Journal of the Korean Nuclear Society
Volume 24, Number 2, June 1992

Absorption and Accumulation of Sr–90 by Rice and Soybean and Its Soil–to–Plant Transfer Coefficients

Yong Ho Choi, Chang Woo Lee, Kang Suk Lee, and Jeong Ho Lee
Korea Atomic Energy Research Institute

Jae Seong Jo
Chungnam National University

Kyu Hoi Chung
Kyonggi University

(Received November 27, 1991)

벼와 콩에 의한 Sr-90 흡수.축적 및 토양–작물체간 전이계수

최용호 · 이창우 · 이강석 · 이정호
한국원자력연구소

조재성
충남대학교

정규회
경기대학교

(1991. 11. 27 접수)

Abstract

Radio–tracer experiments on the Sr–90 absorption by rice and soybean from a sandy–loam soil of pH 6.35 treated with 5.2 and 31.2Bq Sr–90 per g–soil were carried out through pot cultivations. Sr–90 absorption rates of both crops increased till the mature stage when the rates were about 1.0%. Concentrations in their whole tops, however, decreased or changed little as they grew. Sr–90 concentrations in plant parts of both crops increased with the increase of those in soil. Soil–to–plant transfer coefficients of Sr–90 for rice and soybean at mature stages ranged, on the dry weight basis, from 0.07(unpolished seed) to 3.67(leaf) and from 0.86(seed) to 9.26(leaf), respectively. Only the unpolished rice seed showed a significant difference in the coefficient with 0.17 in 5.2Bq treatment and 0.07 in 31.2Bq treatment. Sr–90 retention rates of the upper 15cm soil after crop harvests were about 80%. Sr–90 absorptions had no effect on the plant growth and yield of the crops.

요 약

pH 6.35의 사질양토에 g당 5.2 및 31.2Bq의 Sr-90을 처리하여 벼와 콩에 의한 Sr-90 흡수 실험을 pot재배를 통하여 실시하였다. 두 작물에 의한 Sr-90 흡수율은 성숙기까지 계속 증가하였고 성숙기에 흡수율은 공히 1.0% 정도였다. 그러나 전지상부내 농도는 성장과 함께 계속 감소하거나 거의 변하지 않았다. 두 작물의 부위별 Sr-90 농도는 처리농도의 증가에 따라 증가하였다. 성숙기에 Sr-90의 토양-작물체간 전이계수는 건조중 기준으로 벼의 경우 0.07(현미) −3.67(잎), 콩의 경우 0.86(종실) −9.26(잎)의 분포를 보였다. 현미에 있어서는 전이계수가 5.2Bq 처리에서는 0.17, 31.2Bq 처리에서는 0.07로 처리농도간에 유의차가 인정되었다. 작물 수확후 상부 15cm 토양내 Sr-90의 잔류율은 약 80%였다. Sr-90 흡수는 두 작물의 생육이나 수량에 영향을 미치지 않았다.

1. Introduction

The use of nuclear energy, which has rapidly increased in Korea for last two decades, inevitably entails the release of radionuclides into the environment. Released radionuclides can become internal radiation sources to the human body after their intakes by man through food–chains[1−3]. Accordingly, understanding the transport behaviors of radionuclides in the agricultural ecosystem is necessary for assessing the environmental impact of the nuclear facilities and for preparing agricultural counter–measures against the farm–land contamination with radionuclides.

Strontium–90 with a long half–life of 28 years is highly produced as one of fission products[4] and it remains in the root zone in available forms for many years after its deposition[5−8]. Moreover, Sr–90 absorbed by man accumulates in the bone marrow, so its intake results in a long–term internal exposure to radiations[9].

For those reasons, numerous studies on the uptake of Sr–90 from soil by various crops have been conducted in western countries since early 1950's when the nuclear energy began to be widely used. Many of those studies were carried out by means of the radio–tracer technique for investigating the soil–to–plant transfer coefficient which is defined as the ratio of the radionuclide concentration in plant to that in soil[1−3,10]. Publications about the Sr–90 absorption by rice or soybean, however, are few because these crops are of little importance in western countries.

Pot experiments, therefore, were carried out with different concentrations of Sr–90 in a specific type of soil to understand the absorption and accumulation patterns of Sr–90 by rice and soybean plants, to investigate soil–to–plant transfer coefficients for various plant parts at different growth stages and to see the effect of Sr–90 contamination of soil on the plant growth and yield.

2. Materials and Methods

The rice and soybean cultivars used for this experiment were Dongjin–byeo and Hwangkeum–kong, respectively. Plants were grown on the plastic pot(diameter 25.5cm, height 29.5cm) containing 14kg of an air–dried sandy–loam soil mixed uniformly with Sr–90($SrCl_2$, carrier–free, Amersham) solution. Sr–90 concentrations treated were two levels of 5.2 and 31.2Bq per gram soil. Control was also included. Physico–chemical properties of the soil used are given in Table 1.

Nitrogen, phosphate, potassium and slaked lime applied as basal fertilizers were 0.55, 0.55, 0.71, and 7.8g per pot for rice and 0.24, 0.39, 0.71, and 7.8g per pot for soybean, respectively.

Experimental units of each crop were placed in the green house built in the KAERI by the com-

Table 1. Physico–chemical properties of the soil used in the experiment

pH (1 : 5)	O.M (%)	T.N (%)	P_2O_5 (ppm)	C.E.C. (me/100g)	E.C.(me/100g)				Silt (%)	Clay (%)	Sand (%)	Class
					K	Ca	Mg	Na				
6.35	0.42	0.01	440	7.5	0.36	4.5	0.29	0.14	16.4	4.7	78.9	SL

O.M. : Organic matter
T.N. : Total nitrogen
C.E.C. : Cation exchange capacity
E.C. : Exchangeable cation
SL : Sandy loam.

pletely–randomized design with 3 replications. The rice pots were irrigated to about 5cm in water depth immediately after the placement.

Five hills(three plants/hill) of rice seedlings were transplanted to a pot, and 15 soybean seeds were put into five holes(three seeds/hole) on a pot, on June 2, 1988. About 0.5cm of soil in depth was added on the surfaces of the soybean pots to prevent contaminated soil particles from being splashed.

Both sides of the vinyl cover on the frame were kept open to minimize the temperature difference between inside and outside of the house. Proper amount of water was supplied almost everyday and rice pots were not drained until the yellow–ripening stage. 0.39 and 0.17g of nitrogen per pot for rice were additionally added on July 2 and 27, respectively. Soybean plants were thinned out at an early growth stage for one plant per hole in the standing density.

One hill per pot of rice was sampled on July 21(maximum–tillering stage) and August 26(early–ripening stage) and two hills per pot were done on October 12(mature stage). One plant per pot of soybean was sampled on July 18(flowering stage) and August 26(early–ripening stage) and two plants per pot were done on October 10(mature stage). Root parts of the crops were not taken for the samples.

Fresh plant samples were divided into several parts such as leaf, stem, seed, and chaff or pod. Parted plant samples were oven–dried at 80℃ for 14 hours after sunlight–dried and their dry weights were measured. About 1kg of soil per pot was sampled from the top 15cm soil layer after the third plant sampling and oven–dried at 110℃ for 14 hours after sunlight–dried.

Dried plant samples were ashed at 450℃ for 8 hours, then proper amounts of the ash samples were put into 5 inch planchets and mounted on a G.M. counter(detector : window 1.5mg–mica/㎠, operating voltage 1100, Aloka) at least 20 days after the sampling to carry out the radiation detection in the state of radioactivity equilibrium between Sr–90 and its daughter Y–90 which the standard source used for the measurement of detection efficiency existed in. Three samples of 3.2g dried soil per pot were put into 5–inch planchets and radiations were detected in the same way as mentioned above. The average was taken from the three measurements for the radiatioin count of the soil. Net counts of all radioactive samples were obtained by subtracting the counts of corresponding control samples from their total counts.

Soil–to–plant transfer coefficients of Sr–90(Bv) were calculated with the equation below.

$$Bv = \frac{\text{Sr–90 concentration in the plant at each sampling(Bq/g–dry)}}{\text{Sr–90 concentration in the soil at the last plant sampling(Bq/g–dry).}}$$

3. Results and Discussions

Sr–90 absorption rates investigated at three different growth stages of rice and soybean are shown in Table 2. There was not any significant difference in the rate between 5.2 and 31.2Bq treatments. The rates of rice and, to a less extent, soybean got higher and higher till the mature stage when the rates of rice and soybean were about 2.5 and 1.5 times, respectively, higher than those at the maximum–tillering stage and at the flowering stage, respectively. Sr–90 absorption rates of the soybean plant were, on the whole, 3–5times higher than those of the rice plant.

The absorption rates by a rice and soybean plant at the mature stage were as low as about 0.1% and 0.3%, respectively. From approximation with these values, 1.0% can be obtained for both crops as the Sr–90 absorption rate by all mature plants under the pot cultivation. In field conditions, the absorption rate vary greatly depending on the planting density, the degree of the plant growth, and the concentration distribution in soil. Yamata et al.[11] reported that the Sr–90 absorption rate of rice ranged from 0.42% to 1.66% in Japanese field condition.

Table 2. Sr–90 absorption rates of rice and soybean[a] at three growth stages[b] in two different soil treatments of Sr-90

Crop	Sr–90 conc. treated (Bq/g–dry soil)	Sr-90 absorption rate (%)[c]		
		lst stage	2nd stage	3rd stage
Rice	5.2	0.05	0.07	0.12
	31.2	0.04	0.07	0.10
	t–value	NS	NS	NS
Soybean	5.2	0.20	0.24	0.32
	31.2	0.20	0.26	0.31
	t–value	NS	NS	NS

NS : Statistically not significant.

a : Root was not included for either crop.

b : Refer to Fig. 1. and 2.

c : $\frac{\text{total Sr–90 activity in a plant}}{\text{total Sr–90 activity added to a pot.}} \times 100$

Sr–90 concentrations of rice and soybean at two different Sr–90 levels in soil were investigated at three different growth stages as shown in Fig. 1 and Fig. 2, respectively. For both crops, neither the Sr–90 concentration distribution within the plant nor the changing pattern of the Sr–90 concentration in each part of the plant with growing time was greatly different between 5.2 and 31.2Bq treatments of soil. Except for the rice chaff and seed, Sr–90 concentrations in each part of both crops in the 31.2Bq treatment were about 5–6 times higher than those in the 5.2Bq treatment.

Sr–90 concentration in the whole top of the rice plant went on decreasing from the maximum–tillering stage till the early–ripening stage while little change occurred after this stage. This means that the increasing rate of the plant weight was higher than that of the total Sr–90 activity in the palnt. Sr–90 concentration in the straw(stem+leaf) increased about 50% at the mature stage as compared with that at the early–ripening stage while

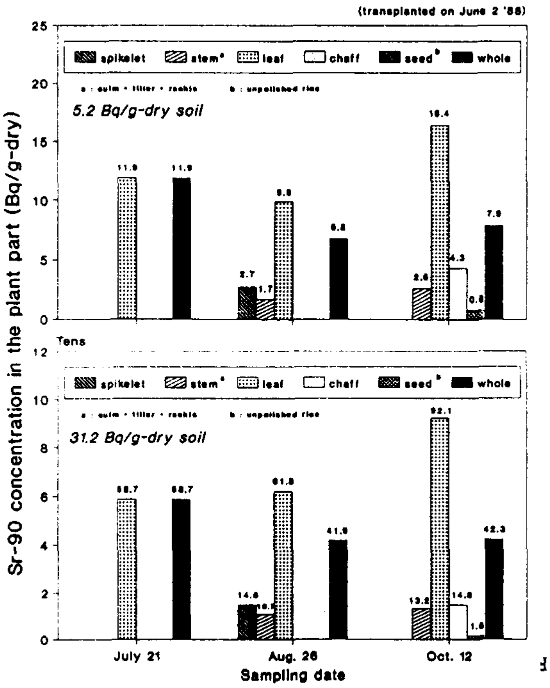

Fig. 1. Changes in Sr–90 concentrations in several parts of rice with growing time in two different soil treatments of Sr–90.(July 21 : maximum–tillering stage, Aug. 26 : early–ripening stage, Oct. 12 : mature stage)

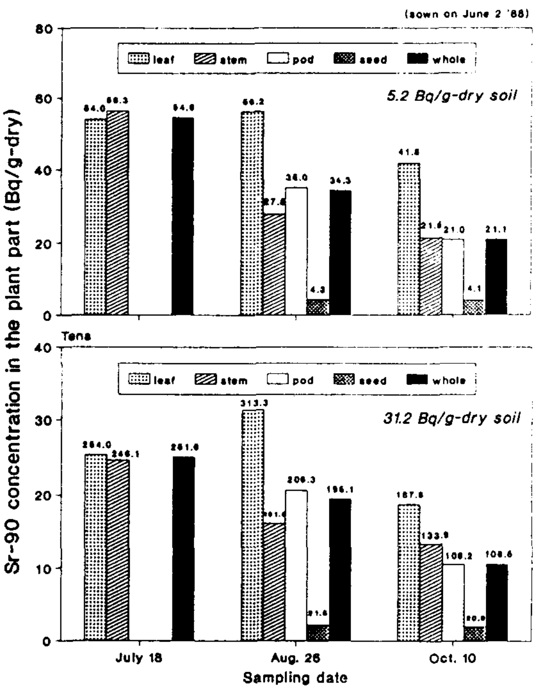

Fig. 2. Changes in Sr–90 concentrations in several parts of soybean with growing time in two different soil treatments of Sr–90. (July 18 : flowering stage, Aug. 26 : early–ripening stage, Oct. 10 : mature stage)

Sr–90 concentration in the spikelet(chaff+seed) decreased greatly because of the rapid accumulation of photosynthetic products in the spikelet for ripening.(Refer to Table 5.)

Ratios of Sr–90 concentrations in chaff and unpolished seed in 31.2Bq treatment to those in 5.2Bq treatment were as low as 3.4 and 2.0, respectively. So, it can be said that the translocation and accumulation of Sr–90 into the spikelet is remarkably retarded at its higher concentration.

The order of Sr–90 concentration in each part of the rice plant was leaf>chaff>stem>unpolished seed. Kim[8] reported a somewhat different order of leaf>stem>chaff>unpolished seed in his pot experiment. This difference is thought to be, as mentioned above with present data, due to the fact that higher concentrations of Sr–90(37, 74 and 148Bq/g–soil) were used in his experiment. Tensho et al. [12] reported in their pot experiment that Sr–90 concentration in the straw was much higher than that in the seed. Coughtrey and Thorne[13] reported by quoting Abbazov et al. [14] that the ratio of Sr–90 concentration in the seed to that in the straw was as low as 0.046.

Sr–90 concentration in the whole top of the soybean plant went on decreasing from the flowering stage till the mature stage although the total Sr–90 activity in it went on increasing(Table 2). The concentration in the leaf was highest at the early–ripening stage while it decreased more or less after this stage. That in the stem got lower and lower as the plant grew. Between early–ripening stage and mature stage, the concentration in the pod decreased about to the half and that in

Table 3. Transfer coefficients of Sr–90 for several parts of rice at two growth stages in two different soil treatments of Sr–90

(transplanted on June 2, '88)

Sr–90 conc. treated (Bq/g–dry soil)	Transfer coefficient[a]								
	Early–ripening stage				Mature stage				
	Leaf	Stem[b]	SK	Whole	Leaf	Stem[b]	Chaff	UR	Whole
5.2	2.18	0.37	0.60	1.50	3.58	0.56	0.95	0.17	1.73
31.2	2.41	0.42	0.59	1.64	3.67	0.52	0.58	0.07	1.66
t–value	NS	NS	NS	NS	NS	NS	NS	*	NS

SK : Spikelet UR : Unpolished rice seed

NS : Statistically not significant.

* : Statistically significant at p=0.05.

a : $\dfrac{\text{Bq/g–dry plant part at the time of each sampling}}{\text{Bq/g–dry soil at the last plant sampling.}}$

b : culm+tiller+rachis.

the seed kept almost constant because of the sharp increases in dry matter for the period.(Refer to Table 6.)

At the flowering stage, leaf and stem showed almost the same Sr–90 concentration. At the early–ripening stage, the order of the Sr–90 concentration in plant parts was leaf>pod>stem>seed but at the mature stage, it changed into leaf>stem>pod>seed owing to the rapid accumulation of photosynthetic products in the pod. Evans and Dekker[15] reported in their field experiment that Sr–90 concentration in the straw was 9 times higher than that in the seed.

Sr–90 concentrations in the leaf, stem, pod, and seed of soybean were about 2–6, 8–16, 5–7, and 5–13 times higher than those in the corresponding parts of rice, respectively. It is known to be a general tendency that the leguminous crop shows a higher concentration of Sr–90 as compared with other cereal or forage crops[13].

Soil–to–plant transfer coefficients of Sr–90 for rice(Table 3) ranged from 0.6 of the spikelet to 2.41 of the leaf at the early–ripening stage and from 0.07 of the unpolished seed to 3.67 of the leaf at the mature stage. Tsumura et al.[16] reported in their pot experiment that Sr–90 transfer coefficients for the unpolished rice seed were 0.016–0.025. These values are several times lower than those from this experiment. This difference seems to result mainly from the fact that they used a clay–loam soil of a higher clay content and higher cation exchange capacity(14.0me/100g), a higher application of lime(5–30g/3kg–soil) or compost(100–300g/3kg–soil) and a higher concentration of Sr–90(about 60Bq/g–soil) all of which can act as factors lowering the Sr–90 transfer coefficient[3,13,17].

The coefficients for soybean(Table 4) ranged from 0.92 of the seed to 13.42 of the leaf at the early–ripening stage and ranged from 0.86 of the seed to 9.26 of the leaf at the mature stage. These show a little difference from Coughtrey and Thorne[13]'s report that the coefficient was 0.53 for the seed and 4.81 for the straw.

According to Ng et al.[10], soil–to–plant transfer coefficients of Sr–90 for a number of crops and soils ranged widely from 0.05 to 17.5 on the dry weight basis. It is, therefore, necessary that the coefficient should be investigated for various types of crop and soil.

Only the unpolished rice seed and the soybean stem at their mature stages showed significantly

Table 4. Transfer coefficients of Sr–90 for several parts of soybean at two growth stages in two different soil treatments of Sr-90

(sown on June 2, '88)

Sr–90 conc. treated (Bq/g–dry soil)	Transfer coefficient[a]									
	Early–ripening stage					Mature stage				
	Leaf	Stem	Pod	Seed	Whole	Leaf	Stem	Pod	Seed	Whole
5.2	12.28	6.19	7.69	0.93	7.55	9.26	4.70	4.58	0.91	4.60
31.2	13.42	6.93	8.87	0.92	8.35	8.09	5.73	4.55	0.86	4.57
t–value	NS	NP	NS	NS	NS	NS	*	NS	NS	NS

NS : Statistically not significant.

* : Statistically significant at $p=0.05$.

a : $\dfrac{\text{Bq/g–dry plant part at the time of each sampling}}{\text{Bq/g–dry soil at the last plant sampling.}}$

different Sr–90 transfer coefficients between Sr–90 concentration treatments. Although the difference is less meaningful for the latter because of its inedibility to man, a great regard must be paid to the difference for the former because of its high consumption by Koreans.

In the radiation dose assessment, this kind of difference indicates that the linearity assumption for the relationship between the radionuclide concentration in soil and that in the plant[17] may be inapplicable to the unpolished rice seed and that its Sr–90 concentration and resulting radiation dose may be underestimated if present data are applied to the normal environmental conditions. So, an additional experiment using a wider range of Sr–90 concentration level is required for testing the applicability of the assumption for the rice seed in details. Such a significant difference in the rice seed is thought to have occurred mainly from the retarded translocation of absorbed Sr–90 to the seed at its higher concentration as mentioned earlier.

The rice and soybean have various uses depending on the plant part and the harvesting time. Proper value for the Sr–90 transfer coefficient, therefore, has to be chosen according to their uses.

Sr–90 retention rates of the upper 15cm soil were calculated from laboratory data on Sr–90 concentrations in soil samples which were taken from the upper 15cm soil layer of the pot after crop harvests. The rates turned out to be about 80% for both crops without any significant difference between 5.2 and 31.2Bq treatments. This value is not so different from those reported by Polyakov et al.[5], Squire[6], and Lee et al.[7]. These facts mean that most Sr–90 still remains in the active absorption zone after the crop harvest.

On the other hand, it seems that the loss of 20% was mainly due to the underground leaching of the nuclide because the loss by its decay and plant absorption was estimated to be only a few percent in this experiment. These losses must be counted in the long–term environmental assessment to prevent overestimations of the radionuclide concentrations in soil and foods.

Dry weights of several plant parts of rice and soybean measured for control and two treated groups at their different growth stages are given in Table 5 and 6, respectively. No significant difference in the dry weight between control and treated groups was observed in any case studied. This means that Sr–90 absorption has no effect on the growth of rice and soybean. This result almost agrees with Kim's report[8] that Sr–90 treatments

Table 5. Effects of the soil treatment of Sr-90 on dry weights of several parts of rice at three different growth stages

(transplanted on June 2, '88)

Sr-90 conc. treated (Bq/g-dry soil)	Dry weight (g/plant)									
	M.T.S.	Early-ripening stage				Mature stage				
	Leaf	Leaf	Stem[a]	SK	Whole	Leaf	Stem[a]	Chaff	UR	Whole
0	2.74	5.02	1.78	0.64	7.44	4.73	2.22	0.78	2.93	10.66
5.2	3.02	4.46	2.07	0.72	7.25	4.51	2.26	0.90	3.20	10.86
31.2	3.14	4.31	1.99	0.87	7.16	4.20	2.04	0.78	3.19	10.20
F value	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

M.T.S :Maximum-tillering stage SK : Spikelet
UR : Unpolished rice seed NS : Statistically not significant.
a : culm+tiller+rachis.

Table 6. Effects of the soil treatment of Sr-90 on dry weights of several parts of soybean at three different growth stages

(sown on June 2,'88)

Sr-90 conc. treated (Bq/g-dry soil)	Dry weight (g/plant)												
	Flowering stage			Early-ripening stage					Mature stage				
	Leaf	Stem	Whole	Leaf	Stem	Pod	Seed	Whole	Leaf	Stem	Pod	Seed	Whole
0	1.78	0.60	2.37	2.00	1.65	0.77	1.09	5.51	3.05	2.58	2.13	4.17	11.94
5.2	1.95	0.78	2.72	1.89	1.54	0.70	1.02	5.14	2.97	2.59	2.16	3.21	10.92
31.2	2.42	1.00	3.41	2.17	1.60	0.81	1.24	5.82	3.46	2.96	2.56	3.61	12.59
F value	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

NS :Statistically not significant.

applied up to 148Bq/g-soil had no effect on the rice growth and yield.

4. Conclusions

Sr-90 absorption rates of rice and soybean got higher and higher till the mature stage. Concentrations in their whole tops, however, decreased or changed little as they grew.

Absorption rates at the mature stage were estimated to be about 1.0% for both crops although Sr-90 absorbed by a soybean plant was about three times more than that absorbed by a rice plant.

Sr-90 concentrations of rice and soybean increased, in most cases, almost proportionally with the increase of the Sr-90 concentrations treated in soil.

For the rice seed, however, Sr-90 accumulation and soil-to-plant transfer coefficient were significantly lowered in the treatment with higher concentration of Sr-90, so further studies for obtaining more reliable data applicable to the assessment of Sr-90 contamination of the rice seed for a wide range of the concentration in soil are required.

Sr-90 concentrations and transfer coefficients of each part of the soybean plant were several times higher than those of the rice plant. In both crops, Sr-90 transfer coefficients for the seed were much lower than those for the straw.

Sr–90 retention rates of the upper 15cm soil after crop harvests were about 80%, and most loss of Sr–90 treated to soil was believed to occur by the underground leaching.

The absorption of Sr–90 from soil had no effect on the plant growth and yield of the crops.

References

1. Baes III C.F., R.D. Sharp, A.L. Sjoreen and R.W. Shor, "A Review and Analysis of Parameters for Assessing Transport of Environmentally Released Radionuclides through Agriculture", ORNL–5786, Oak Ridge National Laboratory, Oak Ridge, TN.(1984).
2. Simmonds J.R., G.S. Linsley and J.A. Jones, "A General Model for the Transfer of Radioactive Materials in Terrestrial Food Chains", NRPB–R89, National Radiological Protection Board, Harwell, U.K.(1979).
3. Till J.E. and H.R. Meyer(Eds.), "Radiological Assessment– A Textbook on Environmental Dose Analysis", NUREG/CR–3332, ORNL–5968, U.S. Nuclear Regulatory Commission, Washington D.C.(1983).
4. Glasstone S. and W.H. Jordan, "Nuclear Power and Its Environmental Effects", American Nuclear Society, La Grange Park, Illinois(1980).
5. Polyakov Y.A., G.M. Kader and V.V. Krintskii, "Behaviour of Sr–90 and Cs–137 in Soils", in V.M. Klechkovskii, C.G. Polikarpov and R.M. Aleksakhin(Eds.), Radioecology, pp. 78 –102, Wiley, New York(1973).
6. Squire H.M., "Long–term Studies of Strontium–90 in Soils and Pastures", Radiat. Bot. 6:49–67(1966).
7. Lee J.H. et al., "Studies on the Standardization of the Environmental Monitoring of Nuclear Facilities", KAERI/RR–423/83(1984).
8. Kim J.S., "Studies on the Adsorption and Desorption of Strontium–90 and Cesium–137 in Paddy Soils and Their Absorption Aspect in Rice Plant", Ph.D. Thesis, Korea University(1985).
9. Comar C.L., "Radioisotopes in Biology and Agriculture : Principles and Practice", McGrawhill Book Company, New York(1955).
10. Ng Y.C., S.E. Thompson and C.S. Colsher, "Soil–to–plant Concentration Factors for Radiological Assessments", NUREG/CR–2975, UCID–19463, U.S. Nuclear Regulatory Commission, Washington D.C.(1982).
11. Yamata Y. et al., "Mechanism and Interpretation of the Soil Contamination", Industrial Book Co., Tokyo(1979).
12. Tensho K., K. Yeh and S. Mitsui, "The Uptake of Strontium–90 and Calcium by Lowland and Upland Rice from Soil and Their Distribution in the Plants", Soil and Plant Food. 5(1):1–9(1959).
13. Coughtrey P.J. and M.C. Thorne, "Radionuclide Distribution and Transport in Terrestrial Ecosystems –A Critical Review of Data", Vol. 1, A. A. Balkema, Rotterdam(1983).
14. Abbazov M.A., I.D. Dergunov and R.G. Mikulin, "Effect of Soil Properties on the Accumulation of Sr–90 and Cs–137 in Crops", Soviet Soil Sci. 10:52–56(1978).
15. Evans E.J. and A.J. Dekker, "Comparative Sr–90 Content of Agricultural Crops Grown in a Contaminated Soil", Can. J. Plant Sci. 42 : 252–258(1962).
16. Tsumura A. et al., "Studies on the Behavior of Radioactive Strontium and Cesium in Soil and in Soil–Plant System", Agri. Tech. Res. Inst. Report B(36), pp. 57–113(1984).
17. Zach R., "Transfer Coefficients to Terrestrial Food Products in Equilibrium Assessment Models for Nuclear Installations", AECL–6449, Atomic Energy of Canada Limited(1980).