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Influence of Radioactive Contamination to Agricultural Products Due to Rain During a Nuclear Accident

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Abstract

The previous dynamic food chain model was improved for the consideration of the influence of radioactive contamination to agricultural products due to rain during the environmental releases of radionuclides in a nuclear accident. Wet interception coefficients for the agricultural plants were derived as a function of radionuclide and rainfall amount, and mathematical formulations of the previous model were modified. As a result, rain during accidental releases was influential in agricultural contamination. The contamination level of agricultural products decreased dramatically according to increasing rainfall amount. It means that predictive concentrations in agricultural products using the previous model, in which dry interception to the agricultural plants is only considered, can be overestimated. The influence of rainfall in agricultural contamination was the most sensitive for ^{131}I, and the least sensitive for ^{90}Sr among the radionuclides considered in this study.

Key Words : dynamic food chain model, wet interception coefficients, nuclear accident, rainfall, agricultural contamination

1. Introduction

Radioactive materials released into the environment during a nuclear accident lead to the widespread contamination of agricultural ecosystems. The accident at Chernobyl in 1986 showed that agricultural contamination can be affected hundreds and even thousands of kilometers from the accident site. In addition, for the inhabitants living in neighboring countries, it was confirmed that the ingestion of contaminated foods were the highest exposure pathway which cause radiation health effects to the human[1,2]. The contamination levels of agricultural products was observed variously region by region. It is mainly due to the meteorological characteristics including rain.

In the case of short-term deposition of radionuclides after a nuclear accident, the radionuclide concentration in agricultural products is strongly dependent on the date or season when the deposition of radioactive material occurs and on the time since deposition, due to factors such as crop growth and biokinetics of radionuclides intaked by cattle. Therefore, the predictive results of equilibrium models, which describe the steady-state radionuclide concentration in different components of the environment, are not suitable for applications related to the implementation of actions to reduce the exposure dose. In such applications, a dynamic model describing the variation of radionuclide concentrations in environmental components after deposition is necessary. A dynamic food chain model considering Korean agricultural conditions[2], which is a module for evaluating ingestion dose in the Korean real-time dose assessment system FADAS (Following Accident Dose Assessment System)[3], has been developed to predict time-dependent radionuclide concentration in agricultural products from the radionuclide concentrations on the ground. Radionuclides to agricultural plants may be intercepted by dry processes, wet processes, or a combination of both. In the present model, interception by dry processes is only considered.

In this study, for the consideration of influence of wet processes, wet interception coefficients for the agricultural plants were derived as a function of radionuclide and rainfall amount, and mathematical formulations of the previous model was modified. Using the improved model, the influence of agricultural contamination due to rain is comprehensively investigated.

2. Interception of Radionuclides

Radionuclides released into the atmosphere when a nuclear accident occurs are deposited onto plant and soil surfaces. The ratio of the amount deposited onto plants to the amount of total radionuclide deposition is defined as the interception fraction f. Chamblain[4] gives a functional dependence between f and agricultural productivity above ground B_f (dry-kg/m^2) as follows :

$$f = 1 - e^{-\alpha B_f} \tag{1}$$

Interception coefficient α(m^2/dry-kg) is defined as the ratio of plant concentration (Bq/dry-kg) to the total deposition (Bq/m^2). Radionuclides to agricultural plants may be intercepted by dry processes, wet processes, or a combination of both. In the present model, interception by dry processes is only considered. The dry interception coefficient is applied 3.0 m^2/dry-kg for all agricultural products except for fruits, and 0.3 m^2/dry-kg for fruits[2]. Eq. (1) is applicable both dry and wet interceptions[5]. Therefore, dry and wet interception coefficients can be expressed as follows :

$$\begin{aligned} f_{dry} &= 1 - e^{-\alpha_{dry} B_f} \\ f_{wet} &= 1 - e^{-\alpha_{wet} B_f} \end{aligned} \tag{2}$$

The radionuclide concentrations in agricultural products will probably be different depending on whether dry processes follow wet processes or wet processes follow dry processes. If wet processes occur following dry processes, radionuclide deposited onto the plant leaves due to dry interception can be removed by rain. However, approximately 90% of radionuclides intercepted by dry processes is fixed each day or each time step, only 10% is mobile[6]. Also, approximately 70% of mobile is fixed the next day or the next time step[6]. Therefore, assuming that it is no rain for the first day of accidental releases and it is rain for the next day, only 3% can be removed by rain. Consequently, the order of dry and wet processes dose not so much affect in total amount of radionuclides intercepted onto agricultural products.

Some authors analyse results in terms of the interception coefficient α, others in terms of the interception fraction per unit weight of the biomass f/B_f assuming linear interception of the depositing material. If f is less than about 0.3, there is little practice difference[5]. When f approaches unity, as may happen when B_f is large, it is more appropriate to use α[5]. The experimental data for f/B_f can be found easier than those for α from several literatures. Especially, in case of the wet processes, it is more true. Therefore, in this study, wet interception coefficients α_{wet} were derived from the experimental data of a reference [5] with an assumption that α values are equivalent to f/B_f values. Fig. 1 shows the dry interception coefficients interpolated from experimental data as a function of rainfall amount for pasture grass. Similarly dry interception coefficients, wet interception coefficients for pasture grass were applied to all agricultural plants except for fruits. The dry interception coefficients for the fruits is 1/10 of those for other agricultural plants. Therefore, it was assumed that wet interception coefficients for fruits are 1/10 of those for the other agricultural plants because of lack of experimental data.

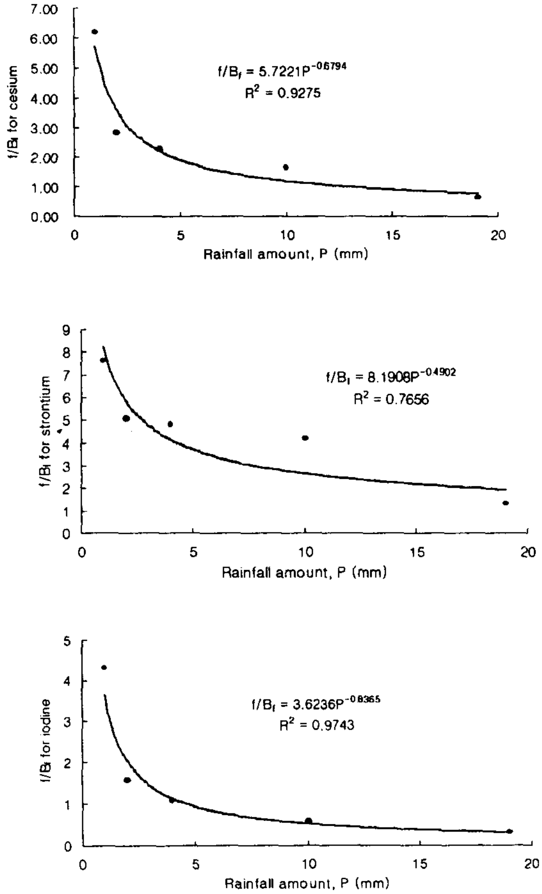

Fig. 1. Wet Interception Coefficient as a Function of Rainfall Amount. ($f/B_f \approx \alpha_{wet}$, R^2: Coefficient of Determination)

3. Modification of Mathematical Model

The mathematical formulations of the previous dynamic food chain model were modified for the consideration of the influence of agricultural contamination due to rain during accidental releases. This model is based on the compartmental approach, which describes radionuclide transfers between compartments by ordinary differential equations. The initial input parameter is radionuclide concentrations on the ground (Bq/m^2) which is a measurable quantity in the environment. For the consideration of wet processes, the mathematical formulations and intial conditions should be modified for plant surface(X_A, Bq/dry-kg) and soil surface (X_C, Bq/m^2) compartments as follows ;

$$\frac{dX_A}{dt} = -(\lambda_w + \lambda_g + \lambda_{tr} + \lambda_d)X_A + \left(\frac{\lambda_{re} \cdot f_{dry}}{B_f}\right)X_C$$

$$X_A(0) = \frac{(f_{dry} \cdot F_{dry}) + (f_{wet} \cdot F_{wet})}{B_f} \tag{3}$$

$$\frac{dX_C}{dt} = -(\lambda_{pe} + \lambda_{re} \cdot f_{dry} + \lambda_d)X_C + (\lambda_w \cdot B_f)X_A$$

$$X_C(0) = (1 - f_{dry})F_{dry} + (1 - f_{wet})F_{wet} \tag{4}$$

where,

λ_w : weathering removal rate (1/d)

λ_g : dilution rate due to plant growth (1/d)

λ_{tr} : translocation rate from plant surfaces to edible parts (1/d)

λ_d : : radioactive decay rate (1/d)

λ_{re} : resuspension rate (1/d)

λ_{pc} : : percolation rate from surface soil to root zone soil (1/d)

F_{dry} : time-integrated radionuclide concentration on the ground during no rain (Bq/m^2)

F_{wet} : time-integrated radionuclide concentration on the ground during rain (Bq/m^2)

The mathematical formulations and initial conditions for the other environmental compartments are identical with the previous model.

4. Results and Discussion

The previous dynamic food chain model was improved for the consideration of influence of agricultural contamination due to rain during accidental releases. Using the improved model, the results was comprehensively investigated. It was assumed that the deposition of radionuclides occurred on August 15 when a number of agricultural plants are fully developed in Korean agricultural conditions.

Fig. 2 shows the radionuclide concentrations in rice and fruits at harvest due to a combination of dry and wet processes. It was assumed that the radionuclide concentration on the grounds during no rain and rain of 100 mm is each 1 Bq/m^2 for each different radionuclide. It is clear that rain is an important mechanism in agricultural contamination. For rice, the contribution of wet processes to total contamination was approximately 17%, 36% and 7% for ^{137}Cs, ^{90}Sr and ^{131}I, respectively. For fruits, it was approximately 15%, 28% and 10% for each radionuclide. Consequently, for the same radionuclide concentration on the ground, agricultural contamination due to wet processes is far lower than that due to dry processes because of lower interception coefficients. The agricultural contamination due to wet processes was the most influential for ^{131}I and was the least influential for ^{90}Sr. Fig. 3 shows the radionuclide concentrations in milk, which is continuously produced, for the same assumptions with Fig. 2. Similarly rice and

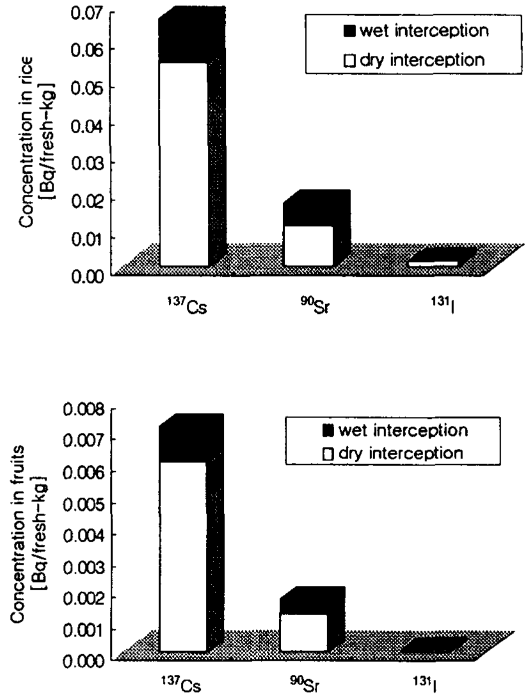

Fig. 2. Radionuclide Concentrations in Rice and Fruits at Harvest Due to a Combination of Dry and Wet Processes (Deposition Date : August 15, Rainfall Amount : 100 mm, Radionuclide Concentration on the Ground During Rain and No Rain : Each 1 Bq/m^2)

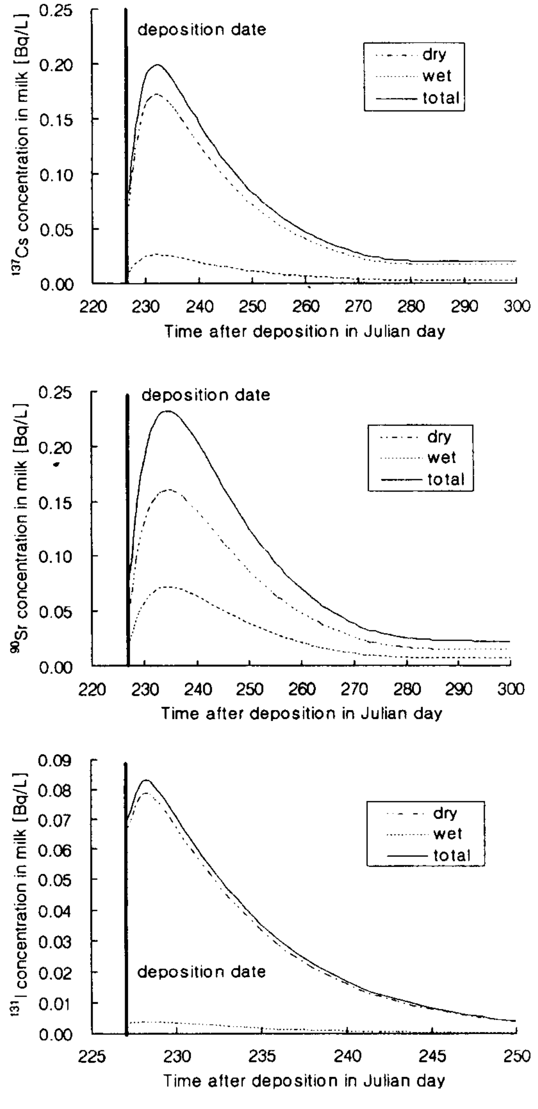

Fig. 3. Radionuclide Concentrations in Milk Due to a Combination of Dry and Wet Processes (Same Conditions as Fig. 2 are applied)

fruits, rain was an important contamination mechanism.

Fig. 4 shows the radionuclide concentrations in rice at harvest as a function of rainfall amount. It was assumed that it is rain over total period of accidental releases with time-integrated radionuclide concentration on the ground of 1 Bq/m^2. In contamination according to rainfall amount, the most influential radionuclide was ^{131}I and the least influential radionuclide was ^{90}Sr. The ^{137}Cs and ^{90}Sr concentrations in rice for scanty rain below 1 mm were higher than those for no rain. Authors think that it is due to stronger

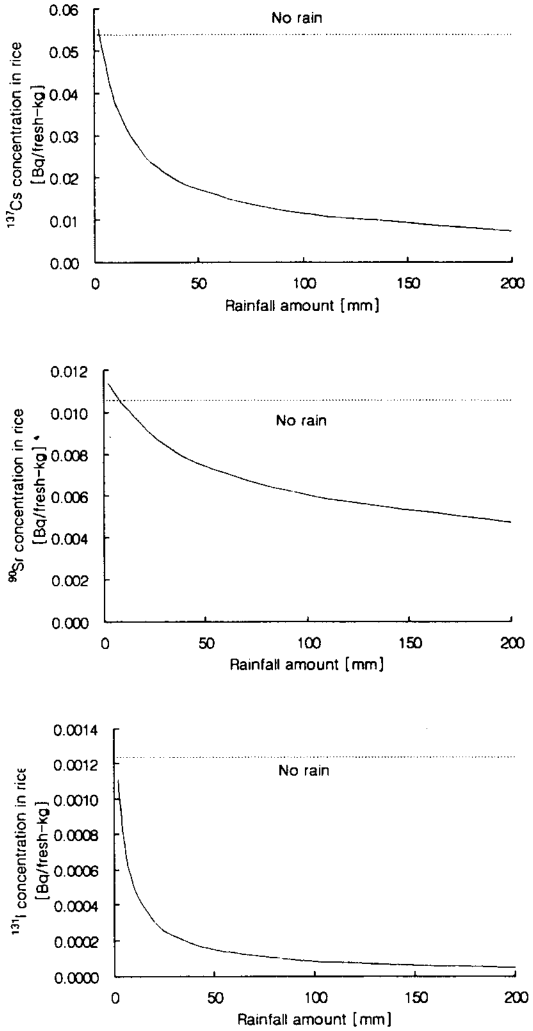

Fig. 4. Radioactive Contamination in Rice at Harvest as a Function of Rainfall Amount (Deposition Date : August 15, Radionuclide Concentration on the Ground : 1Bq/m^2)

adhesion between radionuclides and surface of agricultural plants.

It should be borne in mind that the initial input parameter in the model is time-integrated radionuclide concentration on the ground, not time-integrated air concentration. Therefore, if initial input parameter is time-integrated air concentration, rain during accidental releases may cause higher agricultural contamination because of higher wet deposition velocity from air to ground.

5. Conclusions

For the consideration of influence of agricultural contamination due to the rain, the mathematical formulations of the previous model were modified with the derivation of wet interception coefficients as a function of rainfall amount and radionuclides for agricultural products.

As a result, the difference of contamination level in agricultural products between without and with rain was so large for the same time-integrated radioactive concentrations on the ground. Agricultural contamination decreased dramatically according to increasing rainfall amount. It means that predictive concentrations in agricultural products using the previous model can be overestimated. Influence of rainfall for agricultural contamination was the most sensitive for ^{131}I, and the least sensitive for ^{90}Sr among the radionuclides considered in this study.

The occurrence possibility of rain during accidental releases of a nuclear facility is exist. Therefore, the modified model may give more reliable predictive results.

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