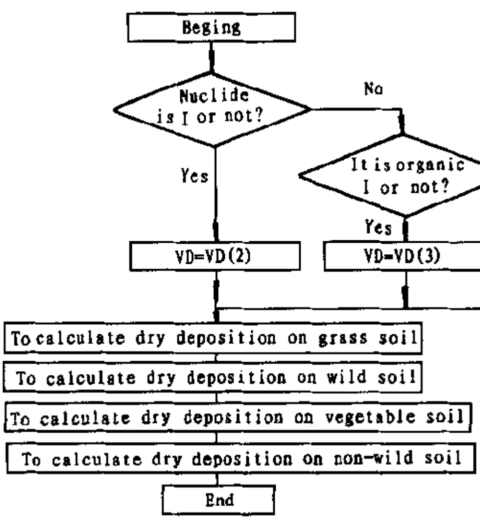

Fig. 3 Flow chart of DRYDEP sub-code

10 Simple description of program "DYFOM-95"

"DYFOM-95" consists of one main code and five sub-codes. Sub-code "DRYDEP" and "WET, DEP" are used to calculate the dry and wet deposition of nuclides on vegetable and soil. Sub-code "TRANS" calculates the ratio of nuclide which transfers into edible parts of vegetable from leaf and root zone of soil. Sub-code "ANEM" estimates the activity in prepared product of vegetable and animal. Sub-code "ANIPRT" is made to estimate activity intake rate of human through ingestion of prepared product of vegetable and animal. Fig.3 shows the flow chart of sub-code "DRYDEP".

References

Brenk H D, Voget K J. Reassessment of wet deposition from radioactive plumes with respect to practical application, Draft. 1980

IAEA. Handbook of parameter values for the prediction of radionuclide transfer in temperate environments. Draft, Vienna, Jam. 1993

IAEA. Modelling of resuspension, seasonality and losses during food processing. LAEA-TEC. DOC-647, Vienna: INIS Clearinghouse, 1992. 35--59

Koch J, Tadmor J. Health Physics, 1986, 50(6):721—737

Proehl G, Hoffman F O. The interception, initial and post deposition-retention by vegetation of dry and wet deposited radionuclides. VAMP terrestrial working group. IAEA. 1993

Simmonds J R, Linsley G S. Health Physics, 1982, 43(5): 679—691

Vokgt G, Miiller H. Health Physics, 1989, 57(6): 967—973

Whicker F W, Kirchner T B. Health Physics, 1987, 52(6):717—737

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