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Improvement on the KFOOD Code for More Realistic Assessment of the Annual Food Chain Radiation Dose Due to Operating Nuclear Facilities

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가동중 원자력 시설에 의한 년간 섭식경로 피폭선량 평가의 현실성 제고를 위한 KFOOD 코드의 개선

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Abstract

More realistic calculation models for evaluating man's annual intakes of radionuclides released from operating nuclear facilities were established. For the application of these models, the harvest years of food and feed crops consumed in the year of dose assessment and every year's average concentrations of a radionuclide in air and in water for the whole period of real operation had to be taken into account. KFOOD, an existing equilibrium food chain computer code for the Korean dose assessment, was modified according to the models. Sample runs of the modified code on the assumption of a constant release during 10 years' operation were made with three kinds of the input data files enabling the dose assessment in the improved method, the KFOOD method and another existing method, respectively, and the results were compared. Annual committed effective doses to Korean adult by intakes of Mn-54, Co-60, Sr-90, I-131 and Cs-137 calculated in the improved method were about 11, 2, 5, 60 and 3%, respectively, lower than the corresponding KFOOD dose. To the intakes of the radionuclides except Sr-90 evaluated in the improved method, foliar uptake contributed much more than root uptake did but, in the case of Sr-90, the result was opposite.

요 약

가동중 원자력 시설에서 방출되는 방사성 핵종의 년간 인체 흡수량을 보다 현실적으로 평가하기 위한 계산 모델을 수립하였다. 이 모델을 적용하기 위해서는 평가년도 중에 소비되는 식량 및 사료 작물의 수확년도와 실제 가동된 전기간내 매년의 공기중 및 수중 평균농도가 고려되어야 한다. 한국인에 대한 평형 섭식경로 평가코드인 KFOOD 코드를 수립된 계산모델에 따라 수정하였다. 가상적인 10 년간의 균일방출에 대하여 개선된 방식, KFOOD 방식, 그리고 또다른 현존 방식에 의한 평가가 이루어 질 수 있도록 입력 데이타 파일을 차례로 변경하여 수정된 코드를 실행시키고 세가

지 결과들을 비교하였다. Mn-54, Co-60, Sr-90, I-131 그리고 Cs-137의 흡수를 통한 한국 성인의 년간 예탁실효선량을 개선된 방식으로 계산한 결과는 KFOOD 방식에 비해 각각 11, 2, 5, 60, 3% 정도 낮았다. 개선된 방식에 따른 평가에 있어서는 Sr-90을 제외한 핵종들의 인체흡수에 대해서는 엽면흡수 경로의 기여가 훨씬 컸으나 Sr-90의 경우에는 뿌리흡수 경로의 기여가 훨씬 컸다.

1. Introduction

In the existing equilibrium food chain models [1–5], radionuclide concentrations in foods are calculated on the assumption that those consumed in the year of assessment are all produced in that year and that radionuclides are deposited onto the land surface at a constant rate during whole operation time. This is reasonable on the lincensing stage of nuclear facilities when the purpose of the assessment is to show that annual radiation dose predicted even for the final one year of its planned operation with source terms estimated conservatively and constantly for its whole longevity does not exceed the dose limit irrespective of the starting date of the final one year.

When annual internal radiation doses due to operating nuclear facilities are calculated, however, this is not reasonable because much portions of most agricultural products consumed this year were harvested last year and because source terms are different year by year. So, for more realistic assessment of annual human intake of radionuclides released from operating nuclear facilities, radionuclide concentrations in portions of agricultural products harvested this year and last year have to be calculated separately and the radionuclide build-up in soil has to be estimated on the yearly basis with annually different source terms. For such things, it is necessary that the exsisting food chain computer code be modified following the establishment of new calculation models reflecting those considerations.

Although the calculation result by the modified code can vary more or less with the starting date of the year, setting the date at January 1 makes the calculation easier and more straightforward because source terms and food chain–related statistics are published mainly on the basis of one year period from January 1 to December 31.

Choi et al.[6] calculated 1984's food chain radiation dose to the adult inhabitant resulting from the operation of Kori #1 reactor. They also, however, assumed that foods consumed in 1984 are all produced in the same year. Moreover they disregarded the radionuclide build–up in soil caused by the release having occurred before the assessment year so that a great underestimation could be expected for the radionuclide of a relatively long half–life and large soil–to–plant transfer coefficient such as Sr–90.

In this study, a food chain computer code KFOOD, developed for the Korean radiation dose assessment by Lee et al.[5], was modified for resolving those problems and assessing the annual internal radiation dose due to operating nuclear facilities more realistically. The results of the code executions in three different ways using the improved method, KFOOD method and Choi et al's method were compared to analyze the effectiveness of the code improvment.

2. Establishment of Calculation Models and Modification of KFOOD Code

New calculation models were established under the following considerations and the KFOOD code was modified according to the new models.

Consideration 1

For the estimation of man's and animal's annual intake of radionuclides through this year's food or feed consumption, radionuclide concentrations in foods or feeds consumed this year but harvested last year and those consumed and harvested this year are calculated separately.

Consideration 2

In the calculation of radionuclide concentrations in food and feed harvested this or last year, contributions by the foliar uptake are estimated with this or last year's source terms, respectively, and those by the root uptake are estimated with source terms of every year from the 1st year of the operation to this or last year, respectively.

In those models, radionuclide concentrations in the edible parts of food and feed crops are calculated as follows ;

$$C_{iv1}=C_{ivd1}+C_{ivs1} \tag{1}$$

$$C_{iv2}=C_{ivd2}+C_{ivs2} \tag{2}$$

C_{ivd1}, C_{ivs1}, C_{ivd2} and C_{ivs2} can be calculated as follows ;

$$C_{ivd1}=\frac{(86400\ V_{ti}X_{i1}f_r+IW_{i1}f_w)(1-e^{-\lambda_{ei}T_e})T_v}{Y_{v1}\lambda_{ei}} \tag{3}$$

$$C_{ivs1}=\sum_{j=1}^{N}\frac{(86400\ V_{ti}X_{ij}+I_yW_{ij})(1-e^{-\lambda_i T_{b1}})}{P\lambda_i}e^{-\lambda_i T_1}B_{iv} \tag{4}$$

$$C_{ivd2}=\frac{(86400\ V_{ti}X_{i2}f_r+IW_{i2}f_w)(1-e^{-\lambda_{ei}T_e})T_v}{Y_{v2}\lambda_{ei}} \tag{5}$$

$$C_{ivs2}=\sum_{j=1}^{N-1}\frac{(86400\ V_{ti}X_{ij}+I_yW_{ij})(1-e^{-\lambda_i T_{b2}})}{P\lambda_i}e^{-\lambda_i T_2}B_{iv} \tag{6}$$

Radionuclide concentrations in terrestrial animal foods are calculated with C_{iv1} and C_{iv2} as follows ;

$$C_{ia1}=f_pf_sC_{iv1}Q_fS_{ia}e^{-\lambda_i T_{hf}}+\{f_p(1.0-f_s)+(1.0-f_p)\}C_{iv1}Q_fS_{ia}e^{-\lambda_i T_{hs}} \tag{7}$$

$$C_{ia2}=C_{iv2}Q_fS_{ia}e^{-\lambda_i T_{h2}} \tag{8}$$

$$C_{iaw}=W_{i1}Q_wS_{ia}e^{-\lambda_i T_{h1}} \tag{9}$$

Since radioactive decay should be counted when radionuclide concentration in food at the time of its consumption by man is calculated,

$$C_{Hiv1}=C_{iv1}\ e^{-\lambda_i T_{h1}} \tag{10}$$

$$C_{Hiv2}=C_{iv2}\ e^{-\lambda_i T_{h2}} \tag{11}$$

$$C_{Hia1}=C_{ia1}\ e^{-\lambda_i T_{ha}} \tag{12}$$

$$C_{Hia2}=C_{ia2}\ e^{-\lambda_i T_{ha}} \tag{13}$$

$$C_{Hiaw}=C_{iaw}\,e^{-\lambda_i T_{ha}} \tag{14}$$

Man's annual intake of radionuclide i through food consumption is estimated by ;

$$A_{vi}=\{C_{Hiv1}R_v+C_{Hiv2}(1-R_v)\}\ U_v \tag{15}$$

$$A_{ai}=\{C_{Hia1}R_a+C_{Hia2}(1-R_a)+C_{iaw}\}\ U_a \tag{16}$$

Annual committed effective dose given by radionuclide i taken through total food consumption is represented as follows ;

$$H_i=\sum_{j=1}^{M}E_iA_{ij} \tag{17}$$

Values of parameters appearing newly in the modified models are given in table 1. For Y_{v1} and Y_{v2}, the same values were used so that results of the code execution in those three different ways can be compared under equal conditions of the factors except those considered. Normally yearly difference in crop yield is not so great as to have significant effect on calculated concentration of the radionuclide in plant. Values of T_{hf} and T_{h1} are the same as T_h values in KFOOD model [5] and those of T_{h2} are equivalent to days between average harvest date and December 31. R_v and R_a values were estimated roughly from harvest dates and seasonal consumption patterns of foods belonging to each food type.

In addition, 30 days was taken for T_{hs} and dose conversion factors calculated based on ICRP's recent recommendations by Phipps et al. [7] were taken for E_i's. For other parameters, KFOOD values were taken. B_{iv}'s for different food types are shown in table 2.

3. Input Concentrations and Code Executions

In the modified code, the input of annual average radionuclide concentrations in the atmosphere and in water for every year between the start of

Table 1. Values of Parameters Appearing Newly in the Improved Model

Food type	Parameter value						
	Y_{v1}(kg/m^2)	Y_{v2}(kg/m^2)	T_{h1}(d)	T_{hf}(d)	T_{h2}(d)	R_v	R_a
Rice	0.44	0.44	14.0	–	70.0	0.19	–
Other grains	0.26	0.26	14.0	–	120.0	0.33	–
Legumes	0.13	0.13	14.0	–	70.0	0.19	–
Leafy veget.	5.65	5.65	1.0	–	30.0	0.80	–
Root veget.	4.06	4.06	1.0	–	30.0	0.80	–
Fruit veget.	1.96	1.96	1.0	–	120.0	1.00	–
Potatoes	0.55	0.55	10.0	–	70.0	0.50	–
Fruits	1.39	1.39	10.0	–	70.0	0.70	–
Egg*	0.26	0.26	–	14.0	70.0	–	0.33
Pork*	0.26	0.26	–	14.0	70.0	–	0.33
Poultry*	0.26	0.26	–	14.0	70.0	–	0.33
Milk*	2.20	2.20	–	1.0	120.0	–	0.58
Beef*	2.20	2.20	–	1.0	120.0	–	0.58

* Data for feed crops.

Table 2. Soil–to–Plant Transfer Coefficients of Radionuclides for Various Types of Food

Food type	Soil–to–plant transfer coefficient				
	Mn–54	Co–60	Sr–90	I–131	Cs–137
Rice	0.240	0.0039	0.170	0.020	0.028
Other grains	0.680	0.0086	0.430	0.020	0.055
Legumes	0.420	0.150	0.910	0.020	0.180
Leafy veget.	0.210	0.017	2.000	0.020	0.110
Root veget.	0.034	0.0092	0.420	0.020	0.046
Fruit veget.	0.035	0.0093	0.160	0.020	0.031
Potatoes	0.029	0.0094	0.027	0.020	0.011
Fruits	0.029	0.0018	0.200	0.020	0.002
Egg*	0.680	0.0086	0.430	0.020	0.055
Pork*	0.680	0.0086	0.430	0.020	0.055
Poultry*	0.680	0.0086	0.430	0.020	0.055
Milk*	0.030	0.0097	0.700	0.020	0.030
Beef*	0.030	0.0097	0.700	0.020	0.030

* Data for feed crops.

the operation and the assessment is required. To compare calculation results from different ways of the code execution, a single value 1.0×10^{-4}Bq/m^3 was taken for every year's atmospheric concentration of every radionuclide and another single value 1.0×10^{-2}Bq/l, which was derived from the atmospheric concentration using the method reported by Choi et al.[6], was taken for every year's water concentration of every radionuclide.

Three different ways of the code execution are described in table 3. Run A, B and C represent the improved method, the KFOOD method, and Choi et al's method, respectively. Not–consideration of harvest year and that of earlier deposition onto soil could be achieved by taking 1.0 for Rv

Table 3. Description of Three Different Ways of the Code Execution

Label of execution	Factors of interest		Assessment method
	Year of crop harvest	Earlier deposition onto soil	
Run A	+	+	improved
Run B	–	+	KFOOD
Run C	–	–	Choi et al's

+ : considered
– : not considered.

and Ra and by taking 0 for radionuclide concentrations in air and water for years prior to the assessment year, respectively.

Code executions in those three ways were conducted in turn by amending related input date files at each time in such a way that each amendment reflected the description of each run.

4. Execution Result and Discussion

Annual intakes of Mn–54, Co–60, Sr–90, I–131 and Cs–137 by Korean adult through food consumptions estimated in three different ways of the code execution are shown in Fig. 1–5, respectively.

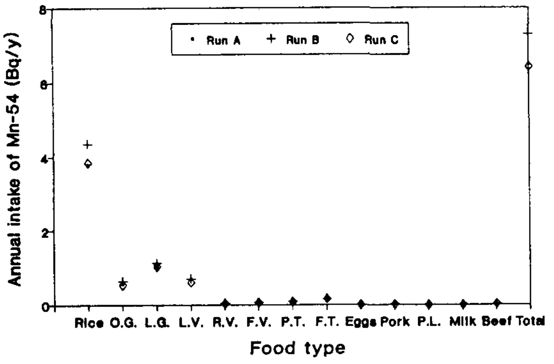

Fig. 1. Annual Intake of Mn–54 by Korean Adult through Food Consumptions Estimated in Three Different Ways of the Code Execution.

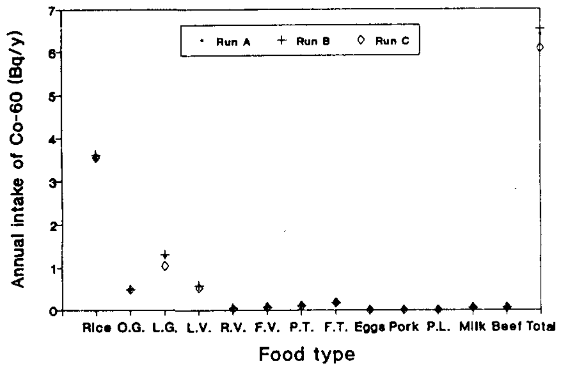

Fig. 2. Annual Intake of Co–60 by Korean Adult through Food Consumptions Estimated in Three Different Ways of the Code Execution.

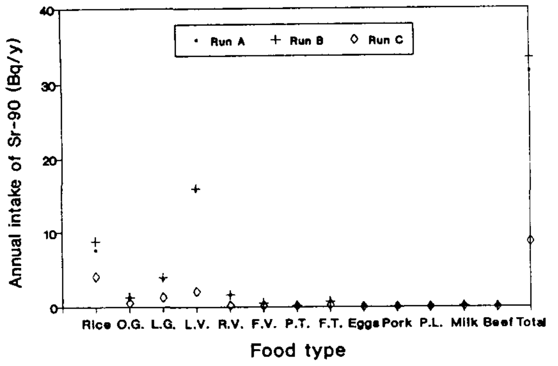

Fig. 3. Annual Intake of Sr–90 by Korean Adult through Food Consumptions Estimated in Three Different Ways of the Code Execution.

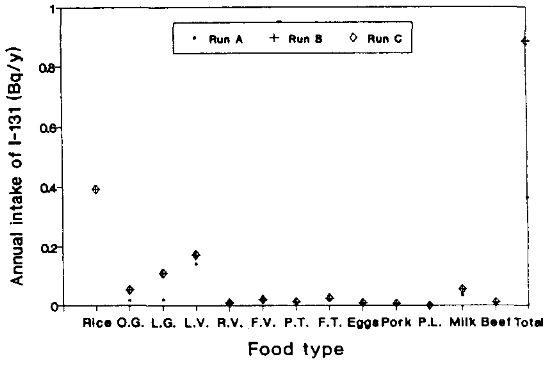

Fig. 4. Annual Intake of I–131 by Korean Adult through Food Consumptions Estimated in Three Different Ways of the Code Execution.

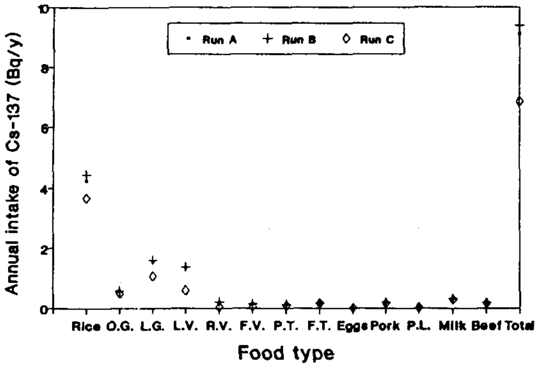

Fig. 5. Annual Intake of Cs–137 by Korean Adult through Food Consumptions Estimated in Three Different Ways of the Code Execution.

In any run of the code, estimated intakes of different radionuclides decreased, on the whole, in the order of Sr–90>Cs–137>Mn–54>Co–60>I–131. The highest intake of Sr–90 can be attributed to its relatively long half–life and large soil–to–plant transfer coefficient.

The intake of every radionuclide except I–131 through total food consumption was calculated to be highest in run B and to be lowest in run C. In Sr–90 and, to a less extent, Cs–137, run C showed much lower value than run B and A. In Mn–54, the difference between run A and C was negligible and in Co–60, values of three runs were not so different from any other. Total intakes of I–131 estimated by those three runs produced a peculiar distribution where run B and C formed a higher group at a single point and run A located at a much lower point than run B and C.

This difference in the variation with run type among radionuclide species results from the fact that the effectiveness of each consideration shown in table 3 changes with the half–life and soil–to–plant transfer coefficient of a radionuclide. For example, the consideration of earlier deposition caused significant increases in the intake amount of Sr–90 and Cs–137 because of their long half–lives. Of the two, Sr–90 showed much higher increase because of its large soil–to–plant transfer coefficients. The consideration of earlier deposition made no difference in the intake amount of I–131 at all because of its very short half–life but that of harvest year produced a significant decrease in I–131 intake for the same reason.

Variation in the total intake of every radionuclide with run type is mostly related with only a few kinds of Korean staple food such as rice, legume and leafy vegetable the consumption of which accounts for most part of the total intake of a radionuclide in every case.

Internal radiation doses to Korean adult by intakes of Mn–54, Co–60, Sr–90, I–131 and Cs–137 through annual food consumption calculated in three different ways of the code execution are given in table 4.

Radiation doses estimated in the improved method were about 11%, 2%, 5%, 60% and 3% lower in Mn–54, Co–60, Sr–90, I–131 and Cs–137, respectively, compared with those estimated in the KFOOD method. Those relatively high decreases in Mn–54 and, to a much greater extent, I–131 doses can be attributed to their shorter half–lives for which the consideration of harvest year lowered their calculated concentrations in food crops consumed this year but harvested last year significantly. For Sr–90, having

Table 4. Internal Radiation Doses by the Intake of Radionuclides Calculated in Three Different Ways of the Code Execution

Radio-nuclide	Committed effective dose(Sv/y)		
	Run A	Run B	Run C
Mn–54	4.741E–09	5.321E–09	4.681E–09
Co–60	4.607E–08	4.697E–08	4.367E–08
Sr–90	8.851E–07	9.351E–07	2.441E–08
I–131	8.000E–09	1.950E–08	1.950E-08
Cs–137	1.181E–07	1.221E–07	8.898E–08

much longer half–life than Co–60, to show a higher dose decrease than Co–60 did, is due to its much larger soil–to–plant transfer coefficient for which excluding the root uptake of Sr–90 deposited this year in calculating Sr–90 concentration in food crop consumed this year but harvested last year resulted in a relatively high dose decrease.

On the other hand, they were about 1%, 5%, 260% and 32% higher in Mn–54, Co–60, Sr–90 and Cs–137, respectively, but 60% lower in I–131, compared with those estimated in Choi et al's method. Those relatively high increases in Sr–90 and Cs–137 doses can be attributed to their longer half–lives for which the consideration of earlier deposition increased their calculated concentrations in foods significantly. The much higher increase in Sr–90 dose than in Cs–137 dose is due to its much larger soil–to–plant transfer coefficient for which the consideration of earlier deposition was more effective for dose increase in Sr–90 than in Cs–137. The exceptional decrease in I–131 dose is due to the fact that its half–life is so short that the dose decrease by considering the harvest year was significant but that the dose increase by considering the earlier deposition was almost nothing.

From the above, it can be said that the assessment in the improved method would result in a somewhat lower internal radiation dose than that in the KFOOD method owing to a more realistic approach to the estimation of yearly radionuclide intake. A more important point is that the existing KFOOD code can not be executed without the input of annual average radionuclide concentrations in air and in water constant for all the years of real operation which cannot be obtained in an actual situation. Choi et al's method turned out to underestimate the dose from long–lived radionuclides such as Sr–90 and Cs–137 by disregarding earlier deposition but to overestimate the dose from the short–lived radionuclide such as I–131 by disregarding the year of food harvest.

Contributions to man's intake of radionuclides by different pathways in run A were calculated as in table 5. Root uptake contributed to the intake of different radionuclides in the order of Sr–90>Cs–137>Mn–54>Co–60>I–131. It made a much higher contribution to the Sr–90 intake than foliar uptake because of its long half–life and large soil–to–plant transfer coefficient. Foliar uptake accounts for most part of the intake of Co–60 and, to a greater extent, I–131. Animal water consumption contributed more to the I–131 intake than root uptake but it did almost nothing to the intake of others.

Contributions by root uptake can decrease by the leaching loss of radionuclides in soil [8,9] and the effect of ageing on their soil–to–plant transfer coefficients [10,11]. This kind of decrease can be expected to be significant in the radionuclide of a long half–life and a large soil–to–plant transfer coefficient such as Sr–90. Further decrease in the calculated internal radiation dose may be achieved by a future modification where those factors are to be covered.

If the starting date of the year changes, values of R_v, R_a and T_{h2} should change and, as the result, calculated amount of the radionuclide intake will vary more or less. So, when the radiation dose estimated in the improved method is not far below a dose limit, a number of code executions for different starting and ending dates of the year

Table 5. Contributions to Korean Adult's Intake of Radionuclides by Different Pathways in Run A

Radio-nuclide	Contribution by different pathways(%)		
	Root uptake	Foliar uptake	Animal water intake
Mn–54	21.6	78.4	0.0
Co–60	78	92.2	0.0
Sr–90	81.1	18.9	0.0
I–131	0.3	96.1	3.6
Cs–137	28.0	71.8	0.2

are necessary for making sure that the limit is not exceeded for any type of one year period.

5. Conclusions

For more realistic assessment of the annual internal radiation dose due to operating nuclear facilities, an equilibrium food chain computer code KFOOD was modified so that the harvest year of food and feed crops could be taken into account and that annually different radionuclide concentrations in air and in water could be input.

This improvement decreased the calculated annual committed effective doses to Korean adult by intakes of Mn–54, Co–60, Sr–90, I–131 and Cs–137 from a 10 years' constant release about 11%, 2%, 5%, 60% and 3%, respectively.

Further decrease in the calculated radiation dose is expected to occur if the leaching loss of radionuclides in soil and the effect of ageing on their soil–to–plant transfer coefficients are included in the models for calculating radionuclide concentrations in agricultural products.

It is important, when the radiation dose estimated in the improved method is not far below the dose limit, to make sure that the limit is not exceeded for any type of one year period, through a number of code executions for different starting dates of the year and in turn different values of other related parameters.

Nomanclature

A_{ai}	man's annual intake of radionuclide i through the consumption of the animal product (Bq/y).
A_{ij}	man's annual intake of radionuclide i through the consumption of food j (Bq/y).
A_{vi}	man's annual intake of radionuclide i through the consumption of the edible plant part (Bq/y).
B_{iv}	soil–to–plant transfer coefficient of radionuclide i.
C_{Hia1}	C_{ia1} corrected for radioactive decay during hold–up time between food production and man's consumption (Bq/kg or Bq/l).
C_{Hia2}	C_{ia2} corrected for radioactive decay during hold–up time between food production and man's consumption (Bq/kg or Bq/l).
C_{Hiaw}	C_{iaw} corrected for radioactive decay during hold–up time between food production and man's consumption (Bq/kg or Bq/l).
C_{Hiv1}	C_{iv1} corrected for radioactive decay during hold–up time between food production and man's consumption (Bq/kg).
C_{Hiv2}	C_{iv2} corrected for radioactive decay during hold–up time between food production and man's consumption (Bq/kg).
C_{ia1}	concentration of radionuclide i in animal product for the fraction of this year that feed harvested this year is consumed (Bq/kg or Bq/l).
C_{ia2}	concentration of radionuclide i in animal product for the fraction of this year that stored feed harvested last year is supplied (Bq/kg or Bq/l).
C_{iaw}	concentration of radionuclide i in animal product by water intake (Bq/kg or Bq/l).
C_{iv1}	concentration of radionuclide i in edible part of the crop harvested and consumed this year (Bq/kg).
C_{iv2}	concentration of radionuclide i in edible part of the crop consumed this year but harvested last year (Bq/kg).
C_{ivd1}	contribution to C_{iv1} by foliar uptake (Bq/kg).
C_{ivd2}	contribution to C_{iv2} by foliar uptake (Bq/kg).
C_{ivs1}	contribution to C_{iv1} by root uptake (Bq/kg).
C_{ivs2}	contribution to C_{iv2} by root uptake (Bq/kg).
E_i	conversion factor from unit intake of radionuclide i to committed effective dose

	(Sv/Bq).
f_p	fraction of a year that the animal is fed on fresh feed.
f_r	fraction of air-deposited radionuclide that is retained by above-ground part of the crop plant.
f_s	fraction of feed that is fresh during fp.
f_w	fraction of irrigation water that is retained by above-ground part of the plant.
H_i	annual committed effective dose given by radionuclide i taken through total food consumption(Sv/y).
I	daily irrigation rate for the growing season (l/m^{3}d).
I_y	daily irrigation rate averaged for T_{b1} or T_{b2}(l/m^{2}d).
M	number of food types included for dose assessment.
N	number of years having passed since the nuclear facilities started to operate.
P	effective soil surface density (kg-dry/m^2).
Q_f	daily feed consumption by animal (kg/d).
Q_w	daily water consumption by animal (l/d).
R_a	fraction of a year that the product of the animal fed with feed harvested this year is consumed.
R_v	fraction of a year that the food harvested this year is consumed.
S_{ia}	translocation factor of radionuclide i from daily intake to animal product (d/kg or d/l).

T_1	days between radionuclide accumulation in soil and harvest for calculating C_{ivs1} (d).
	for Nth year, 0 ($j=1$)
	for (N−1)th year, Tb for Nth year ($j=2$)
	for (N−2)th year, (Tb for Nth year)+(1×365) ($j=3$)
	⋮ ⋮
	for 1st year, (T_b for Nth year)+((N−2)×365) ($j=N$).

T_2	days between radionuclide accumulation in soil and harvest for calculating C_{ivs2} (d).
	for (N−1)th year, 0 ($j=1$)
	for (N−2)th year, T_b for (N−1)th year ($j=2$)
	for (N−3)th year, (T_b for (N−1)th year)+(1×365) ($j=3$)
	⋮ ⋮
	for 1st year, (T_b for (N−1)th year)+((N−3)×365) ($j=N-1$).

T_{b1}	time of radionuclide build-up in soil for calculating C_{ivs1} (d). for Nth year, days between Jan. 1 and harvest ($j=1$) for others, 365 days ($j=2,3,\cdots\cdots,N$).
T_{b2}	time of radionuclide build-up in soil for calculating C_{ivs2} (d). for (N−1)th year, days between Jan. 1 and harvest ($j=1$) for others, 365 days ($j=2,3,\cdots\cdots,N-1$).
T_e	time of above-ground exposure of the plant to contamination (d).
T_{h1}	hold-up time between harvest and man's consumption of the edible plant part harvested this year (d).
T_{h2}	hold-up time between harvest and consumption of food or feed crop harvested last year (d).
T_{ha}	hold-up time between production and man's consumption of animal product (d).
T_{hf}	hold-up time between harvest and consumption of feed that was harvested this year and fresh (d).
T_{hs}	hold-up time between harvest and consumption of feed that was harvested this year and stored (d).
T_v	translocation factor of radionuclide from above-ground plant surface to edible plant part.
U_a	annual consumption of the animal product by man(kg/y or l/y).
U_v	annual consumption of the edible plant part by man(kg/y).
V_{ti}	total deposition velocity of radionuclide i

	from atmosphere (m/s).
W_{i1}	this year's average concentration of radionuclide i in irrigation water (Bq/l).
W_{i2}	last year's average concentration of radionuclide i in irrigation water (Bq/l).
W_{ij}	average concentration of radionuclide i in irrigation water in the (N−j+1)th year of the operation for calculating C_{ivs1} and that in the (N−j)th year of the operation for calculating C_{ivs2} (Bq/l).
X_{i1}	this year's average atmospheric concentration of radionuclide i (Bq/m^3).
X_{i2}	last year's average atmospheric concentration of radionuclide i (Bq/m^3).
X_{ij}	average atmospheric concentration of radionuclide i in (N−j+1)th year of the operation for calculating C_{ivs1} and that in (N−j)th year of the operation for calculating C_{ivs2} (Bq/m^3).
Y_{v1}	this year's yield of the edible plant part(kg–fresh/m^2).
Y_{v2}	last year's yield of the edible plant part(kg–fresh/m^2).
λ_{ei}	effective removal constant of radionuclide i from above–ground plant surface (d^{-1}).
λ_i	decay constant of radionuclide i (d^{-1}).

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