

〈Original〉

## Sorption and Migration Studies of Fission Products for Ground Waste Disposal

Sang Hoon Lee and Kwan Sik Chun

Korea Atomic Energy Research Institute Seoul, Korea

Young Ku Yoon

Korea Institute of Science and Technology, Seoul, Korea

(Received Sep., 2. 1978)

### Abstract

The problems of solid waste disposal into the ground in connection with environmental aspects in the vicinity of a site would be very significant, though ground disposal for solid waste is safe and economical method. Studies of the waste-movement and migration of radionuclides (Sr-90 and Cs-137) for the disposal into the ground were performed under laboratory and field conditions.

Affinity of the soils for radionuclide solution was higher than that in the acid solution. The sorption of radionuclides by the soils showed a time-dependent reaction. The migration rates of radiostrontium and radiocesium were a range of  $3.73 \times 10^{-3}$  to  $10.9 \times 10^{-3}$  cm/day. The nuclides in the soil migrate much more slowly than the water, probably due to its high exchange capacity.

The observed distribution of tritium was compared with that calculated by a mathematical model based on diffusivity. This study suggests that the tritiated water can be used to trace the movement of ground water.

### 요 약

부지주변 환경과 관련한 방사성 고체 폐기물의 지중처분 문제는, 비록 안전하고 경제적인 것이라 할지라도, 대단히 중요하다. 지중처분을 위한 방사성 핵종(Sr-90, Cs-137)의 이동과 물의 이동에 관한 연구가 실험실과 야외에서 수행되었다.

방사성 핵종에 대한 토양의 친화력은 알칼리성 용액에서 더 강하고, 흡착은 시간에 대한 함수관계가 있음을 나타내었다. 방사성스트론튬과 세슘의 이동율은  $3.73 \times 10^{-3} - 10.9 \times 10^{-3}$  cm/day 로서, 물의 이동 속도 보다 훨씬 낮은 값을 나타내었으며, 이것은 아마도 높은 이온이온교환능에 기인되는 것이다.

확산에 기초를 둔 수학적인 모형에 의거 얻은 값과 측정 트리튬의 분포가 비교되었다. 지하에서의 물의 이동 현상을 규명하는데 삼중수를 추적자로 이용할 수 있음을 암시하고 있다.

### 1. Introduction

At the present time nearly three quarters of the world's effective energy input comes from

oil and gas. But the world nuclear power growth is expected to rise between 227 and 247 GWe in 1981, between 961 and 1,113 GWe in 1991 and between 2,005 and 2,480 GWe in the year 2000<sup>(1)</sup>. In addition, the development of nuclear

techniques which has inspired a remarkable increase in the industrial, the medical, and the scientific use of radionuclides has been brought in the production of a large volume of radioactive wastes. The ground disposal<sup>(2-7)</sup> of the various method for radwaste disposal has been in practice and is actively studied in many countries.

Due to the large areas and volumes of soil available in most locations, the potential capacity for sorption of waste is great. And operations by ground disposal have advantages in economy and simplicity. The possibility of contamination of water resources is important in the site selection for the ground disposal of radioactive wastes. Investigations of ground water and the associated migration of radionuclides at the site are necessary to discover any possible hazard from leakage of radioactive materials into the ground.

The migration of radionuclides in the sub-

soil is dependent upon two mechanisms: diffusion and dispersion.

The purpose of this work was to make laboratory measurement of the parameters required for the analysis of the migration of radionuclides and to test the applicability of the diffusion theory to explain the observations of the water-movement.

## 2. Experiments

### 1) Sample preparation

The soil samples were taken at three different points (Fig. 1) so that the difference between surface soil (subscript 1) and subsoil (subscript 2) was found. The samples were placed in desicator after these were air-dried and screened through 2 mm sieve (U. S. standard).

### 2) Physical properties

Particles greater than 2 mm were fractionated by sieve. Air-dried fine soil samples were boiled

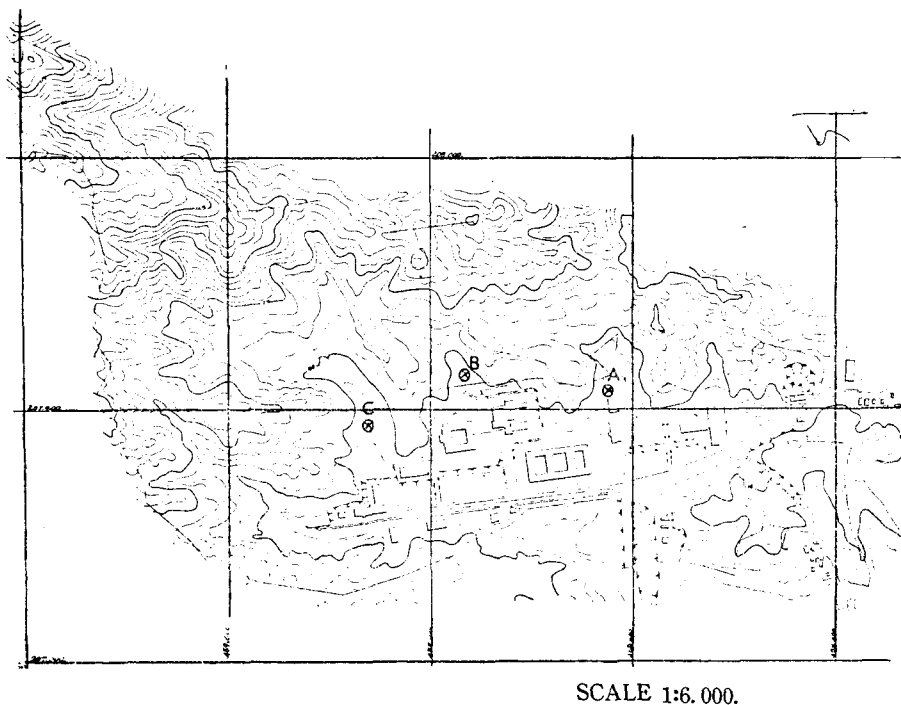


Fig. 1. K, A, E, R, I. Site

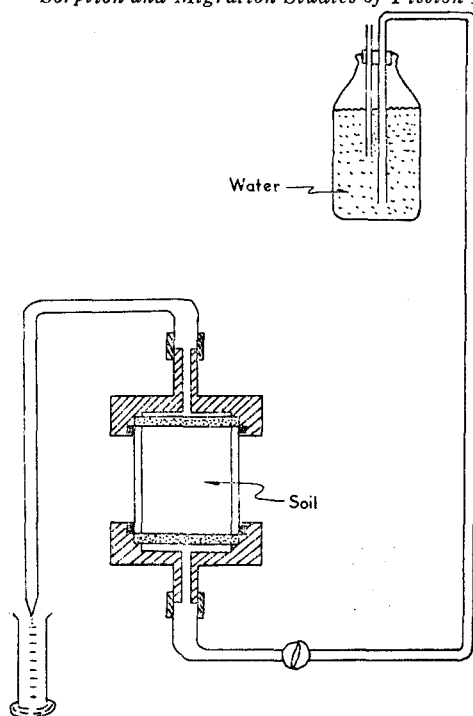


Fig. 2. Schematic diagram of hydraulic conductivity measuring unit.

with 6% hydrogen peroxide, and soluble salts were removed by washing with distilled water and shaken for dispersion. Coarse sand was fractionated by sieve, and clay and silt portions were determined by pipet methods<sup>8)</sup> using Stoke's law.

The hydraulic conductivity of soil was measured by the constant head method<sup>9)</sup> using a device as shown in Fig. 2. Air-dried fine soil was packed in cylindrical container and saturated with water which was applied through hydraulic head at the vertical height of 100 cm at a time interval measured. The values of hydraulic conductivity,  $K$ , were calculated by Darcy's equation:

$$K = \frac{Q}{At} \cdot \frac{d}{H}$$

where

$Q$ : amount of water flow

$A$ : cross action of the soil container

$t$ : time of water flow

$H$ : hydraulic head

$d$ : thickness of the soil layer

### 3) Chemical properties

There were two methods used in analysis of soils, one of which is decomposed by heating with HF and HClO<sub>4</sub> and the other by fusion with Na<sub>2</sub>CO<sub>3</sub>. From the samples prepared by these, chemical composition (SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, and Fe<sub>2</sub>O<sub>3</sub>) of the soil was determined by the method of colorimetry<sup>10-12)</sup> with Beckman DU-2 Spectrophotometer.

The total exchangeable metallic cation was estimated by extraction with NH<sub>4</sub>OAc and with HCl<sup>10)</sup>.

### 4) Distribution coefficient

The distribution coefficient  $K_d$  does not depend on the radioactivity of the nuclides but it depends on the concentration of gross ion contained in the solution and adsorbed on the soil, and pH.

The solution was composed of 0.3M NaNO<sub>3</sub>, 0.2M NaOH (except the change of pH), and contained the mass equivalent of approximately 1  $\mu$ Ci of <sup>137</sup>Cs per milliliter or 10<sup>-2</sup>  $\mu$ Ci of <sup>90</sup>Sr per milliliter. One hundred milliliters of the above radioisotope spiked solution with soil samples ranging from 0.5 to 1.2 gr was employed to determine distribution coefficient by batch process.

The change in  $K_d$  with increasing contact time (0.5 hr, 1 hr, 2 hr, ...etc.) was calculated as follows<sup>13)</sup>:

$$K_d = \frac{X_1 - X_2}{X_2} \cdot \frac{\text{ml of solution}}{\text{g of soil}}$$

where

$X_1$ : cpm of the influent solution, and

$X_2$ : cpm of the supernatant solution.

### 5) Column operation

Ion exchange columns were prepared by packing 35 g of soil sample in a 2.0 cm inner diameter glass tube to a height of 20 cm. The soil sample was supported on a glass wool plug with a wire screen on top. The 35 g portions of soil were soaked in water prior to

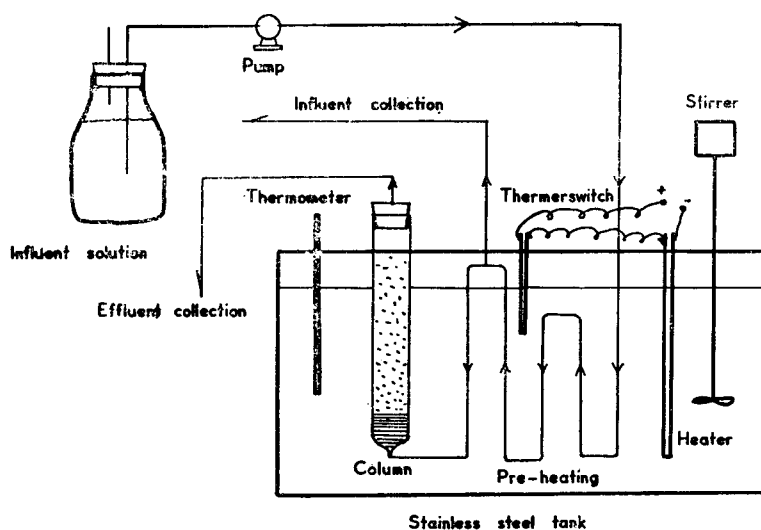


Fig. 3. Experimental apparatus for column process

packing in the tubes to allow air to escape from the pores of the soil. The columns were packed under water to exclude air bubbles.

Solutions were pumped downflow through the columns by means of peristaltic action pumps. Effluent samples were collected periodically for analysis. The volume of water above and below the column was subtracted from effluent volume measurements. The columns were suspended in a controlled temperature water bath maintained at 25°C. The temperature of feed solutions (composed of 0.3 M NaNO<sub>3</sub>, 0.2 M NaOH, and contained the mass equivalent of approximately 1  $\mu$ ci of <sup>137</sup>Cs per milliliter or 10<sup>-2</sup>  $\mu$ ci of <sup>90</sup>Sr per milliliter) was controlled at the temperature of 25°C in soils in the water bath before entering the columns (Fig. 3).

#### 6) Water and radionuclides movement

For the estimation of diffusion coefficient of water, columns were prepared in a 5 cm inner diameter glass tube to a height of 30 cm. The soil samples (100 g) were compacted on a glass wool plug. On the top of soil a tiny drop of tritiated water was deposited.

After a prechosen time, 1 day and 11 days, the soil plugs at the interval of 1 cm depth

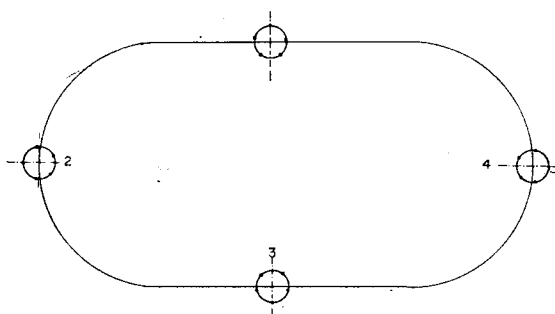


Fig. 4. Tracer injection points and sampling points

were collected. The tritium contained in the water, collected in a multicell vacuum distillation system, was counted in Automatic Liquid Scintillation Spectrometer.

The best way to apply to tracer is with a syringetype injector. 20 point injections at 4 areas, were made along four circle lines (20 cm diameter) at a depth of 0.5 meter (Fig. 4). The amount of trace injection per a time at an individual point was 50 ml of solution contained tracers (<sup>3</sup>H, <sup>90</sup>Sr, and <sup>137</sup>Cs) at 2  $\mu$ Ci/1. Soil core were taken with an auger and divided into 10-cm section and collected in wide neck bottles. These bottles are weighed in the laboratory.

**Table 1. Mechanical composition of the soils**

Soil	Fine soil					
	Graval 2 mm (%)	G. S 2 mm	F. S 0.2— 0.02 (%)	Silt 0.02— 0.002	Clay 0.002	Tex- ture
A <sub>1</sub>	18.8	45.7	25.6	11.9	16.8	SCL
A <sub>2</sub>	15.6	28.8	24.4	28.8	17.9	CL
B <sub>1</sub>	28.5	59.2	25.0	8.8	7.0	LS
B <sub>2</sub>	35.5	59.6	27.9	4.1	8.4	LS
C <sub>1</sub>	59.6	69.0	25.5	0.4	5.2	LS
C <sub>2</sub>	63.0	63.2	26.2	4.6	6.0	LS

**Table 2. Hydraulic conductivities of the soil samples.**

Soil	Pore ratio(%)	C (cm/sec)
A <sub>1</sub>	50.0	0.111
A <sub>2</sub>	48.2	0.079
B <sub>1</sub>	53.4	0.265
B <sub>2</sub>	53.8	0.283
C <sub>1</sub>	55.9	0.576
C <sub>2</sub>	54.6	0.394

**Table 3. Chemical composition**

Soil	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>
A <sub>1</sub>	21.5	7.6	0.17
B <sub>1</sub>	24.5	14.0	0.25
C <sub>1</sub>	23.0	2.2	0.17

**Table 4. Exchange capacity**

Soil	Mep/100g pf soil
A <sub>1</sub>	21.5
A <sub>2</sub>	25.8
B <sub>1</sub>	16.5
B <sub>2</sub>	18.2
C <sub>1</sub>	13.3
C <sub>2</sub>	15.7

The soil samples remaining in the bottles were dried in a multicell vacuum distillation system. The water was collected in small glass bottles and dried soil samples were weighed again.

**Table 5. Time dependency of the cesium sorption reaction for soil samples.**

Time (hr)	Distribution Coefficient, Kd(ml/g)					
	A <sub>1</sub>	A <sub>2</sub>	B <sub>1</sub>	B <sub>2</sub>	C <sub>1</sub>	C <sub>2</sub>
0.5	65	98	32	36	15	27
1.0	77	116	35	44	15	32
2.0	88	139	41	48	18	38
5.0	110	173	49	57	23	41
10.0	127	208	52	68	27	85
20.0	150	245	61	75	31	63
50.0	184	304	72	91	41	81
100.0	202	384	84	194	48	95
200.0	221	416	93	118	47	102

**Table 6. Time dependency of the strontum sorption reaction for soil samples**

Time (hr)	Distribution Coefficient, Kd(ml/g)					
	A <sub>1</sub>	A <sub>2</sub>	B <sub>1</sub>	B <sub>2</sub>	C <sub>1</sub>	C <sub>2</sub>
0.5	742	2394	480	463	182	337
1.0	790	2408	485	475	198	341
2.0	838	2443	494	496	204	345
5.0	903	2457	502	505	225	352
10.0	947	2516	518	516	236	359
20.0	991	2560	522	524	252	363
50.0	1006	2615	537	536	274	366
100.0	1068	2624	546	541	292	381
200.0	1143	2709	549	548	293	388

Tritium containing the water was counted in Automatic Liquid Scintillation Spectrometer. 10-gram of the soil was weighed into a 250-ml polyethylene beaker, to which 100ml of distilled water is added and the mixture stirs for 2 hours. The suspended material was then filtered out on a buchner funnel and leached with the distilled water until 200 ml of leachate had been collected. The samples and extracts were then counted by NaI(Tl) Crystal Scintillation Counter and G.M. Counter.

#### 4. Results and discussion

The mechanical composition of the soil analysed is given in Table 1. The samples denoted A, B and C are all sandy and they are dominated by the coarse portion.

It is found that clay portion is increased slightly as the depth is increased.

In general, the hydraulic conductivity of soil is dependent upon the size and distribution of the pore spaces. Table 2 demonstrates the variation of hydraulic conductivities obtained are medium or high<sup>(14)</sup>. Various theoretical attempts<sup>(15)</sup> have been made to justify the correlation of hydraulic conductivity with porosity(P). Kozeny<sup>(8)</sup> has proposed that the value of hydraulic conductivity  $K$  varies according to the ratio,  $P^3/(1-P)^2$ .

Chemical composition of the samples is shown in Table 3. These samples generally contain more amount of silica component than others,

and exchange capacity of A indicates the high distribution in Table 4.

The sorption of strontium or cesium by soils at various initial pH values was evaluated in terms of the distribution coefficient(Kd). Results are given in Fig. 5 and 6 where the Kd was plotted as a function of the initial pH of the soil suspension. Data for some soils for Sr and Cs in dilute solutions increased with the increase in pH. The slight drop in the magnitude of Kd for the B and C soils at pH 10 indicated the loss of sorption sites as the increasing portions of the soils were brought into solution phase with increasing pH.

A second parameter investigated according to slurry techniques was the time dependency of the Sr- or Cs- sorption reaction. The value of distribution coefficient obtained under laboratory condition is summarized in Table 5 and 6. The Sr- or Cs- sorption by the soils showed the

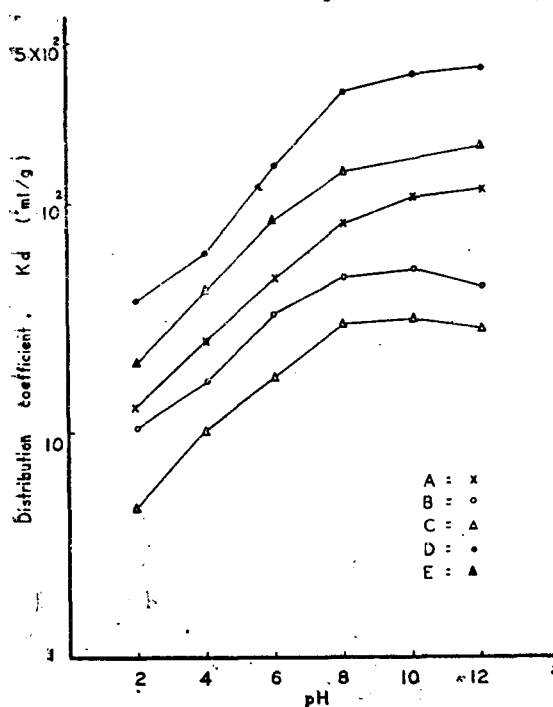


Fig. 5. The sorption of  $^{137}\text{Cs}$  by soils as a function of pH

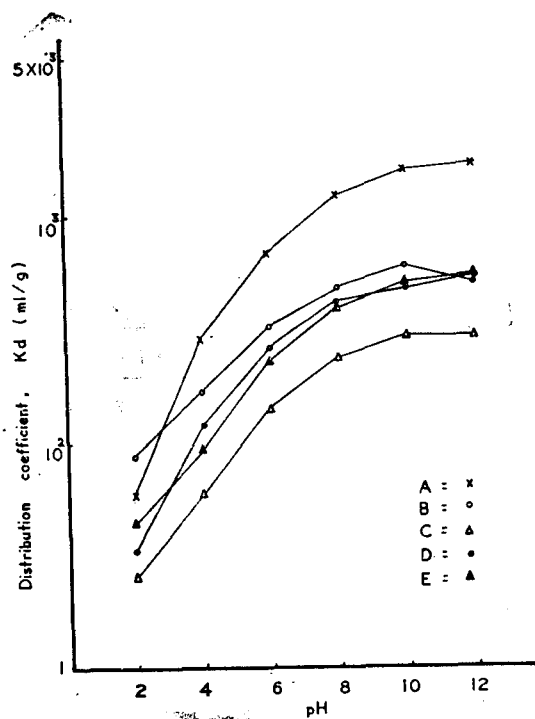


Fig. 6. The sorption of  $^{90}\text{Sr}$  by soils as a function of pH

time-dependent reaction. Kd-value of A-soil was high.

The above results indicated that the affinity of soils for Sr or Cs increased with the increase in clay-fraction, and in the strontium sorption A-soil had the very good affinity.

The results obtained in column operation are shown graphically in Fig. 7-8. Analysis of these data revealed as follows:

(1) Non symmetric break-through curves are at low break-through becoming more diffuse as the percentage of break-through increase. There is an increase in the Sr- or Cs- loading capacity as contact time increases.

(2) The symmetric break-through curves are a result of the more clay-fraction and are suggestive of particle diffusion.

It is assumed that A-site is suitable to dispose into the ground from the above results.

By the above results, A-site was selected for field test. Boring was undertaken with continuous flight augger up to 2 inches in diameter.

As shown in Table 7, underground of the site is composed of, from surface to subsurface, decayed, weathered and fresh rock. The site is consist of two parts; one is excavated part and another is the part of filling-up. In the

**Table 7. Depth of each soil or rock layer**  
unit: meter

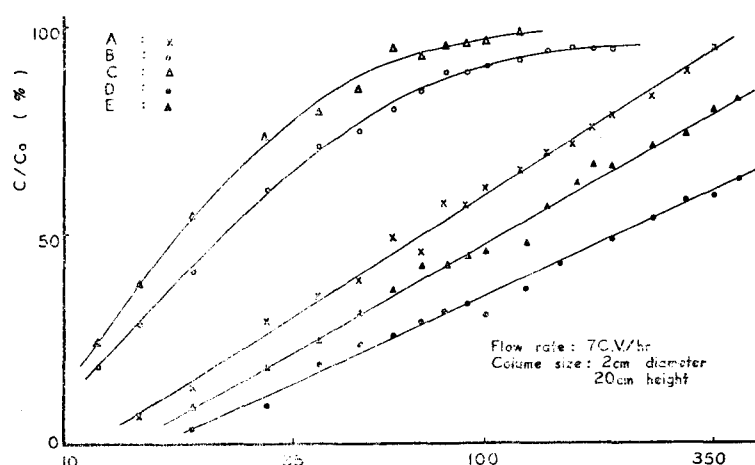
Layer Hole Number	Filling Soil	Sandy Clay	Granite	
			Soft	Hard
1		1.6	1.5	1.4
2	2.3	1.1	0.3	1.2
3	2.0	1.1	1.4	5.5
4	1.2		3.8	1.2
Remarks	Filling Soil	Decayed Rock	Weathered Rock	Fresh Rock

**Table 8. Grain Size distribution and cation exchange capacity with depth**

Depth (m)	Grain Size Distribution(%)				C. E. C. meq. per 100 g
	Coarse Sand	Fine Sand	Silt	Clay	
0.5-1.0	39.0	22.9	21.8	16.3	17.5
1.0-1.5	25.8	28.8	29.0	16.4	16.2
1.5-2.0	25.4	30.9	31.8	11.9	11.0
2.0-2.5	23.8	31.9	36.1	8.2	7.9
2.5-3.0	25.6	39.7	27.8	6.9	7.4

former weathered rocks are seen in the surface, but in the latter under the filling-up of decayed rocks, alluvial soil layers about 1.1 m thickness above the granite layers are seen and are composed of sandy clay as weathered rocks.

As regards the underground water no under-



**Fig. 7. Cesium breakthrough curves for soil samples with a simulated solution**

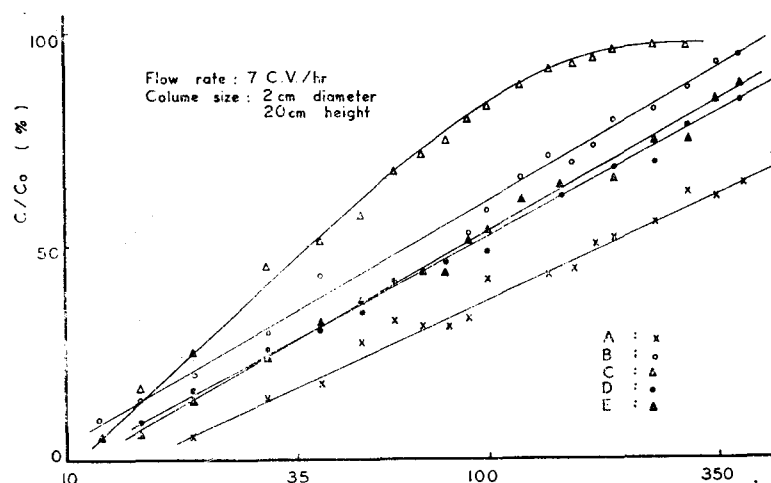


Fig. 8. Strontium breakthrough curves for soil samples with a simulated solution.

ground water level was found within the depth at hole No. 3 and 4 but at hole No. 1 and 2 underground water was found at 4.2 m and 4.5 m respectively, and the amount of water was a little.

Some of this soil characteristics with depth are listed in Table 8. The soil contains mainly sand and silt but a lower clay content ranging from 7% to 18%. Dation exchange capacity is decreased with the decrease of clay fraction.

Migration of radionuclides in soil is closely related with water-movement in soil. The number of theories of water-movement and migration of radionuclides in soil have been studies by authors<sup>(16-19)</sup>.

Solutions of Fick's law diffusion can be applied to description of the water-movement under a variety of boundary conditions. Convective flow also causes dispersion due to the various paths that the fluid follows as it moves. The distribution of a tracer has been described by formulas relating a diffusivity to time, distance, and physical characteristics of the media. In order to test the applicability of these theories in explaining the observed data, the following equation<sup>20)</sup> was utilized:

$$C_x = \frac{Q}{\sqrt{\pi Dt}} \exp\left[-\frac{(x-vt)^2}{4Dt}\right] \quad (1)$$

where  $Q$  is the amount of trace component,  $C_x$  is the tracer concentration at time  $t$  and at depth  $x$  from the injection surface,  $D$  is the diffusion coefficient,  $v$  is the average interstitial velocity of flow and  $x$  is the distance traveled in vertical coordinate.

If the velocity of flow is negligible, the tracer concentration ratio ( $C_x/C_0$ ) will be given by

$$(C_x/C_0) = \exp\left(-\frac{x^2}{4Dt}\right) \quad (2)$$

Then, by measuring  $C_x/C_0$ , the diffusion coefficient can be calaulated from the equation<sup>21)</sup>.

The diffusion coefficients of the tritiated water by the column operation were derived and are listed in Table 9. The values were closely approached to the published values of the diffusion coefficient for water in soils, clays and a matrix of fine glass spheres<sup>21)</sup>.

When the same amounts of tracers will be injected twice at the time interval, the raio( $R_x$ ) of the tracer concentration at depth  $x$  to the initial concentration will be derived from the equation<sup>1)</sup> as the following:

$$R_x = \frac{\sqrt{t_2} e^{-\frac{(x-vt_1)^2}{4t_1^2}} + \sqrt{t_1} e^{-\frac{(x-vt_2)^2}{4t_2^2}}}{\sqrt{t_1} + \sqrt{t_2}} \quad (3)$$

The existance of the peaks shows that downward water-movement is predominantly by interglular seepage<sup>22)</sup>. From the positions of these



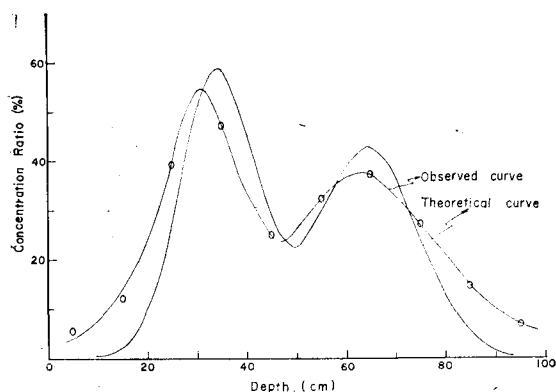


Fig. 9. Distribution Ratio of tritium in the Point 1

Table 10. Peakl values of tritium concentration

Sampling Point	Travel Time (day)	Ratip(%)	Depth from the Injection Point (cm)	Mean Velocity (cm/day)
1	8	57.0	25	3.57
	15	40.8	50	
2	8	48.2	26	3.43
	15	38.0	50	
3	8	54.2	31	4.28
	15	37.3	61	
4	8	56.1	18	2.43
	15	35.7	35	

peaks, the mean velocities of downward water-movement are 3.57 cm/day at point 1 and 4.28 cm/day at point 3 as shown in Fig. 9 and 10. The first peaks on the observed profiles are slightly lower than those on the calculated one, presumably due to the adsorption of the tritium on the soil. These show that the equation is one possible interpretation of these profiles.

It is due to the formation of fresh rock layer from about 2 meter depth that peaks were observed at the point 2 and 4. If we assume that the sharp peak is plotted on the injection point, the mean velocity of downward

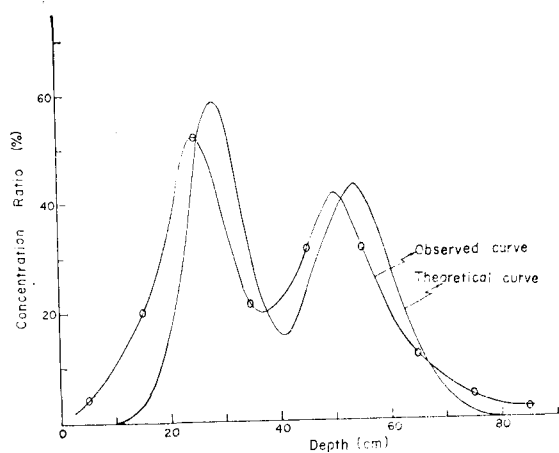


Fig. 10. Distribution Ratio of Tritium in the Point 3

Table 9. Diffusion coefficients of THO at A-site

Run Number	Diffusion Coefficient(cm <sub>2</sub> /sec)			
	Point 1	Point 2	Point 3	Point 4
1	2.12×10 <sup>-5</sup>	1.88×10 <sup>-5</sup>	4.18×10 <sup>-5</sup>	1.18×10 <sup>-5</sup>
2	2.43×10 <sup>-5</sup>	2.12×10 <sup>-5</sup>	3.73×10 <sup>-5</sup>	1.36×10 <sup>-5</sup>
3	2.31×10 <sup>-5</sup>	2.21×10 <sup>-5</sup>	4.03×10 <sup>-5</sup>	1.35×10 <sup>-5</sup>
4	2.25×10 <sup>-5</sup>	1.95×10 <sup>-5</sup>	3.97×10 <sup>-5</sup>	1.16×10 <sup>-5</sup>
5	2.19×10 <sup>-5</sup>	2.05×10 <sup>-5</sup>	4.25×10 <sup>-5</sup>	1.05×10 <sup>-5</sup>
Average Value	2.26×10 <sup>-5</sup>	2.04×10 <sup>-5</sup>	4.03×10 <sup>-5</sup>	1.21×10 <sup>-5</sup>

water-movement at the point 2 and 4 3.43 and 2.43 cm/day, respectively (Table 10).

By Marter and Aiken<sup>23)</sup>, a percolation rate of 21.2—27.3 cm/day has been reported for saturated flow but only 3.0 cm/day or less for unsaturated flow.

Many theories on the migration of radionuclides have been developed for radionuclides migrating unidirectionally through homogeneous geological formations. Inoue<sup>24)</sup>, however, developed a theoretical equation<sup>4)</sup> which could be used for the migration of radionuclides through actual field strata.

$$\frac{V}{V_A} = 1 + \frac{1-P}{S \cdot P} \rho K_d \quad (4)$$

where  $V$  is the movement of ground water,  $V_A$

Table 11. Migration rates of radiostrontium and radiocesium

Sampling Point	Porosity	Density (g/cm <sup>3</sup> )	Saturation factor	Distribution Coefficient(ml/g)		Migration Rate (cm/day)	
				Sr-90	Cs-137	Sr-90	Cr-137
1	0.484	2.42	0.82	254	113	$4.46 \times 10^{-3}$	$10.0 \times 10^{-3}$
2	0.479	2.90	0.82	216	121	$4.12 \times 10^{-3}$	$7.35 \times 10^{-3}$
3	0.431	2.65	0.73	239	82	$3.73 \times 10^{-3}$	$10.9 \times 10^{-3}$
4	0.512	2.23	0.86	124	98	$7.90 \times 10^{-3}$	$9.99 \times 10^{-3}$

is the migration rate of a radionuclide  $A$  through porous media,  $P$  is the porosity of the soil,  $\rho$  is the density of the soil,  $K_d$  is the distribution coefficient of the nuclide  $A$ , and  $S$  is the saturation factor.

Radionuclides in the solution extracted with distilled water were not detected and then migration rates of the nuclides were measured by the field test. It is estimated to be due to the lower activity and the short travel time of tracers (Sr-90 and Cs-137). It is also considered that all of these nuclides were fixed on the soil surfaces. After 300 days about 95% of the total activity applied is retained in the first 10 cm of the soil. Between a depth of 10 and 20 cm a slight concentration of radionuclides is noticeable.

Frederikson et al<sup>25)</sup> showed that 12 months after contamination with <sup>106</sup>Ru, <sup>137</sup>Cs and <sup>144</sup>Ce at least 80% of the contamination was found in a layer 2.5 cm below the surface. Peirson and Salmon<sup>26)</sup> pointed out that 80% of the total world-wide fall-out can be found in a layer of 7 cm below the surface.

The migration of radionuclides was determined by equation<sup>4)</sup> and the results are listed in Table 11. These approaches to the previous data<sup>27)</sup>. The nuclides at each point migrate much more slowly than the water. The distribution coefficients of the nuclides showed the same trend as shown in Table 5 and 6. The results indicated that the affinity of the soils for strontium is higher than that for cesium. It is also shown

that strontium at each point migrate more slowly than cesium. The slight downward movement of the nuclides in this soil is probably due to its high exchange capacity.

## 6. Conclusion

This study showed that the tritiated water can be used to trace the movement of ground water. The observed distribution of tritium compared with that calculated by a mathematical model based on diffusivity process.

The migration rate of radionuclides (Sr-90 and Cs-137) in the ground is very slow, about 95% of the total activity can be found in the first 10 cm below the injection surface.

These facts shown clearly that the migration of nuclides is effectively restricted by the exchange capacity of soil to hold radionuclides although the soil has less exchange capacity in unit volume than that of an artificial ion-exchange resin.

## Acknowledgement

The authors wish to acknowledge Dr. S.J. Park, Office of Rural Development, for his discussion during the course of this work and to thank the International Atomic Energy Agency for supporting this work.

## Reference

1. Uranium Resources, Atom No. 335, p. 151

- (1976)
2. J. W. Fenimore, *Health Phys.*, 10, p. 229 (1964)
3. J. W. Enders, *Disposal of Radioactive Wastes into the Ground*, I. A. E. A., p. 17 (1967)
4. C. E. Linderoth and D. W. Pearce, TID-7621, p. 7 (1961)
5. B. L. Schmalz, TID-7621, p. 17 (1961)
6. R. E. Brown, D. W. Pearce, and C. M. Patterson, *Proc. Sec. U.N. Int. Conf. Peac. Uses Atom. Energy*, Geneva, p. 95 (1958)
7. W. de Laguna, K. E. Cowser, and F. L. Parker, *Proc. Sec. U.N. Int. Conf. Peac. Uses Atom. Energy*, Geneva, p. 101 (1958)
8. L. D. Bayer, *Soil Physics*, John Wiley and Sons, Inc., New York (1966)
9. A. Klute, *Laboratory Measurement of Hydraulic Conductivity of Saturated Soil*, Methods of Soil Analysis 1, Madison, Wisconsin (1965)
10. M. C. Jackson, *Soil Chemical Analysis*, Prentice Hall, Inc., Englewood Cliffs, N. J. (1964)
11. A. I. Vogel, *A Text-Book of Quantitative Inorganic Analysis*, Longmans, London (1961)
12. E. B. Sandell, *Ph. D. Colorimetric Determination of Traces of Metals*, Interscience Publishers Inc., New York (1959)
13. R. E. Lewis, T. A. Butler, and E. Lamb, ORNL 3765 (1965)
14. K. Jerzaghi, and R. B. Peck, *Soil Mechanics in Engineering Practice*, John Wiley and Sons, New York (1948)
15. D. W. Taylor, *Fundamentals of Soil Mechanics*, Wiley, New York (1948)
16. A. S. Rogowski and T. Tamura, *Health Phys.*, 11, p. 1393 (1965)
17. S. Iwai, Y. Inoue, and K. Nishimaki, *J. Japan A. E. Soc.*, 10, p. 435 (1968)
18. Y. Inoue, and W. J. Kaufman, *Health Phys.*, 9, p. 750 (1963)
19. D. R. Nielsen, J. W. Biggar, and J. C. Corey, *Soil Sci.*, 113, p. 254 (1972)
20. E. R. Bennett and W. J. Kaufman, *Sanitary Eng. Res. Lab. Report No. 67-8*, Univ. of Calif. (1967)
21. B. I. Schmalz and W. L. Polzer, *Soil Science*, Vol. 108, p. 43 (1969)
22. D. B. Smith and P. C. Wearn, *Isotope Hydrology*, I. A. E. A., p. 73 (1970)
23. W. I. Marter and S. C. Aiken, *Disposal of Radioactive Waste into the Ground*, I. A. E. A., p. 951 (1967)
24. Y. Inoue, *Disposal of Radioactive Waste into the Ground*, I. A. E. A., p. 169 (1967)
25. L. Frederiksson et al., *Proc. Conf. Peaceful Uses Atom. Energy*, Vol. 18, UN, N. Y. p. 449 (1958)
26. D. H. Peirson and L. Salmon, *Nature*, Vol. 184, 1678 (1959)
27. Y. Inoue and S. Marisawa, *J. Atomic Energy Soc. of Japan*, Vol. 14, p. 522 (1972)