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■論 文■

Experimental Studies for Analyzing Direct Contamination Pathway of ^{54}Mn, ^{57}Co, ^{85}Sr, ^{103}Ru and ^{134}Cs in Rice

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벼에 대한 ^{54}Mn, ^{57}Co, ^{85}Sr, ^{103}Ru, ^{134}Cs의 직접오염 경로분석 실험

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Abstract - For analyzing the direct contamination pathway of radionuclides in rice plants, a solution containing ^{54}Mn, ^{57}Co, ^{85}Sr, ^{103}Ru and ^{134}Cs was applied to the aboveground parts of the rice plants in a greenhouse at 6 different times during their growth. The plant interception factor showed little difference among radionuclides and increased with decreasing time intervals between RI application and harvest. Its highest observed value was 0.94. The fractions of the initial plant deposition that remained in rice plants at harvest were in the range of 19~47%, 17~43%, 19~42%, 23~61% and 11~69% for ^{54}Mn, ^{57}Co, ^{85}Sr, ^{103}Ru and ^{134}Cs, respectively, when no decay was assumed. The translocation factors of those radionuclides in hulled seeds were in the range of $6.9\times10^{-4}\sim3.8\times10^{-2}$, $3.6\times10^{-3}\sim1.6\times10^{-1}$, $5.8\times10^{-4}\sim3.2\times10^{-2}$, $1.6\times10^{-4}\sim7.6\times10^{-3}$ and $3.2\times10^{-2}\sim2.0\times10^{-1}$, respectively, and were highest when they were applied at the stage of active seed development. It was indicated that the remaining percentage and translocation factor would not be greatly affected by the difference in the rain frequency if it is within a factor of 2. These results can be utilized for predicting the radionuclide concentrations in rice seeds when an accidental deposition of those radionuclides occurs during the rice-growing season.

Key words : radionuclide, direct contamination, rice, interception factor, remaining percentage, translocation factor, hulled seed

요약 - 벼의 방사성 핵종 직접오염 경로를 분석하기 위하여 동위원소 실험온실내에서 ^{54}Mn, ^{57}Co, ^{85}Sr, ^{103}Ru, ^{134}Cs의 혼합용액을 벼의 생육중 여섯 차례에 걸쳐 작물체 지상부에 처리하였다. 작물체 차단계수는 핵종 간에 차이가 없었고 처리시기가 수확기에 가까울수록 증가하여 최고 약 0.94에 달하였다. 작물체에 침적한 각 핵종의 수확시 잔류율은 방사능 붕괴가 없다고 가정할 때 처리시기에 따라 각각 19~47%, 17~43%, 19~42%, 23~61%, 11~69%였다. 종실 전류계수는 처리시기에 따라 각각 $6.9\times10^{-4}\sim3.8\times10^{-2}$, $3.6\times10^{-3}\sim1.6\times10^{-1}$, $5.8\times10^{-4}\sim3.2\times10^{-2}$, $1.6\times10^{-4}\sim7.6\times10^{-3}$, $3.2\times10^{-2}\sim2.0\times10^{-1}$의 범위였고 모두 종실의 발육성기 처리시 가장 높았다. 강우 빈도의 차이가 2배 이내일 때는 강우빈도가 잔류율과 전류계수에 큰 영향을 미치지 않는 것으로 나타났다. 본 연구결과는 벼의 생육중 사고침적시 쌀알 내 핵종농도 예측에 활용될 수 있다.

중심어 : 방사성 핵종, 직접오염, 벼, 차단계수, 잔류율, 전류계수, 현미

INTRODUCTION

In Korea, rice is the most important food crop and as high as 12% of the national area is occupied for the rice culture[1]. Rice grows for a comparatively long time of approximately 5 months[2]. Accordingly, a nuclear accident in Korea could be widely and frequently accompanied with the exposure of rice plants to radionuclides. If radionuclides are released into the atmosphere during the growing season of the crop plants, direct contamination of the aboveground plant parts would generally contribute much more to the food chain radiation dose than would the root uptake of radionuclides deposited onto soil[3,4].

The above-mentioned condition makes it meaningful to experimentally produce data on the radionuclide transfer involving direct contamination of the rice plant. In Korea, however, experiments on direct contamination have only been carried out for Chinese cabbage[5]. In some advanced countries, a number of experiments[6-13] have been conducted with important food crops of their own like wheat, barley, grasses, lettuce, bean, fruits and so on, but little work has been done with rice. In many experiments[6-9,11], plants were contaminated using a spray or nebulizer and in some other experiments[12,13], they were contaminated using a rain simulator or a micropipette to simulate wet deposition. It can be said that the former is simulating the plant contamination via dry deposition of fine and highly soluble radioactive particulates or via wet deposition by a light rain as long as there is no run-off of the applied solution from the plant surface[6,12,14].

Crop plants can be classified into two types regarding radioactive contamination by a direct pathway. One type is composed of those like grains or fruits and the other is composed of those like leafy vegetables. Only a special part is edible in the former, while the whole aboveground part is edible in the latter. When the rice plant, which belongs to the former type, is exposed to airborne radionuclides, it is important to predict how much activity will accumulate in the mature seed.

For such a prediction, it is necessary to have data on the interception of deposited radionuclides by the aboveground part of the rice plant, loss of radionuclides from the plant and translocation of the remaining activity to the mature seeds[3,4]. The plant interception factor is a parameter used for calculating the activity initially retained by the plant. The fraction of the initially retained activity that remains at harvest, which makes it possible to predict how much activity will remain in the mature plant, is determined by the magnitude of radionuclide loss from the plant. Finally, the activity in the edible part of the mature plant can be estimated by multiplying the remaining activity by the translocation factor.

In this study, such data were produced through a greenhouse experiment in which the rice plants at different growth stages were exposed to radioactive spray containing ^{54}Mn, ^{57}Co, ^{85}Sr, ^{103}Ru and ^{134}Cs, which are the major radionuclides, or their radioisotopes, released from nuclear power plants. With the experimental results, radionuclide concentrations in mature seeds were predicted for the unit deposition of radionuclides onto rice fields during the growing season.

MATERIALS AND METHODS

Plant Culture

Seedlings of a rice cultivar called Dongjin-byeo were transplanted to flooded culture boxes on May 16, 1998. The culture boxes were 60 cm wide, 60 cm long and 100 cm high and installed in trenches built in a greenhouse. The bottom 20 cm of the box was filled with small broken stones and the rest was filled with a field soil. Physical and chemical properties of the top 15 cm of soil in the box are given in Table 1.

Table 1. Physical and chemical properties of the top 15cm soil in the culture box.

pH (1:2.5)	O.M. (%)	T-N (ppm)	C.E.C (me/100g)	E.C.(me/100g)			Sand (%)	Silt (%)	Clay (%)	Soil type
				Ca	Mg	K				
5.1	1.56	904.7	3.3	1.38	0.36	0.67	73	23	4	Sandy loam

O.M. : Organic matter, T-N : Total nitrogen, C.E.C. : Cation exchange capacity, E.C. : Exchangeable cation.

The planting density was 12 hills per box with 4 plants per hill. The culture boxes were irrigated with tap water until the end of September and the depth of the standing water was about 2~5 cm for the irrigation period. Agricultural practices such as fertilization and disease control were performed as required. All windows were removed to allow as much wind as possible to blow in.

RI Application

A 0.015 M HCl solution containing career-free ^{54}Mn, ^{57}Co, ^{85}Sr, ^{103}Ru and ^{134}Cs (30.2kBq, 33.1kBq, 47.4kBq, 70.1kBq and 17.4kBq per mℓ, respectively, as of October 12, 1998) was manually applied using a home spray to the aboveground part of the rice plants in an exposure box mounted onto the culture box. The exposure box was composed of an upper part and a base and, when combined, it was 90 cm wide, 90 cm long and 130 cm high. The bottom of the base is an opening of 60 cm by 60 cm to fit to the top of the culture box.

The spray was manipulated about 50~70 cm above the plant canopy to total 31 shots with 3 shots to the 9 divisions of the planting area and one more shot to the 4 divisions at the corners. It took 14~16 mℓ of the solution and approximately 16 s to complete the spraying. There was no run-off of the applied solution from the plant surface. The culture box was drained 1 d before RI application and the soil surface was covered with absorbent paper to prevent radionuclide deposition onto the soil. The application was made at 6 different times : June 22, July 20, August 11, August 24, September 7 and September 25, which were 112 d, 84 d, 62 d, 49 d, 35 d and 17 d, respectively, before harvest. The ear started to come out on August 16.

For the rain simulation, 6 hills of the rice plants in every contaminated culture box were sprinkled with tap water at the rate of 4.5~6.0 ℓ per 3~5 d depending on the months and the first sprinkling was maed 3 d after RI application. This rain treatment is roughly equivalent to the monthly precipitation of 135~300 mm, which seems to be normal for the rice-growing months in Korea[2]. For the applications made on July 20 and September 7, an experiment in which the frequency of the rain simulation was reduced to the half was included.

Sample Preparation and Measurement

Three hours after RI application, the absorbent paper was removed and 6 hills of the rice plants were cut at 5 cm above the soil surface. The remaining 6 hills of the plants were grown to maturity and harvested on October 12. The plant samples were air-dried in the greenhouse for more than 3 weeks and then divided into straw, chaff and hulled seed. Straw was cut into small pieces using scissors. The absorbent paper was also air-dried in the greenhouse and cut into small pieces.

The radionuclide concentrations in the samples were determined by γ-spectrometry using a HPGe detecter (EG&G ORTEC). The detection time was 0.5~2 h depending on the sample activity.

Calculation of the Parameter Value

The interception factor (I), which is defined as the fraction of the total deposition that was deposited onto the aboveground plant surface[4,15], was calculated as follows;

$$I = \frac{2D_c}{2D_c + D_p} \qquad (1)$$

where D_c (Bq) is the activity of a radionuclide in the 6 hills of plants collected 3 h after RI application and D_p (Bq) is that in the absorbent paper.

The remaining percentage, that is, the percentage of the initial plant deposition that remained in the plant at harvest (R, %) was determined as follows;

$$R\ (\%) = \frac{C_h}{D_{ch}} \times 100 \qquad (2)$$

where C_h (Bq) is the activity of a radionuclide in the 6 hills of the plants collected at harvest and D_{ch} is D_c corrected for decay to harvest.

The translocation factor (T), which is defined as the fraction of the plant's total activity at harvest that is contained in the plant's edible part[3,16], was calculated as follows;

$$T = \frac{C_{sh}}{C_h} \qquad (3)$$

where C_{sh} (Bq) is the activity of a radionuclide in the hulled seeds from the 6 hills of the plants collected at harvest.

RESULTS AND DISCUSSION

Plant Interception

Fig. 1 shows the interception factors of ^{54}Mn, ^{57}Co, ^{85}Sr, ^{103}Ru and ^{134}Cs varying with the times of the RI application. There was little difference in the interception factor among the radionuclides. It increased with a decreasing time interval between RI application and harvest. This is attributable to the fact that the plant biomass increased with time as shown in Fig. 2[5,17]. The interception factor increased rather rapidly during the earlier part of growth but it increased very slowly thereafter and stayed at around 0.9 since the 3rd application, which was made 62 d before harvest. Similar trends were also found in other crops[5,8,15, 17]. The fact that the interception factor was measured to be highest at 35 d and 17 d

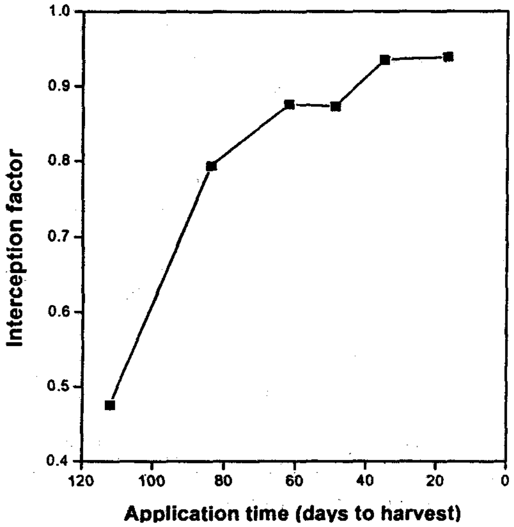

Fig. 1. Variation in the rice interception factor of the radionuclides with time of RI application.

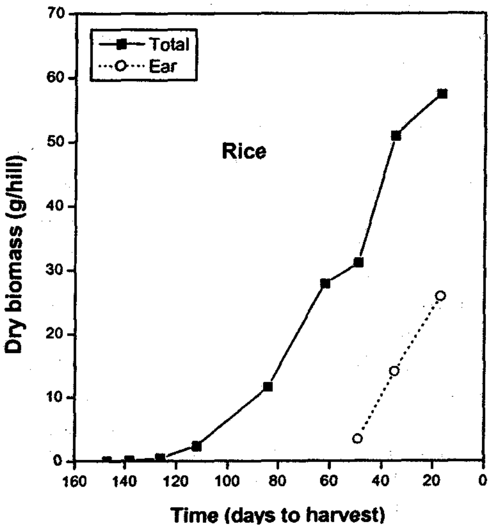

Fig. 2. Change in the biomass of the rice plant with time.

Table 2. Percent of the total plant interception that was contributed by the rice ear.

Application time (days to harvest)	Ear contribution to plant interception^a (%)				
	^{54}Mn	^{85}Sr	^{103}Ru	^{57}Co	^{134}Cs
49	6.3	6.3	6.3	6.5	6.4
35	20.0	20.1	20.2	20.5	20.3
17	16.3	16.5	16.6	17.0	16.9

$$^a\ \frac{\text{Activity deposited onto the ear}}{\text{Activity deposited onto the whole plant}} \times 100$$

before harvest, although many leaves dried up then, can be explained by the relatively great depositions onto the ears on those days (see Table 2). The great deposition onto the ears is due to the fact that most of the ears bent on those days because of their increased weights.

In the crop field, the interception factor may be affected by the planting density because a higher planting density generally leads to a higher biomass density which, in turn, leads to a wider effective area for interception[17]. This tendency seems to be conspicuous when deposition occurs at the early growth stage because the effective area may then be nearly directly proportional to the planting density. The normally recommended planting density for rice is 25~28 hills/m^2, while the planting density in the present experiment was 33.3 hills/m^2. The interception factor might be, therefore, more or less overestimated in this experiment and a somewhat conservative assessment could be expected when the present data are used for the rice plants growing in a normal density.

Percent Remaining at Harvest

Table 3 gives the dry biomasses of the mature rice plants treated with radioactive spray at 6 different times during the growing season. The rice plants treated at the 2 earliest times produced the heaviest biomasses. This can be explained by the fact that the plants were grown to maturity under a more favorable condition because the 6 hills of the contaminated plants in their culture boxes were removed at the early growth stages. The remaining percentage is not, however, likely to be much affected by the final biomass production.

The remaining percentage at harvest also increased with decreasing time intervals between RI application and harvest (see Fig. 3). It was in the range of 19.3~47.4%, 16.6~43.4%, 19.1~42.4%, 22.9~61.7% and 11.3~69.2% for ^{54}Mn, ^{57}Co, ^{85}Sr, ^{103}Ru and ^{134}Cs, respectively. Of the 5 radionuclides, ^{134}Cs had the lowest remaining percentage for the first application, but it had the highest percentage for the last application.

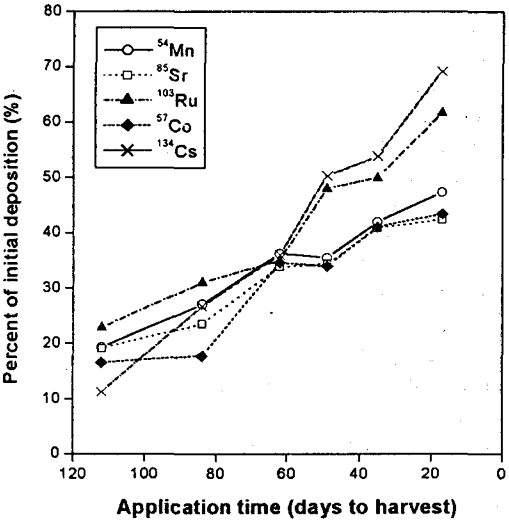

Fig. 3. Percent of the initial plant deposition that remained at harvest.

Table 3. Biomass production of rice at harvest.

Application time (days to harvest)	Biomass production (g-dry/hill)			
	Total	Straw[a]	Hulled rice	Chaff
112	82.3	46.7	29.1	6.5
84	72.5	42.3	24.6	5.6
62	58.1	36.2	17.8	4.1
49	57.5	35.1	18.3	4.2
35	62.2	36.3	21.4	4.5
17	58.6	33.2	21.1	4.3

[a] including rachis.

The remaining percentage is determined by the loss of activity mainly resulting from the environmental weathering process by rain and wind[8,9]. The magnitude of the environmental weathering of a radionuclide would depend on many factors including its solubility, strength of the adsorption to the plant surface and the degrees of permeation into the inner flesh and secretion to the outside. It can be inferred that a very complex mechanism resulting from an interaction of those factors could be behind the difference in the remaining percentage among the radionuclides. The most rapid loss of activity occurred at the last application where 30.8~57.6% of the applied activity, depending on the radionuclides, was removed in 17 d. This fact indicates that a very rapid loss would occur right after radionuclide deposition. This rapid loss is attributable to the fact that, right after deposition, most activity stays not in the leaf inner flesh but on the leaf surface where it is directly exposed to weathering.

In most assessment models, the remaining activity is predicted with the weathering half life (T_w, d) and 14~15 d were used for it regardless of the radionuclide species and deposition time[3,4,16]. Table 4 gives the weathering half lives of the radionuclides calculated with the present experimental results assuming that the half life does not change over the whole period from deposition to harvest. Most half lives observed were longer than 15 d and the older deposition had on the whole the longer half life[9,18]. It indicates that using 14~15 d for T_w would result in the underestimation of the radionuclide concentration in the rice seeds, especially when the radionuclides are deposited at the earlier growth stages. In fact, there are some reports showing that the T_w's of radiostrontium and radiocesium in grasses are longer than 25 d[19,20]. It needs to be noted, however, that this experiment was carried out in a greenhouse, where the effects of wind could be weaker than in real fields and that the results would be better applied to a somewhat severe case.

Translocation to Seed

Fig. 4 shows the relationship between the translocation factors of the radionucldies and the time of their application. The translocation factors decrease on the whole in the order of ^{134}Cs > ^{57}Co > ^{54}Mn > ^{85}Sr > ^{103}Ru indicating that ^{134}Cs is most mobile in rice plants. A similar tendency for the difference in the mobility of radionuclides within the plant was reported for many seed and fruit crops[7,11,21,22]. The translocation factor varied with the radionuclides by factors of about 10~500 depending on the application times. For every radionuclide, the highest translocation factor occurred at the 5th application, which was made 35 d before harvest when the seeds actively developed[2]. A similar trend in wheat and barley was shown by Aarkrog[7]. The variation in the translocation factor of a radionuclide with application times was smallest in ^{134}Cs, which showed a variation by a factor of about 6, while the others showed variations by factors of 45~55.

Table 4. Weathering half lives of the radionuclides applied to the rice plant at 6 different times during its growth.

Application time (days to harvest)	Weathering half life (d)				
	^{54}Mn	^{85}Sr	^{103}Ru	^{57}Co	^{134}Cs
112	47.2	46.9	52.7	43.2	35.6
84	44.5	40.2	49.7	33.7	44.1
62	42.3	39.6	40.9	40.5	42.1
49	32.8	31.8	46.4	31.5	49.4
35	27.9	27.1	35.0	27.3	39.2
17	15.8	13.7	24.4	14.1	32.1

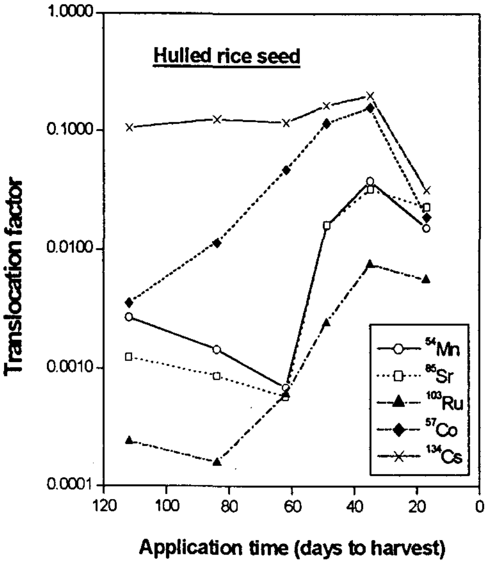

Fig. 4. Variations in the translocation factors of the radionuclides in hulled rice seed with time of their application.

The translocation factor of ^{134}Cs did not greatly change from the 1st to 5th application, but decreased significantly at the 6th application. On the other hand, the translocation factors of ^{54}Mn, ^{85}Sr, ^{103}Ru and, to a lesser degree, ^{57}Co at the last 3 applications, where the ears were directly exposed to the radioactive spray, were much higher than those at the earlier applications. These facts indicate that ^{134}Cs deposited on the rice leaf even at an early growth stage comparatively easily translocates to the rice seed and that the ear contamination is much less important to the seed accumulation of ^{134}Cs compared with the other radionuclides. Aarkrog[7] and Middleton[23] obtained similar results in their experiments with wheat and barley.

Tukey et al.[24] presented data showing that spraying the aboveground parts of tomato plants with radioactive solutions of pH 2 and 6 resulted in no significant difference in ^{89}Sr translocation to the ripe tomato fruits but that it resulted in a few times higher translocation of ^{103}Ru at pH 2 than at pH 6. In the present experiment, the effect of pH is expected to be much weaker because the contaminated plants were sprinkled with tap water several times. However, the possibility of some overestimation especially for the ^{103}Ru concentration in the rice seeds could not be excluded.

Effect of Rain Frequency

Tables 5 and 6 show the effect of rain frequency on the remaining percentage of the radionuclides and their translocation factors, respectively. For the RI application made on July 20, the simulation of a normal rain frequency (type A) resulted in slightly lower remaining percentages than that of a half rain frequency (type B), while for the application made on September 7, little difference was found between the 2 types of simulation. This fact indicates that the difference in the total precipitation due to the different rain frequency would not give rise to a significant difference in the loss of the radionuclides from the rice plant if the difference in the rain frequency is within

Table 5. Percent of initial plant deposition that remained at harvest after 2 different simulations of rain frequency.

Date of RI application	Rain[a] Simulation	Percent remaining at harvest (%)				
		^{54}Mn	^{85}Sr	^{103}Ru	^{57}Co	^{134}Cs
July 20	Type A	27.1	23.5	31.0	17.8	26.7
	Type B	31.0	30.2	38.6	23.1	29.2
Sep. 7	Type A	41.9	40.9	50.0	41.1	53.9
	Type B	43.7	39.5	49.4	40.6	54.5

[a] Type A denotes that the 6 hills of the plants were sprinkled with tap water at the rate of 4.5~6.0 ℓ per 3~5 d and type B denotes that they were sprinkled in half the frequency.

Table 6. Translocation factors of the radionuclides after 2 different simulations of rain frequency.

Date of RI application	Rain[a] Simulation	Translocation factors				
		^{54}Mn	^{85}Sr	^{103}Ru	^{57}Co	^{134}Cs
July 20	Type A	1.5×10^{-3}	8.7×10^{-4}	1.6×10^{-4}	1.2×10^{-2}	1.3×10^{-1}
	Type B	2.4×10^{-3}	9.0×10^{-4}	1.3×10^{-4}	1.5×10^{-2}	1.3×10^{-1}
Sep. 7	Type A	3.8×10^{-2}	3.2×10^{-2}	7.6×10^{-3}	1.6×10^{-1}	2.0×10^{-1}
	Type B	3.3×10^{-2}	2.9×10^{-2}	6.1×10^{-3}	1.5×10^{-1}	1.8×10^{-1}

[a] Type A denotes that the 6 hills of the plants were sprinkled with tap water at the rate of 4.5~6.0 ℓ per 3~5 d and type B denotes that they were sprinkled in half the frequency.

a factor of 2. For the RI application made on July 20, the more frequent rain simulation increased the losses of ^{85}Sr, ^{103}Ru and ^{57}Co more than the losses of ^{54}Mn and ^{134}Cs. Similarly, Middleton[25] showed it in his experiment with wheat, potato and cabbage that the loss of ^{89}Sr by rain was greater than that of ^{137}Cs. Scotti[11] also reported similar experimental results for the loss of ^{85}Sr and ^{134}Cs from bean leaves by sprinkling with distilled water.

There was no significant difference in the translocation factors between the 2 types of the rain simulations except that at the July 20 application, the ^{54}Mn translocation factor was about 60% higher in the half frequency treatment than in the normal frequency treatment. It can, therefore, be expected that when ^{54}Mn is deposited onto the rice plant at its earlier growth stage, the less precipitation due to the lower rain frequency above a certain level may result in its higher translocation to the seed.

Prediction for Unit Deposition

Fig. 5 shows the concentrations of the radionuclides in the hulled rice seeds predicted for the deposition of 1 Bq each per m^2 of the rice field using the present experimental results. The yield of the hulled seeds in the field was assumed to be 0.5 kg/m^2[1,2].

The concentration decreased in the order of Cs isotope > Co isotope > Mn isotope > Sr isotope > Ru isotope. The difference between stable Cs and stable Ru were only by factors of 6~700 depending on the deposition times, but that between their radionuclides were by factors of 9~2800. The concentration of ^{103}Ru, the half life of which is only 39.6 d, increased with a decreasing time interval between deposition and harvest, while the concentrations of the other radionuclides were highest when they were deposited around 35 d before harvest.

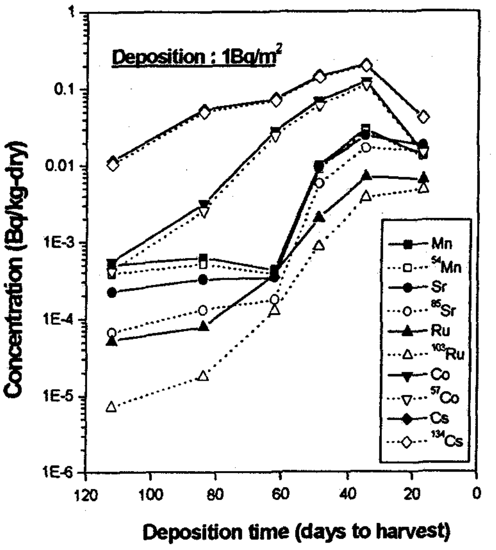

Fig. 5. Estimated radionuclide concentrations in hulled rice seeds when each radionuclide is deposited onto the rice field in 1Bq/m^2.

The difference in the seed concentration between the stable isotope and the radioisotope resulted from the radioactive decay. The concentrations of ^{90}Sr and ^{137}Cs, which are very important radionuclides in the food chain at the time of a nuclear accident[3,4], may be almost the same as those of their stable isotopes because their half lives are as long as 28 y and 30 y, respectively.

The IAEA[26] suggested 1 kBq/kg as the action level of ^{134}Cs, ^{137}Cs and ^{103}Ru in general foods and 0.1 kBq/kg for ^{90}Sr. As estimated with the data in Fig. 5, those levels in mature rice seeds are equivalent to depositions of ^{134}Cs, ^{137}Cs, ^{103}Ru and ^{90}Sr in 5.1, 4.9, 261.1 and 4.0 kBq/m^2, respectively, onto the rice field at the stage of active seed development. If deposition occurs at an early growth stage, protective action may not be necessary even for much higher depositions than mentioned above. At the time of the Chernobyl accident, ^{137}Cs deposition exceeded 4.9 kBq/m^2 in some places in Western Europe[27].

CONCLUSION

The direct contamination pathway of ^{54}Mn, ^{57}Co, ^{85}Sr, ^{103}Ru and ^{134}Cs in rice was experimentally analyzed and plant interception, weathering loss and seed translocation of the radionuclides applied at different growth stages were investigated.

The interception factor, showing little difference among the radionuclides, increased as the plant grew to maturity. There is some difference in the weathering loss among the radionuclides and weathering loss is estimated to be most rapid in the early phase after deposition. It is indicated that the generally used default value for the weathering half life, 14~15 d, needs to be longer when the deposition occurs at the early and middle growth stages. The translocation factors varied with the radionuclides by factors of up to about 10~500 depending on the RI application times. Of the 5 radionuclides, ^{134}Cs had the highest translocation factor, which means that it is most mobile within the rice plant. The translocation factors were highest when the radionuclides were applied at the stage of active seed development. The variation in the translocation factor with the times of RI application was smallest in ^{134}Cs, which showed a relatively high translocation factor even when the rice plant was contaminated at the early growth stage. The weathering loss and translocation factor are not likely to be greatly affected by the difference in rain frequency if it is within a factor of 2.

These experimental results can be referred to in predicting the radionuclide concentrations in rice seeds when the radionuclides are acutely deposited during the growing season. The obtained data may be better fitted for the prediction if radionuclides are deposited in the form of fine and highly soluble particulates or a light rain. In addition, it should be noted that since this experiment was carried out under the condition of a weaker wind effect and a higher planting density than normal, the prediction based on the present results may give rise to an overestimation of the ingestion dose. Regardless, some level of conservatism is often necessary in the environmental impact assessment for a nuclear accident.

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