방사선방어학회지
제18권 제1호 1993

■ 論　文 ■

Development of a Dynamic Ingestion Pathways Model(KORFOOD), Applicable to Korean Environment

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ABSTRACT

The time-dependent radioecological model applicable to Korean environment has been developed in order to assess the radiological consequences following the short-term deposition of radionuclides in an accident of nuclear power plant. Time-dependent radioactivity concentrations in foodstuffs can be estimated by the model called "KORFOOD" as well as time-dependent and time-integrated ingestion doses. Three kinds of critical radionuclides and thirteen kinds of foodstuffs were considered in this model. Dynamic variation of radioactivities were simulated by considering several effects such as deposition, weathering and washout, resuspension, root uptake, translocation, leaching, senescence, intake and excretion of soil by animals, intake and excretion of feedstuffs by animals, etc. The input data to the KORFOOD are the time of the year when the deposition occurs, the kinds of radionuclides and foodstuffs for estimation. The time-dependent specific activities in rice and the ingestion doses due to the consumption of all considered foodstuffs were calculated with deposition time using agricultural data-base in Kori region. In order to validate results of KORFOOD, the calculated results were compared with those by a leading German model, ECOSYS-87. The comparison of results shows good agreements within a factor of ten.

Key words : Dynamic ingestion pathways, Specific activity, Deposition time.

INTRODUCTION

Contamination of agricultural products by radioactive materials is one mechanism which causes exposures of the population following the deposition of radioactive materials in environment. Several studies concerning continuous release from nuclear power plants and subsequent food contamination have been reported. Equilibrium was assumed to be established between the release rate and the radioactivity concentrations in the compartments of the environment. Well-known models utilizing this approach, so called, "concentration factor method", are HERMES[1], FOOD II[2] and AIRDOS-EPA[3] based on Regulatory Guide 1.109 of U.S. Nuclear Regulatory Commission[4].

However, the equilibrium model is not suitable to describe the behavior of radioactive effluents following accidents of nuclear power plant. Radioactivity concentrations in foodstuffs and feedstuffs after an accident are used to vary with time. Therefore, dynamic models based on the "system analysis method" have been developed in order to investigate realistically the transfer of radionuclides in the food-chain. Dynamic modelling study begun from late 1960's. TERMOD[5] was considered as a typical basic model to describe the dynamic transfer of radionuclides through terrestrial food chains to man. RAGTIME[6], ECOSYS[7], FOOD-MARC[8], RADFOOD[9], PATHWAY[10] and ECOSYS-87 [11] were the similar works which were developed recently. The principal limitation of these models to the practical application comes from the scarcity of time-dependent data and the difficulties in describing the complex transport mechanisms of radionuclides in the detailed site -specific environment.

Korea is considerably different from foreign countries in socio-environmental aspects such as food consumption habits, yield and growing period of plants, soil characteristics, climate, etc. Therefore, a dynamic food-chain model applicable to the Korean environment was developed using site-specific data-base in Korea, where additional mechanisms and pathways were included with some modification of previous models. Several sets of first-order differential equations were solved by the numerical solutions using GEAR method[12, 13].

TRANSPORT MECHANISMS OF RADIONUCLIDE IN KORFOOD

The KORFOOD has the following important characteristics in comparison with previous models.

(1) Consideration of direct deposition onto grain and fruit

(2) Realistic simulation of radionuclide behaviors in rice field, which has different soil characteristics and agricultural activities with field

(3) Separate treatment of removal effect by wind turbulence and washout, and the realistic simulation of radionuclide behaviors by using seasonal rainfall data

(4) Consideration of time-dependent resuspension effect

Deposition

Radionuclides released into atmosphere due to an accident of nuclear power plant are deposited onto plant leaves, grain and fruit, and ground surface. Fractional part of the deposited materials is intercepted by and retained on plant leaves, grain and fruit, while the remainder is deposited directly on the ground. Interception and retention of fallout are dependent on the physico-chemical properties of radionuclides, on the surface properties of plants, and on the amount of ground surface covered by plants.

The fractions intercepted by plant is given by[14]

$$S(t) = 1 - \exp(-\mu\ Y(t)) \qquad \cdots\cdots(1)$$

Accordingly, the fraction deposited to the soil surface is

$$S_{soil}(t) = 1 - S(t) \qquad \cdots\cdots(2)$$

Plant growth

The growth of plant was assumed to be a logistic one with the rate constant dependent on temperature and light intensity. It was estimated by the following equation[10].

$$\frac{dY(t)}{dt} = Kg\ FL(t)\ FT(t)\ Y(t)\ \left(\frac{Y_{mas} - Y(t)}{Y_{max}}\right)$$
$$-AD\ C_f\ f_r \qquad \cdots\cdots(3)$$

Growing period, maximum yield, and consumption rate in the typical Korean environment were represented for each food category in table 1[17].

Table 1. Foodstuff groups, selected foodstuffs, growing periods, yields of plants, and consumption rate considered in the KORFOOD.

Foodstuff Group	Selected Foodstuff	Sowing Time	Harvest Time	Maximum Yield of Leaves (kg/m^2)	Maximum Yield of Edible Parts (kg/m^2)	Consumption Rate [kg/yr]
rice	rice	5.01	9.30	0.88	0.44	142.29
other grains	barley	1.01	5.31	0.52	0.26	10.84
legume	soybean	5.01	9.30	0.26	0.13	15.57
leafy vegetable	Chinese cabbage	8.20	11.15	0.35	0.35	33.92
root vegetable	radish	8.20	11.15	0.25	0.25	25.89
fruit vegetable	cucumber	5.01	7.31	0.26	0.13	31.37
potatoes	potatoes	3.20	6.30	0.14	0.14	13.49
fruit	apple	5.01	10.10	1.80	0.20	9.53
pasture-grass	pasture-grass	5.01	9.30	0.49	0.49	–
egg	egg	–	–	–	–	6.29
pork	pork	–	–	–	–	4.31
poultry	chicken	–	–	–	–	1.21
milk	milk	–	–	–	–	7.98
beef	beef	–	–	–	–	5.22

Senescence

Senescence affects variation of plant yield and transport of radionuclide from plant leaves to soil surface. This mechanism is effective in the case of pasture-grass from early August to the harvest time. Time derivative of yield for pasture-grass during period is given by[10]

$$\frac{dY(t)}{dt} = K_g\ FL(t)\ FT(t)\ Y(t)\ \left(\frac{Y_{max}^{*} - Y(t)}{Y_{max}^{*}}\right) - AD\ C_f\ f_r - K_s\ (Y(t) - Y_{min}) \quad \cdots\cdots(4)$$

Use of Y_{max}^{*} preserves the continuity in Y versus time. Y_{max}^{*} may be shown to be

$$Y_{max}^{*} = \frac{K_g\ (Y_{max})^2}{Y_{max}\ (K_g - K_s) + K_s\ Y_{min}} \quad \cdots\cdots(5)$$

Equations (3) and (4) can not be solved analytically; so numerical integration by Runge-Kutta method was performed to obtain the variation of yield with time.

Since it is assumed that the radionuclide is uniformly distributed in the biomass, the rate of transfer of radionuclide from plant leaves to soil surface due to the senescence can be expressed as follows.

$$\lambda_{se} = K_s\ \left(\frac{Y(t) - Y_{min}}{Y(t)}\right) \quad \cdots\cdots(6)$$

Weathering/Washout

Retained radionuclides are removed from surface of leaves and grain by weathering effect such as wind turbulence. The first-order rate constant was used in order to estimate the weathering effect by wind turbulence[15].

Rainfall distribution is not uniform with respect to season in Korea. Accordingly, the consideration of washout effect for radioactivity removal by rainfall is important in such weather condition. The washout rate constant can be represented as follows[15];

$$\lambda_{wash} = C_w \cdot R(t) \quad \cdots\cdots(7)$$

The value of C_w depends on many factors such as properties of radionuclides, plant species, etc. In this model, the seasonal rainfall rate in the Kori region during 1988 was used as shown in Table 2[17].

Table 2. Seasonal average rainfall rate in the Kori region [mm].

March-May	June-August	Sep.-Nov.	Dec.-Feb.
336.5	652.7	298.7	117.1

Resuspension

Radionuclides on the soil surface can be resuspended by weathering effect and subsequently deposited on the surface of plant leaves or grain. Resuspension factor (RF) with time recommended by Linsley was used, which was defined as the ratio of air concentration [Bq/m^3] to surface density [Bq/m^3] [15].

$$RF = 10^{-6}\ \exp(-0.01\ t) + 10^{-9} \quad \cdots\cdots(8)$$

$$\lambda_{re} = RF \cdot V \quad \cdots\cdots(9)$$

Translocation

The transfer rate of radionuclide by translocation is quantified by the translocation factor, which is defined as the fraction of radioactivity deposited on the plant leaves transferred to the edible parts of the plant. It is dependent on the radionuclide, the plant species, and the time span between deposition and harvest time. For the immobile radionuclides such as Sr, translocation factors were assumed to be lower by a factor 0.6 than those for the mobile elements such as Cs and I [16]. Translocation factor from the plant surface to the edible parts was estimated with the following Gaussian function[16].

$$Tr(\delta t) = Tr(max)\exp\{-b[\delta t - \delta t(max)]^2\} \quad \cdots\cdots(10)$$

$$\lambda_{tr} = \frac{Tr(\delta t)}{\delta t} \quad \cdots\cdots(11)$$

Leaching

The downward movement of the radionuclides from the layer of soil surface to deeper soil layer was treated by assigning a leaching mechanism [16].

$$\lambda_{le} = \frac{R_p}{\theta\, L(1 + \frac{\rho}{\theta} K_d)} \quad \cdots\cdots(12)$$

Evaporation rate and relevant parameters in leaching rate in the typical Korean environment were given in Table 3 and 4, respectively[17].

Adsorption/Desorption

Specific radionuclides are fixed and desorbed in the root zone of soil. This mechanism was applicable only to the effective radionuclide such as Cs in non-labile soil. The first-order rate-constants were used for adsorption and desorption [10].

Table 3. Monthly evaporation rates in the typical Korean environment [mm].

Month	Rice field	Field	Pasture-grass
Dec.-Feb.	174.1	120.0	120.0
March	60.0	40.0	40.0
April	65.0	40.0	40.0
May	68.4	51.4	52.2
June	113.9	97.2	84.2
July	225.0	156.8	112.5
August	286.0	115.0	101.7
September	204.5	99.2	69.4
October	65.0	40.0	40.0
November	60.0	40.0	40.0

Table 4. Parameters in leaching rate in the typical Korean environment.

Parameters	Rice field	Field	Pasture land	
(Units)			0~1cm	1~15cm
L (cm)	25	25	1	14
θ (ml/cm^3)	0.6	0.27	0.27	0.27
ρ (g/cm^3)	1.04	1.18	1.18	1.18

Root uptake

In the root zone, radionuclides are absorbed by plant roots, depending on soil, plant, and radionuclide properties. The rate of root uptake is considered to be dependent on the growth rate of plants, which varies logistically[10].

$$\lambda_{up} = \frac{(dY(t)/dt)\ B_{iv}}{X_r\ \ P_s} \quad \cdots\cdots(13)$$

Table 5. Values of plant/soil concentration ratio.

Element	Rice	Barley	Bean	Cabbage	Radish	Cucumber	Potatoes	Fruit	Pasture-grass
Cs-137	2.8E-2	5.5E-2	1.8E-1	1.1E-1	4.6E-2	3.1E-2	1.1E-2	2.0E-3	3.0E-2
I -131	2.0E-2	2.0E-2	2.0E-2	2.0E-2	2.0E-2	2.0E-2	2.0E-2	2.0E-2	2.0E-2
Sr-90	1.7E-1	4.3E-1	9.1E-1	2.0E-0	4.2E-1	1.6E-1	2.7E-2	2.0E-1	6.5E-1

The values of plant/soil concentration factor were obtained by the experiments in the typical Korean environment and represented in Table 5[17].

Pasture-grass intake and excretion by animal

The contamination of meat and animal products results from the radionuclide intake by the animal. It was assumed that animals intaked fresh pasture-grass in grazing season and stored pasture-grass in non-grazing season. The transfer rate of radionuclide to meat or animal products due to intake of pasture-grass was estimated by the following equation[10].

$$\lambda_{ingf} = \frac{C_f\ AD}{Y(t)} \qquad \cdots\cdots(14)$$

$$\lambda_{ingfr} = \lambda_{ingf}\,(A_{mt} + A_{mk}) \qquad \cdots\cdots(15)$$

The intake of pasture-grass also provides for radionuclide transfer from pasture-grass to the soil surface.

$$\lambda_{fex} = \lambda_{ingf}\,\{1-(A_{mt} + A_{mk})\} \qquad \cdots\cdots(16)$$

Radioactivity concentration on the soil surface decreases slightly due to the intake of soil by animals. Only the digested fraction is considered, since the undigested portion is quickly excreted to the soil surface[10].

$$\lambda_{ings} = \frac{FS\ AD}{X_L\ \ P_L} \qquad \cdots\cdots(17)$$

$$\lambda_{ingsr} = \lambda_{ings}\,(A_{mt} + A_{mk}) \qquad \cdots\cdots(18)$$

Urinary excretion that transfers radionuclide to the soil surface results in the biological elimination

Table 6. Digested fractions to meats, milk and eggs, and rate constants for biological elimination from meats.

Nuclides	A_{mt}			λ_b (d^{-1})			A_{mk}	A_{eg}
	Beef	Pork	Chicken	Beef	Pork	Chicken	Milk	Eggs
Cs-137	5.0×10^{-1}	5.0×10^{-1}	8.8×10^{-2}	2.3×10^{-1}	4.1×10^{-1}	1.8×10^{-2}	9.3×10^{-2}	2.5×10^{-2}
I -131	5.0×10^{-2}	5.0×10^{-2}	3.2×10^{-3}	3.9×10^{-2}	6.9×10^{-2}	4.1×10^{-2}	1.1×10^{-1}	1.2×10^{-1}
Sr-90	9.9×10^{-3}	9.9×10^{-3}	1.8×10^{-2}	9.3×10^{-2}	1.7×10^{-1}	8.6×10^{-1}	1.8×10^{-2}	6.4×10^{-3}

of the radioactivity in the meat compartment.

$$\lambda_{uex} = \lambda_b \qquad \cdots\cdots(19)$$

Table 6 shows fractions digested to meats, milk and eggs, and rate constants for biological elimination from meats assumed in this model [11].

MATHEMATICAL FORMULATIONS

The transfer kinetics of radionuclides is described by a set of linear first-order differential equations. Each equation corresponding to each compartment, which represents an environment element, describes the change of the radioactivity concentration

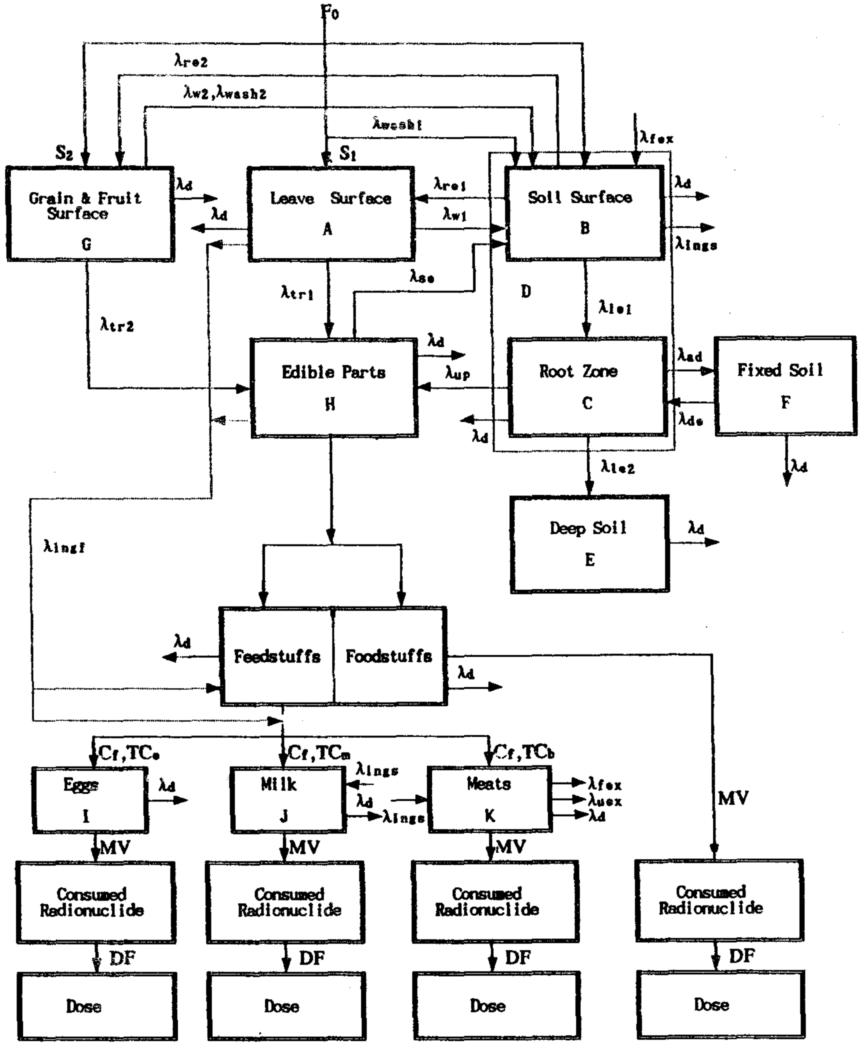

Fig. 1. compartment scheme and transfer mechanisms of radionuclide.

with time based on the mass balance. The established compartment scheme and the transfer mechanisms of radionuclide are shown in Fig. 1 for the simulation.

Differential equations of the KORFOOD model

The following differential equations and initial conditions describe the whole behavior of radionuclide through food-chain in labile soil and non-labile soil. The subscript 1 and 2 represent plant leaves and grain, respectively.

1) Radioactivity on the surface of plant leaves;

$$\frac{dA}{dt} = -(\lambda_{w1}+\lambda_{tr1}+\lambda_{wash1}+\lambda_d)\ A+\frac{\lambda_{rel}\cdot S_1}{Y_1}\ D\text{: In labile soil} \qquad \cdots\cdots(20)$$

$$\frac{dA}{dt} = -(\lambda_{w1}+\lambda_{tr1}+\lambda_{wash1}+\lambda_{se}+\lambda_d)\ A+\frac{\lambda_{rel}\cdot S_1}{Y_1}\ B + \frac{\lambda_{up}}{Y_1}\ C\text{: In non-labile soil} \qquad \cdots\cdots(21)$$

With, $\Lambda(0) = \frac{S_1 \cdot F_0}{Y_1}$ (at $t=0$: initial deposition time)

2) Radioactivity in the surface layer of soil;

$$\frac{dB}{dt} = -(\lambda_{le1} + \lambda_{rel}\ S_1 + \lambda_{ings} + \lambda_d)B + \{(\lambda_{w1} + \lambda_{se} + \lambda_{wash1})Y_1\}\ A+(\lambda_{fex}\ Y_1)K \qquad \cdots\cdots(22)$$

with, $B(0) = (1 - S_1)\ (F_0)$

3) Radioactivity in the root zone of soil;

$$\frac{dC}{dt} = -(\lambda_{le2} + \lambda_{up} + \lambda_{ad}+ \lambda_d)\ C+ \lambda_{le1}\ B+\lambda_{de}\ F \qquad \cdots\cdots(23)$$

with, $C(0) = 0$

4) Radioactivity in the labile layer of soil;

$$\frac{dD}{dt} = -(\lambda_{rel}\ S_1 + \lambda_{re2}\ S_2+ \lambda_{up}+ \lambda_{le}+ \lambda_d)\ D + \{(\lambda_{wash1} + \lambda_{w1})Y_1\}\ A+ \{(\lambda_{wash2} + \lambda_{w2})Y_2\}\ G \qquad \cdots\cdots(24)$$

with, $D(0)=\{1-(S_1 + S_2)\}\ F_0$

5) Radioactivity in the deep layer of soil;

$$\frac{dE}{dt} = -\lambda_d\ E+ \lambda_{le}\ D\ ;\ \text{In labile soil} \qquad \cdots\cdots(25)$$

$$\frac{dE}{dt} = -\lambda_d\ E+ \lambda_{le2}\ C\ ;\ \text{In non-labile soil} \qquad \cdots(26)$$

with, $E(0) = 0$

6) Radioactivity in the fixed layer of soil;

$$\frac{dF}{dt} = -(\lambda_d + \lambda_{de})\ F + \lambda_{ad}\ C \qquad \cdots\cdots(27)$$

with, $F(0) = 0$

7) Radioactivity on the surface of grain;

$$\frac{dG}{dt} = -(\lambda_{tr2}+ \lambda_{w2} + \lambda_{wash2} + \lambda_d)\ G+\frac{\lambda_{re2}\cdot S_2}{Y_2}\ D \qquad \cdots\cdots(28)$$

with, $G(0) = \frac{S_2 \cdot F_0}{Y_2}$

8) Radioactivity in the edible parts(or inner tissue);

$$\frac{dH}{dt} = -\lambda_d H+\frac{\lambda_{up}}{Y_2}\ D + \frac{\lambda_{tr1}\cdot Y_1}{Y_2}\ A+ \lambda_{tr2}\ G\text{; In labile soil} \qquad \cdots\cdots(29)$$

$$\frac{dH}{dt} = -\lambda_d H + \frac{\lambda_{up}}{Y_1} C + \lambda_{tr1} A; \text{ In non-labile soil} \quad \cdots\cdots(30)$$

with, $H(0) = 0$

9) Radioactivity in the egg;

$$I = (C_f \cdot TC_e) H_{h} \exp^{-(\lambda_d t_s)} \quad \cdots\cdots(31)$$

$$TC_e = \frac{A_{eg}}{P_{eg}}$$

10) Radioactivity in the milk;

$$J = \left(\frac{\lambda_{ingfr} Y_1}{AD\ P_{mk}}\right)(A+H) + \left(\frac{\lambda_{ingsr}}{AD\ P_{mk}}\right) B \quad \cdots\cdots(32)$$

11) Radioactivity in the meat;

−For beef

$$\frac{dK}{dt} = -(\lambda_{fex} + \lambda_{uex} + \lambda_d)K + \frac{\lambda_{ingsr}}{AD\ M} B + \frac{C_f}{M} A_{mt} (A+H) \quad \cdots\cdots(33)$$

with, $K(0) = 0$

−For chicken and pork

$$K = (C_f \cdot TC_b) H_h \exp-(\lambda_d t_s) \quad \cdots\cdots(34)$$

$$TC_b = \frac{A_{mt}}{\lambda_\beta \cdot M}$$

Dose Calculation

The committed dose equivalent(H_{50}) due to ingestion of contaminated foodstuffs within time TF after deposition is given by

$$H_{50} = \sum_{j=1}^{m} \sum_{j=1}^{n} \int_0^{TF} [CF_{j,i}(t) \cdot MV_i \cdot DF_j]\, dt \quad \cdots\cdots(35)$$

It is assumed in this model that the foodstuffs produced in contaminated area are consumed by the residents living within that area.

SAMPLE CALCULATIONS

The sample calculations were performed in order to evaluate the transfer of radionuclides through the food-chain for rice after deposition of unit Becquerel per area. The values of the input parameters to the KORFOOD were selected to represent the site-specific Korean environment as much as possible and agriculture data-base in the Kori region were used. Table 7 showed the

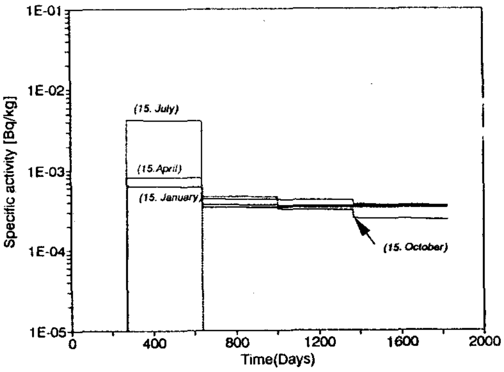

Fig.2. The variation of specific activity of Cs-137 in rice for each deposition time.

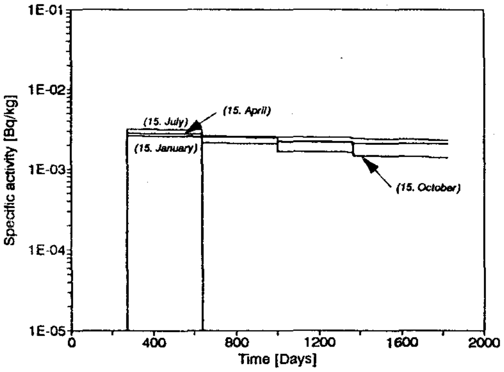

Fig.3. The variation of specific activity of Sr-89 in rice for each deposition time.

Table 7. Parameters selected for sample calculations.

Symbol	Values and Remarks
AD	4.9×10^{-4}[m^{-2}] for dairy cow and 2.0×10^{-5}[m^{-2}] for beef cow from Reference (10)
b	0.0012 from Reference (7)
C_f	21.0[kg/d] for dairy cow and 10.92[kg/d] for beef cow from Reference (17)
C_w	0.025[mm^{-1}] from Reference (15)
DF	1.4×10^{-8}, 1.3×10^{-8} and 3.5×10^{-8}[Sv/Bq] for Cs-137, I-131 and Sr-90 from Reference (11), respectively
FS	4% of dry feedstuffs from Reference (11)
FT, FL	1.0, 1.0 for conservative calculation
fr	1.0
K_d	1000, 100 and 100[ml/g] for Cs-137, I-131 and Sr-90 from Reference (11), respectively
K_g	0.12[d^{-1}] for leaves from Reference (10) and 0.167[d^{-1}] for grain by reverse calculation
K_s	0.05[d^{-1}] from Reference (10)
M	180, 115, 0.95, and 25[kg] for dairy cow, beef cow, chicken and pork from Reference (10), respectively
P_{eg}	0.024[kg/day] from Reference (10)
P_L	1.04, 1.18 [g/cm^3] for rice field, field from Reference (17), respectively
P_{mk}	13.1[L/day] from Reference (10)
P_s	1.18[g/cm^3] from Reference (17)
R_p	predicted using 1050[mm/yr] irrigation rate in rice field from Reference (17), and assumed 100, 100 and 80% utilization fraction of rainfall in pasture-grass, field and rice field, respectively
Tr(max)	0.1 for partial edible foodstuffs, 1.0 for total edible foodstuffs and 0.15 for potatoes from Reference (7)
V	173[m/d] from Reference (10)
X_L	0～1cm from Reference (10)
X_r	0～25cm for labile soil and 1～25cm for non-labile soil from Reference (11)
Y_{min}	0.015[kg/m^2] from Reference (10)
μ	2.74[m^2/kg] for leaves from Reference (14) and 0.125[m^2/kg] for grain by reverse calculation
λ_{ad}	1.9×10^{-3}[d^{-1}] from Reference (10)
λ_d	6.31×10^{-5}, 8.66×10^{-2} and 6.66×10^{-5}[d^{-1}] for Cs-137, I-131 and Sr-90 respectively
λ_{de}	2.1×10^{-4}[d^{-1}] from Refernece (10)
λ_w	3.01×10^{-2}[d^{-1}] from Reference (10)

selected parameters for sample calculations.

The middles of January, April, July and October were selected as the deposition times of typical winter, spring, summer and autumn, respectively. Selected radionuclides were Cs-137 and Sr-90 which used to contribute significantly to the ingestion doses in the case of a nuclear accident. Fig.'s 2 and 3 show the variations of specific activities of Cs-137 and Sr-90 in rice for each deposition time, respectively. In the case of Cs-

137 deposition, the variation of radioactivity concentration was very pronounced with deposition time during the first year after deposition. It was because the direct deposition onto plant leaves or grain resulted in an important contamination due to high translocation in the case of Cs-137. In the case of Sr-90 deposition, the variation of radioactivity concentration with deposition time was smaller than that of Cs-137 with deposition time due to low translocation and more effective root uptake.

Fig. 4 shows effective ingestion dose for adult by the consumption of considered foodstuffs during the first year after deposition. In the cases of Cs-137 and I-131, ingestion doses were shown as the distinct seasonal variation with time. In the case of I-131, the timespan between deposition time and harvest was a dominant factor due to short half-life.

The simulation results were compared with those by the German model, ECOSYS-87 for rice and leafy vegetable. Fig.'s 5 and 6 show specific activities of Cs-137 in rice and leafy vegetable (Chinese cabbage in KORFOOD) calculated together with this model and ECOSYS-87 in the cases of deposition in summer and winter, respectively. The comparison of results showed good agreements within a factor of ten in the case of specific

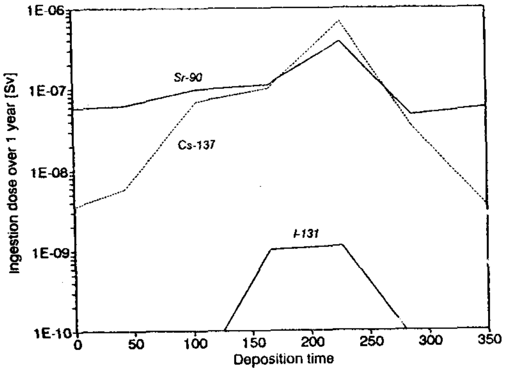

Fig.4 The effective ingestion dose for adult by consumption of all considered foodstuffs during the first year after deposition with deposition time.

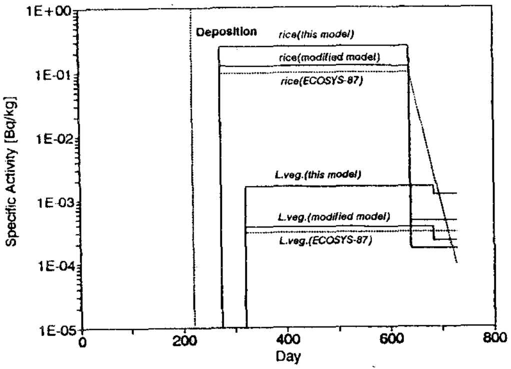

Fig.5 The specific activities of Cs-137 in rice and leafy vegetable calculated together with this model and ECOSYS-87 in the case of deposition in summer.

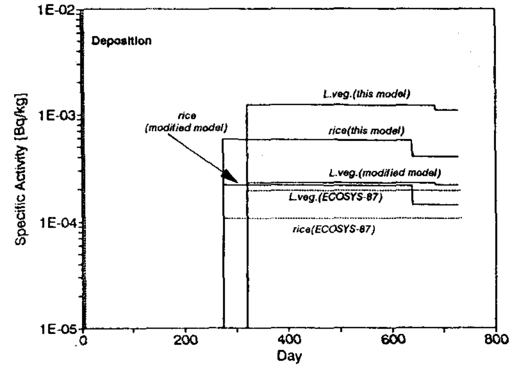

Fig.6 The specific activities of Cs-137 in rice and leafy vegetable calculated together with this model and ECOSYS-87 in the case of deposition in winter.

activities. Meanwhile, it should be noted again that analytic methods were different between two models in such fields as model algorithm, treatment of transfer processes and site-specific data. And additional pathways were considered differently in this study with the ECOSYS-87 such as deposition on grain surface. For the additional validation of KORFOOD, food processing factor and plant/soil concentration factor considered in the ECOSYS-87 were used without modifications to this model in the case of rice. The calculated results were 1.5 and 2 times as high as those by the ECOSYS-87. Chinese cabbage was selected in this study as a typical leafy vegetable in Korea. The plants/soil concentration factor for leafy vegetable used in ECOSYS-87 were inputted to this model. The calculated results were 1.3 times as high as those by the ECOSYS-87.

CONCLUSIONS

Since the ingestion doses are very important in the case of long-term exposures, it is necessary that the dynamic behavior of radionuclides released in an accident of nuclear power plant should be analyzed following the site-specific environment. In this study, a dynamic model of ingestion pathway was developed in order to consider several Korean characteristics in socio-environment, agricultural practices, and food consumption behavior, etc.

In order to validate this model, numerical comparisons were done with the German model, called ECOSYS-87. The differences of specific activities of Cs-137 calculated by both models with deposition time were within a factor of ten for the major foodstuffs such as rice and Chinese cabbage. This dynamic radiological model describing Korean environment can provide a tool for a comprehensive ingestion dose assessment due to an accidental release of radionuclides.

Nomenclature

A : radioactivity on the surface of plant leaves, Bq/kg
AD : grazing animal density, animal heads/m^2
A_h : radioactivity of A as feedstuff at harvest, Bq/kg
A_{eg} : transferred fraction of intaken radionuclide to egg
A_{mt} : transferred fraction of intaken radionuclide to meat
A_{mk} : transferred fraction of intaken radionuclide to milk
B : radioactivity in the surface layer of soil, Bq/m^2
b : parameter characterizing the slope of curve
B_{iv} : plant/soil concentration ratio
C : radioactivity in the root zone of soil, Bq/m^2
CF : radioactivity concentration in foodstuffs, Bq/kg
C_f : daily intake rate of feedstuffs by animal, kg/day
C_w : coefficient, mm^{1}
D : radioactivity in the labile layer of soil, Bq/m^2
DF : dose conversion factor, Sv/Bq
E : radioactivity in the deep layer of soil, Bq/m^2
F : radioactivity in the fixed layer of soil, Bq/m^2
FL : growth-rate modifier for light

FT : growth-rate modifier for temperature

FS : soil ingestion rate, kg/day-animal

fr : fraction of intake rate contributed by field grazing

F_0 : initial surface radioactivity of fallout, Bq/m^2

G : radioactivity on the surface of grain, Bq/kg

H : radioactivity in the edible parts, Bq/kg

H_h : radioactivity of H as feedstuff at harvest, Bq/kg

I : radioactivity in the egg, Bq/kg

J : radioactivity in the milk, Bq/L

K : radioactivity in the meats, Bq/kg

K_d : distribution coefficient, mL/g

K_g : growth-rate constant, day ^{1}

K_s : senescence-rate constant, day ^{1}

L : soil depth, cm

M : mass of meat per an animal head, kg

MV : consumption rate, kg/day

P_L : bulk density of soil surface, kg/m^3

P_{eg} : egg production rate, kg/day

P_{mk} : milk production rate, L/day

P_s : bulk density of soil, kg/m^3

R : rainfall rate, mm/hr

RF : resuspension factor, m ^{1}

R_p : percolation velocity of water, cm/yr

S : interception factor for plant

S_{soil} : fraction allocated to the soil surface

t : elapsed time after deposition, day

Tr : translocation factor

TC_e : transfer coefficient of radionuclide to the egg, day/kg

TC_b : transfer coefficient of radionuclide to the meat, day/kg

TC_m : transfer coefficient of radionuclide to the milk, day/L

t_s : storage period of feedstuffs, day

V : deposition velocity, m/day

X_r : depth of root zone, m

X_L : depth of surface layer of soil subject to intake, m

Y : yield, dry-kg/m^2

Y_{max} : maximum potential yield, dry-kg/m^2

$Y_{max}{*}$: adjusted maximum yield, dry-kg/m^2

Y_{min} : minimum yield in winter, dry-kg/m^2

μ : coefficient, m^2/kg

θ : ratio of water content in soil, mL/cm^3-soil

ρ : soil density, g/cm^3-soil

δt : time before the harvest, day

$\delta t(max)$: time before the harvest when the translocation factor is maximum, day

λ_{ad} : adsorption rate, day ^{1}

λ_b : biological elimination rate, day ^{1}

λ_d : decay constant, day ^{1}

λ_{de} : desorption rate, day ^{1}

λ_{fex} : fecal excretion rate, day ^{1}

λ_{ingf} : intake rate of feedstuff by animal, day ^{1}

λ_{ingfr} : transfer rate of radionuclide into meat or products by intaking feedstuffs of by animal, day ^{1}

λ_{ings} : soil intake rate, day ^{1}

λ_{ingsr} : transfer rate of radionuclide into meat or products by soil intake, day ^{1}

λ_{le} : leaching rate, day ^{1}

λ_{re} : resuspension rate, day ^{1}

λ_{se} : senescence rate, day ^{1}

λ_{tr} : translocation rate day ^{1}

λ_{uex} : urinary excretion rate, day ^{1}

λ_{up} : root uptake rate, day ^{1}

λ_w : removal rate by wind turbulence, day ^{1}

λ_{wash} : washout rate, day ^{1}

Subscript

i : kinds of foodstuff
j : kinds of radionuclide
m : number of radionuclides
n : number of foodstuffs

References

1. J. F. Fletscher, and W. L. Dotson, "HERMES - A Digital Computer Code for Estimating Regional Radiological Effects from the Nuclear Power Industry", HEDL-TME-71-168, U.S.A., (1971).
2. R. Zach, et al., "FOOD II : An Interactive Code for Calculating Concentrations of Radionuclides in Food Products", AECL-6305, Canada, (1978).
3. R. E. Moore, et al., "AIRDOS-EPA : A Computerized Methodology for Estimation Environmental Concentrations and Dose to Man from Airborne Releases of Radionuclides", ORNL-5532, Oak Ridge National Lab., (1979).
4. U.S. Nuclear Regulatory Commission, Regulatory Guide 1. 109, "Calculation of Annual Doses to Man from Routine Release of Reactor Effluents for the Purpose of Evaluating Compliance with 10 CFR Part 50, Appendix I, Rev. 1", (1977).
5. R. S. Booth and S. V. Kaye, "A Preliminary Systems Analysis Model of Radioactivity Transfer to Man from Deposition in a Terrestrial Environment", ORNL-TM-3135, Oak Ridge National Lab., U.S.A., (1971).
6. J. C. Pleasant, et al., "RAGTIME : A Fortran Ⅳ Implementation of Time-Dependent Model for Radionuclides in Agriculture Systems", NUREG/CR-1196, Oak Ridge National Lab., U.S.A., (1980).
7. M. Matties, et al., "Simulation des Transfers von Radionukliden in landwirtschaftlichen Nahrungsketten", GSF-Bericht S-882, F.R.G., (1982).
8. G. S. Linsley, et al., "FOOD-MARC : The Food Chain Transfer Module in the Methodology for Assessing the Radiological Consequences of Accidental Releases", NRPB-M-76, National Radiological Protection Board, Chilton, Great Britain, (1982).
9. J. Koch and J. Radmor, "RADFOOD : A Dynamic Model for Radioactivity Transfer through the Human Food Chain", *Health Physics*, **50**, 721~737, (1986).
10. F. W. Whicker, et al., "PATHWAY : A Dynamic Food Chain Model to Predict Radionuclides Ingestion after Fallout Deposition", *Health Physics* **52**, 717~737, (1987).
11. H. Müller, et al., "ECOSYS-87, ein Rechenmodell zur abschatzung der Strahlennesposition nach kurzzeitiger Deposition von Radionukliden auf landwirtschaftlich genutzten Flachen", Benutzer Handbuch, GSF-Institut fur Strahlenschutz, 8020 Neuherberg, F.R.G., (1989).
12. A. C. Hindmarsh, et al., "EPISODE : An Effective Package for the Integration of Systems of Ordinary Differential Equations", UCID-30112, Rev. 1, Lawrence Livermore Lab., U.S.A., (1977).
13. International Mathematical and Statistical Labraries, INC., "For the IMSL Library of FO-

RTRAN Subroutines in Mathemetics and Statistics", IMSL, Houston, U.S.A.

14. A. C. Chamberlain, "Interception and retention of radioactive aerosols by vegetation", *Atmos. Env.* **4**, 57~78, (1970).
15. U. S. Nuclear Regulatory Commission, "Radiological Assessment", NUREG/CR-3332, ORNL-5968, U.S.A., (1983).
16. G. Pröhl, et al., "Translocation of Cs in Plants after Foliar Deposition Experimentals and Models", International Symposium on the Validation of Environmental Transfer Models, Stockholm, Sweden, (1990).
17. C. H. Lee, et al., "A Development of Computer Code for Evaluating Internal Radiation Dose through Ingestion and Inhalation Pathways", KAERI/RR-998/90, Korea, (1991).

한국 환경에 적용 가능한 동적 섭식경로 모델 (KORFOOD) 개발

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요 약

원자력발전소의 사고시 방사성물질의 단기간 침적후 오염된 음식물에 의한 영향을 평가하기 위해 한국 환경에 적용이 가능한 동적 방사능영향 평가모델이 개발되었다. KORFOOD라 불리워지는 이 모델은 오염된 음식물의 섭취에 의한 누적선량뿐만 아니라 시간에 따른 선량을 평가하며, 또한 음식물내 시간에 따른 방사능농도의 변화를 해석한다. 섭식경로에 중요한 3가지 핵종과 13가지 음식물이 이 모델에서 고려되었다. 방사능농도의 동적변화는 침적, 풍화와 강우, 재부유, 뿌리흡취, 전이, 토양내 이동, 식물의 노화, 동물의 토양흡취 및 배설, 동물의 사료섭취와 배설 등과 같은 여러 효과를 고려하여 모사되었다. 평가를 위한 입력자료로는 침적되는 방사성물질의 양, 침적시점, 평가하고자하는 핵종 및 음식물의 종류가 요구된다. 고리지역 농작물자료를 사용하여 쌀에 대해 시간에 따른 비방사능농도와 고려되는 모든 음식물의 섭취에 따른 선량이 침적시점에 따라 계산되었다. 모델결과의 타당성 검증을 위해 이 분야에서 이미 공인받고 있는 독일모델 ECOSYS-87의 결과와 비교하였다. 비교결과, KORFOOD의 예측치가 ECOSYS-87의 예측값의 10배 범위내에 있어 좋은 일치를 보여주었다.

중심어 : 동적섭식경로, 비방사능농도, 침적시점