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ENVIRONMENTAL IMPACT ASSESSMENT OF RADIONUCLIDE TRANSPORT AT THE TRIGA REACTOR, KOREA

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The simulation of radionuclide transport at the TRIGA reactor site was carried out to analyze the distribution of residual radionuclide concentrations around the reactor site after reactor decommissioning. The soil within the study area was sampled and its hydraulic conductivity, porosity, moisture content, and distribution coefficient were measured in the laboratory. Simulation results around the reactor site show the following: the section influenced most critically by the residual radionuclides is within 150 m of the reactor building and a stream in front of the reactor. An average flow velocity of groundwater around the TRIGA reactor site is 0.6~1.8 m/sec. The residual radionuclide concentrations are reduced to about 0.3 percent at a distance of 15 m from the reactor. The stream, located at a distance of 150~200 m, is only slightly affected by residual radionuclides.

INTRODUCTION

The simulation of the underground, long-term radionuclide migration around the TRIGA reactor site, Korea, was studied in an effort to release the site to unlimited reuse after reactor decommissioning. The degree of radioactive impact on the area around the TRIGA reactor by residual radionuclides was modeled in this study. First, streams, valleys, ridges, and the water table in the study area were investigated to establish model boundary conditions. Second, the soil in the study area was sampled and its hydraulic parameters were measured. Third, assuming that the TRIGA reactor site was contaminated by ^{137}Cs, ^{90}Sr, and ^{60}Co with an average concentration of 1.0 mg/l due to reactor decommissioning, the degree of radioactive impact on the area around the TRIGA reactor after 5, 10, 20, and 30 years was analyzed using a 3-dimensional numerical model.

TOPOGRAPHY AND WATER TABLE

The TRIGA reactor was located northeast of Seoul, Korea. Boundary conditions have to be established to simulate the TRIGA area. The north boundary is the stream in the Barrae Valley, and the south boundary is the Sinnae stream. The east boundary is a mountain ridge 80-100 m above sea level, and the west boundary is east longitude 127°04'31". The area surrounded by the boundaries is the study area (Figure 1). The north-south length of the study area is about 3.0 km, and the east-west length is about 1.6 km, and the study area is 3.8 km^2. The study area was divided into four layers for model simulation. The upper side of the first layer is the water table, its thickness is 3 m. The thickness of the second and third layers are 7 and 20 m. The bottom of the fourth layer is 38 m below the sea level, and its thickness varies from 30-100 m. The configuration of the water table and the four layers are shown in Figure 2.

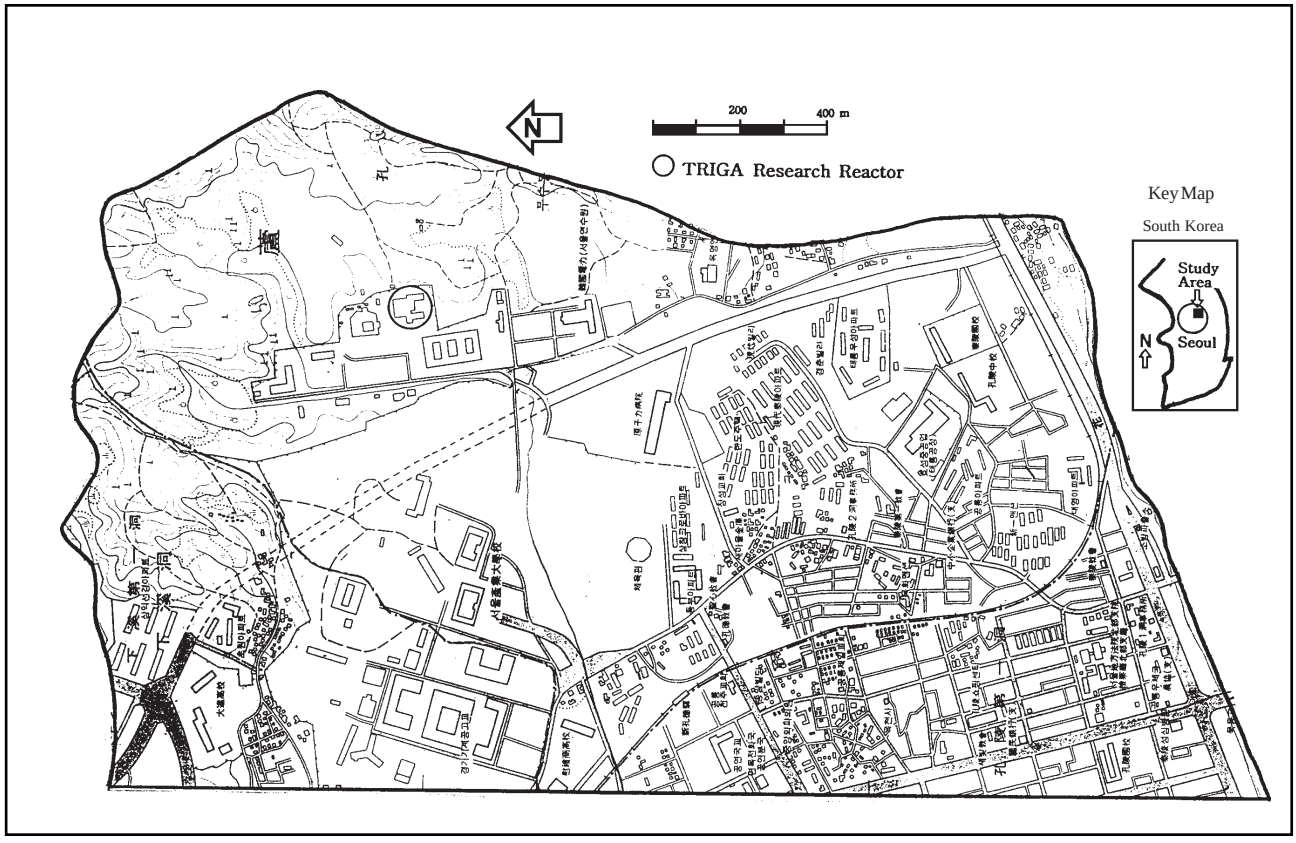

Figure 1. Location and topographical map of the study area.

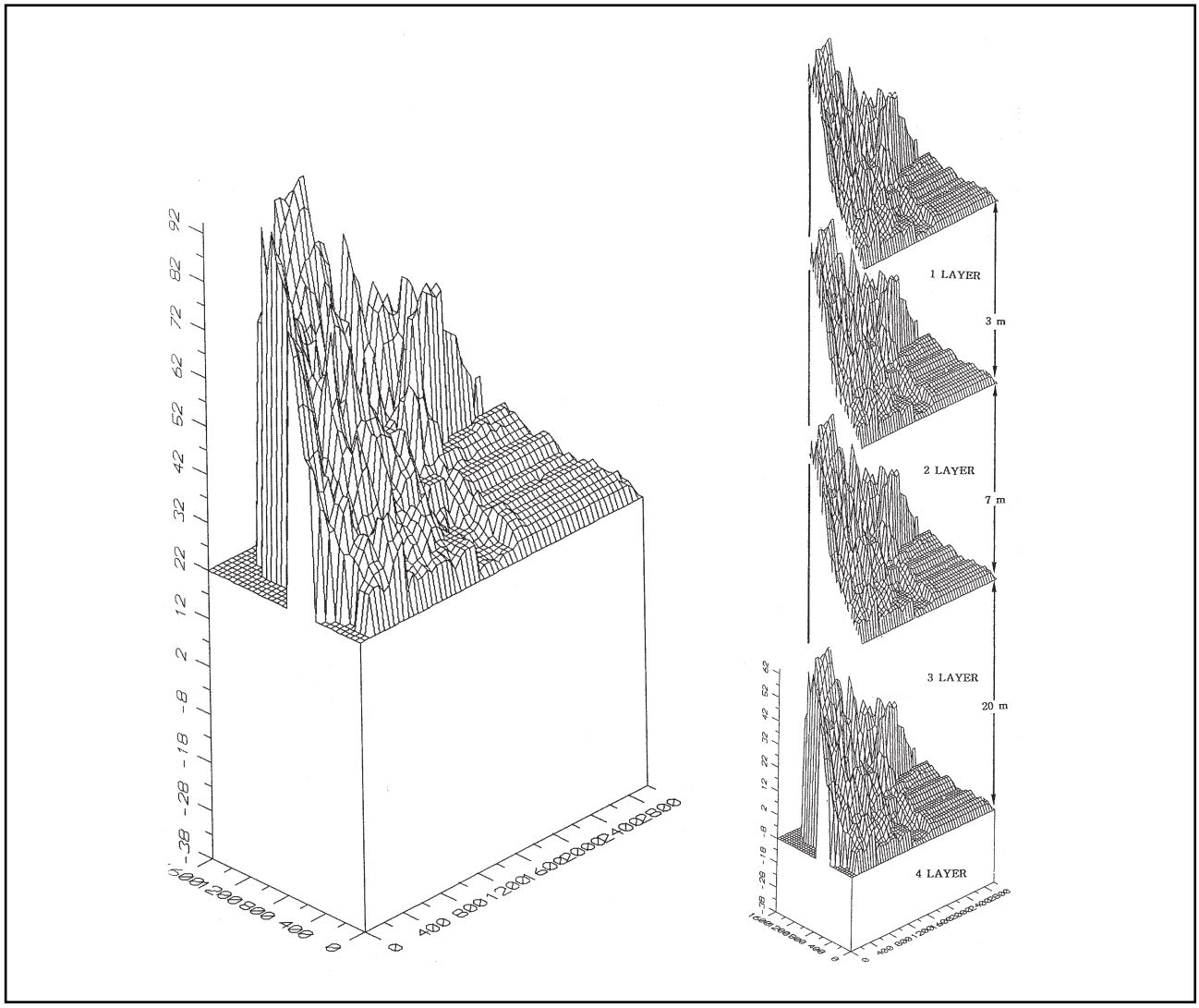

Figure 2. Configuration of the water table and model layers.

The method for computing the water table is as follows. First, the water table at the streams in the study area was determined by the elevations of the stream surfaces from sea level, and at other points were computed based on the point elevations and the distance between the stream and points (Figure 2).

MEASUREMENT OF FIELD HYDRAULIC PARAMETERS

A clay layer about 7 cm thick covers the surface of the study area, while the lower layer consists of silty sandstone as shown in Figure 3.

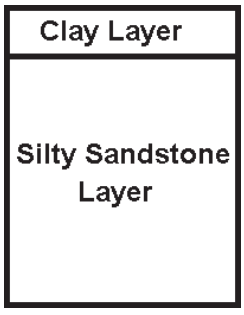

Figure 3. Rock and soil in the study area.

The hydraulic conductivity of the silty sandstone, which is high, was measured by a constant-head method. For the clay, which has a low hydraulic conductivity, the falling-head method was used. The hydraulic conductivities are given in Table 1.

Table 1. Hydraulic Conductivity of Each Layer

Layer		**Horizontal hydraulic conductivity (m/sec)**	**Vertical hydraulic conductivity (m/sec)**
Clay layer		2.9×10^{-8}	--
Silty Sandstone	1st Layer	8.0×10^{-7}	5.0×10^{-7}
	2nd Layer	3.0×10^{-7}	3.0×10^{-7}
	3rd Layer	2.0×10^{-7}	2.0×10^{-7}
	4th Layer	1.0×10^{-7}	1.0×10^{-7}

Porosity (n) was calculated by the following equation .

$$n = 1 - \frac{\rho_b}{\rho_s} \tag{1}$$

ρ_b = Bulk density

ρ_s = Solid particle density

Moisture content (θ) was calculated by the following equation where V_w is the remaining weight, subtracting dry weight of the sample from the total weight, V_T. The porosity and moisture content of each layer are listed in Table 2.

$$\theta = \frac{V_w}{V_T} \tag{2}$$

Table 2. Porosity and Moisture Content of Each Layer

Layer		**Porosity**	**Moisture Content**
Clay layer		29.3	16.7
Silty Sandstone	1st Layer	20	12.7
	2nd Layer	14	--
	3rd Layer	12	--
	4th Layer	10	--

Sedimentary and silty sandstone have similar dispersivity. The dispersivity of the sediments measured directly using a tracer is listed in Table 3 (Han, 1988). The longitudinal dispersivity of silty sandstone is assumed to 30 m and transverse dispersivity is assumed to be 10 m.

Table 3. Dispersivity of Sediments

Field test area	Long. dispersivity (m)	Trans. dispersivity (m)	Test range (m)
Alsace, France alluvial sediments	12	4	--
Rocky Mtn. Arsenal alluvial sediments	30.5	30.5	305
California alluvial sediments	30.5	9.1	305
Arkansas River Valley coalluvial sediments	30.5	30.5	660

The diffusion coefficients of radionuclides in sandstone are given in Table 4 (Jeon, 1995).

Table 4. Diffusion Coefficient of Sandstones

Radionuclides	Diffusion coefficient
Cs	1.0×10^{-12}
Sr	1.0×10^{-11}
Co	3.0×10^{-14}

The procedure for measuring the distribution coefficient of phenol is as follows. First, phenol samples of 5, 10, 20, and 40 mg/l were prepared. Then 2g of dry soil sampled near the reactor was put into each phenol sample of 200 ml. The initial concentration of the phenol sample was measured by the ultraviolet method, and the equilibrium concentration (mg/l) of phenol was measured by an isothermal adsorption test. The mass adsorbed phenol (mg/kg) to equilibrium concentration was plotted and the slope of the plotting line is the distribution coefficient (K_d). The distribution coefficients of radionuclides are given in Table 5 (Jeon, 1995).

Table 5. Distribution Coefficient of Radioactive Nuclides and Phenol (unit : ml/g)

Radionuclides	Concrete	Activated Carbon	Silty Sandstone	Clay
Cs	0.01	20	--	--
Sr	0.01	--	--	530
Co	1000	30000	--	--
Phenol	--	--	1.90	3.14

The radionuclides that leaked from the TRIGA reactor and their half lives are given in Table 6.

GROUNDWATER FLOW MODELING

To analyze the groundwater flow system around the TRIGA reactor, MODFLOW (McDonald and Harbaugh, 1988) developed by U.S. Geological Survey was used. This model uses a finite

Table 6. Half Life of Radionuclides

Radionuclides	A half life	λ (1/yr)
^{137}Cs	30	2.31E-2
^{90}Sr	29.1	2.38E-2
^{60}Co	5.27	1.31E-1

difference method and its governing equation is:

$$\frac{\partial}{\partial x}(K_x \frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(K_y \frac{\partial h}{\partial y}) + \frac{\partial}{\partial z}(K_z \frac{\partial h}{\partial z}) = S_s \frac{\partial h}{\partial t} \quad (3)$$

Where

K_x, K_y, K_z : Hydraulic conductivity (LT^{-1})

h : Hydraulic head (L)

S_s : Specific storage(L^{-1})

t : Time(T)

To examine the modeling results of groundwater flow and the transport of radionuclides more precisely, a base map of the study area was prepared (Figure 4). This base map shows locations of the boundaries of the study area, the TRIGA reactor, the university, atomic energy hospital, and apartments.

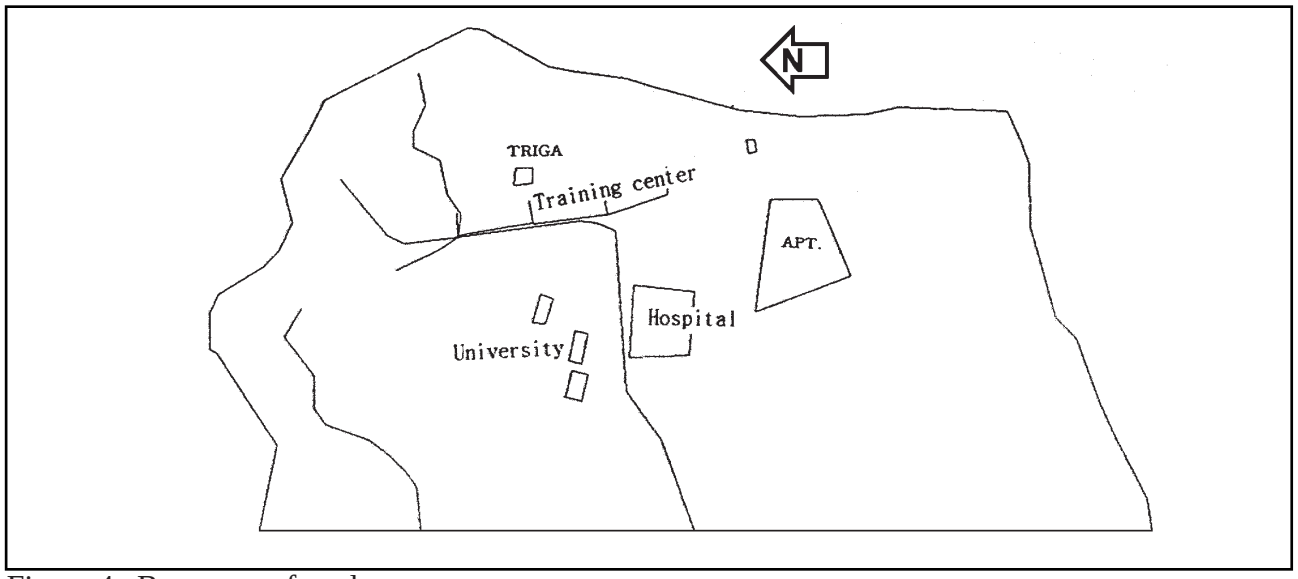

Figure 4. Base map of study area.

The size of the study area is 3,000 x 1,600 m and the number of finite difference cells in the XY direction is 60 x 32 = 1,920 (Figure 5). The size of each cell is 50x50 m. Also, the study area consists of 4 layers. The total number of finite difference cells is 7,680.

The streams on the north and south boundaries were treated as constant head. The ridge on the east boundary was treated as an impermeable boundary due to a divide. The east longitude 127°04'31" line in the west boundary was treated as a constant head. The upper boundary is the water table and

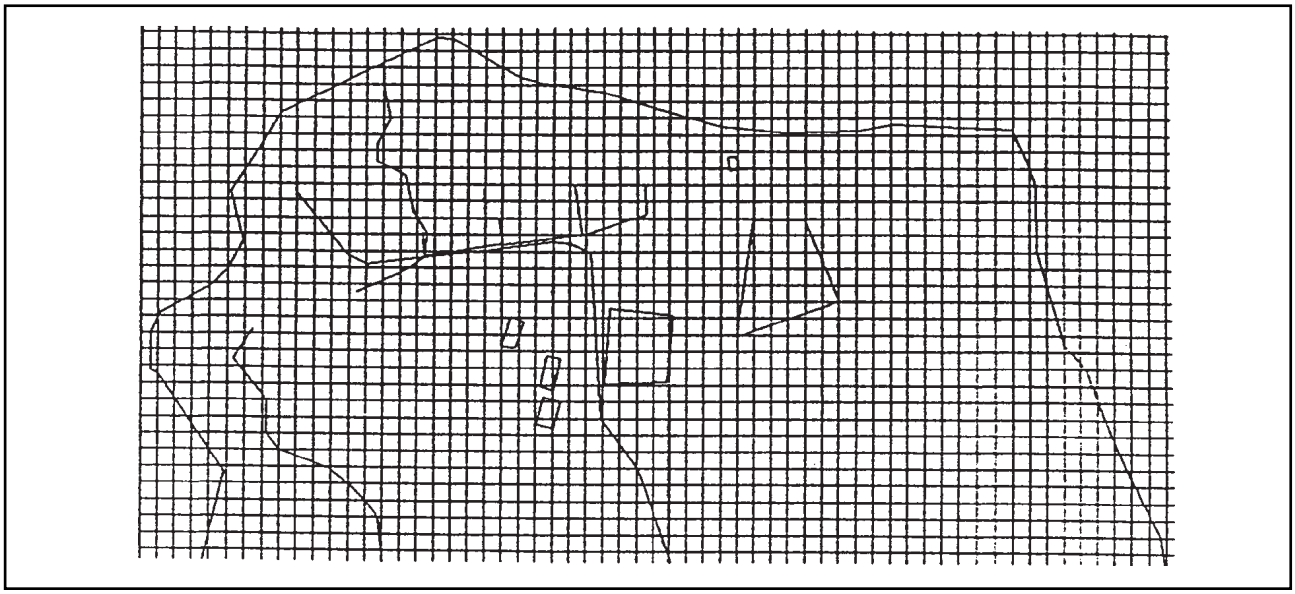

Figure 5. Finite difference net about study area,

the bottom boundary was treated as an impermeable boundary due to a relatively small hydraulic conductivity. The initial value at each node in the boundaries was assumed to be 50 m

The input parameters required for the analysis of groundwater flow are hydraulic conductivity and porosity. They were input on the basis of the above-mentioned measured and assumed values. The groundwater flow was assumed to be steady-state.

The results of the modeling analysis on groundwater flow are shown in Figure 6. A stream is

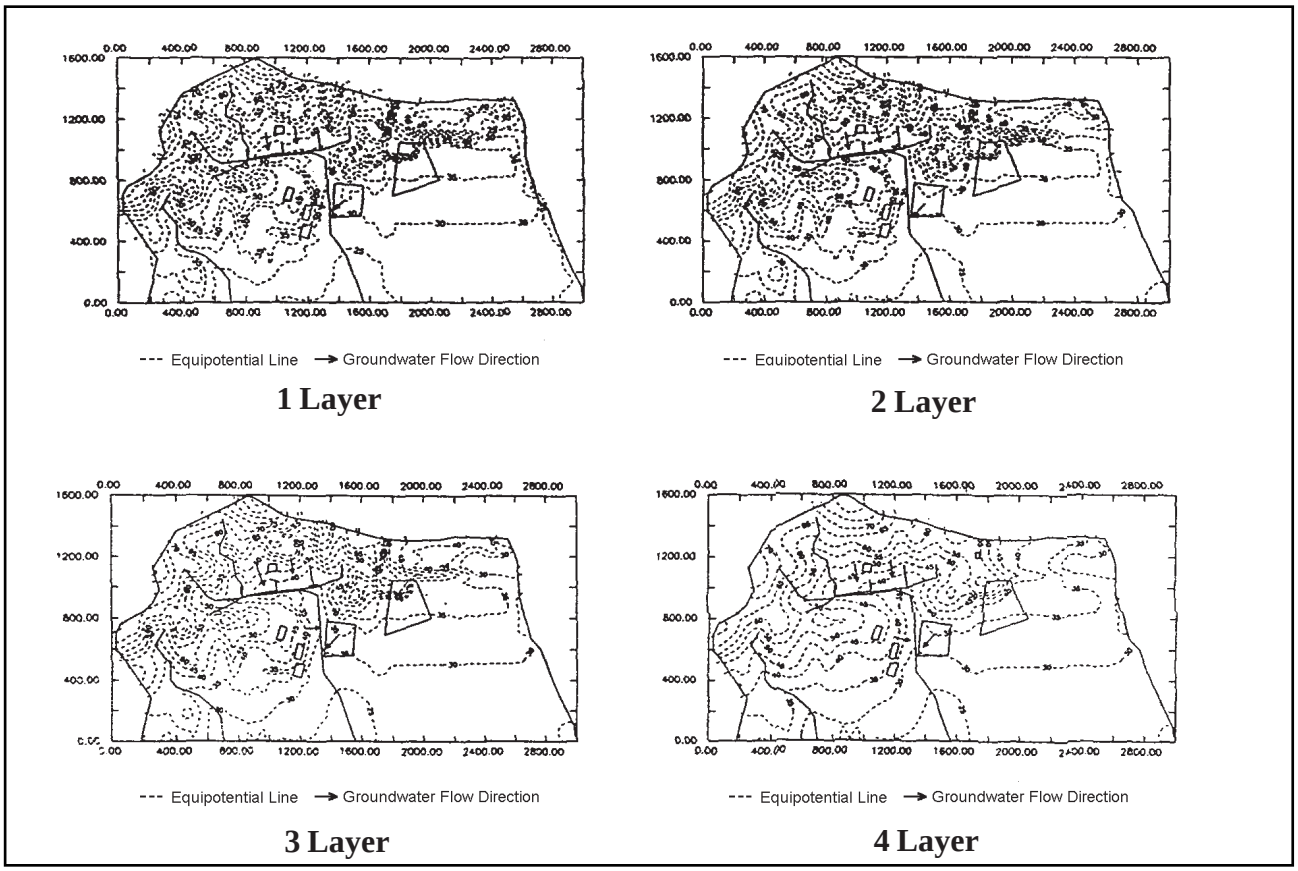

Figure 6. Groundwater flow modeling in layers 1, 2, 3, and 4.

located about 200 m away from the TRIGA reactor in a northerly direction. The stream flows in a westerly direction from the mountain, then south in front of the reactor, then in a westerly direction again. The groundwater under the reactor is mixed with the groundwater flowing in from the mountain, and then flows to the stream. The groundwater under the University of Seoul Industry flows into the stream in a southerly direction. The groundwater under the Atomic Energy hospital flows into the stream in a northwesterly direction. A groundwater pathway that could inflict the most critical damage with radionuclide contamination is assumed to be in the 150 m section from the reactor to the stream in a westerly direction. Meanwhile, the hydraulic head distribution systems in the second, third and fourth layers are similar to that in the first layer, but the hydraulic heads in the east section of each layer in the study area decrease as the layer increases from the second to fourth layer. On the other hand, those of the west section increase as the layer increases from the second to fourth layer. The average flow velocity of groundwater at the study site is analyzed to be 0.6-1.8 m/year.

RADIONUCLIDE TRANSPORT MODELING

To analyze radionuclide transport, MT3D (Zheng, 1990) was used. MT3D uses the finite difference method, and can exchange data with MODFLOW. Its governing equations are:

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} - v\frac{\partial C}{\partial t} + \frac{\rho_b}{n}\frac{\partial S}{\partial t} - \lambda(C + \frac{\rho_b}{n}S)$$
$$S = k_d C \qquad (4)$$
$$D = \alpha v + D^*$$

ρ_b: Bulk density (M/L3)

C : Contaminant concentration (M/L3)

S : Adsorption concentration (M/M)

t : Time(T)

v : Flow velocity (L/T)

D : Dispersion coefficient (L2/T)

λ : Material decay constant (T)

D^*: Molecular diffusion coefficient (L2/T)

α : Longitudinal or transverse dispersivity

Assuming that the TRIGA reactor was contaminated by ^{137}Cs, ^{90}Sr, ^{60}Co at an average concentration of 1.0 mg/l due to an unexpected accident, the radionuclide concentrations distributed in each layer around the TRIGA reactor after 5, 10, 20 and 30 years were calculated with MT3D.

The input parameters required for the analysis of radionuclide transport are dispersion coefficient, material decay constant, and distribution coefficient. Those were input on each layer on the basis of the above-mentioned measured and assumed values.

The radionuclide transport modeling used the groundwater flow velocity calculated with MODFLOW as input and was executed on each layer. The radionuclide concentrations distributed in each layer after 5, 10, 20 and 30 years were calculated with MT3D.

The ^{137}Cs concentrations distributed around reactor in the first layer after 5 years, assuming ^{137}Cs, with an average concentration of 1.0 mg/l contaminated the inside of the reactor site, is shown in Figure 7(a). Figure 7(b) shows an enlargement of the circumference of the TRIGA reactor. The radionuclide concentrations distributed in each layer after 5, 10, 20, and 30 years were calculated with MT3D, and the results are shown in Figures 8 to 10.

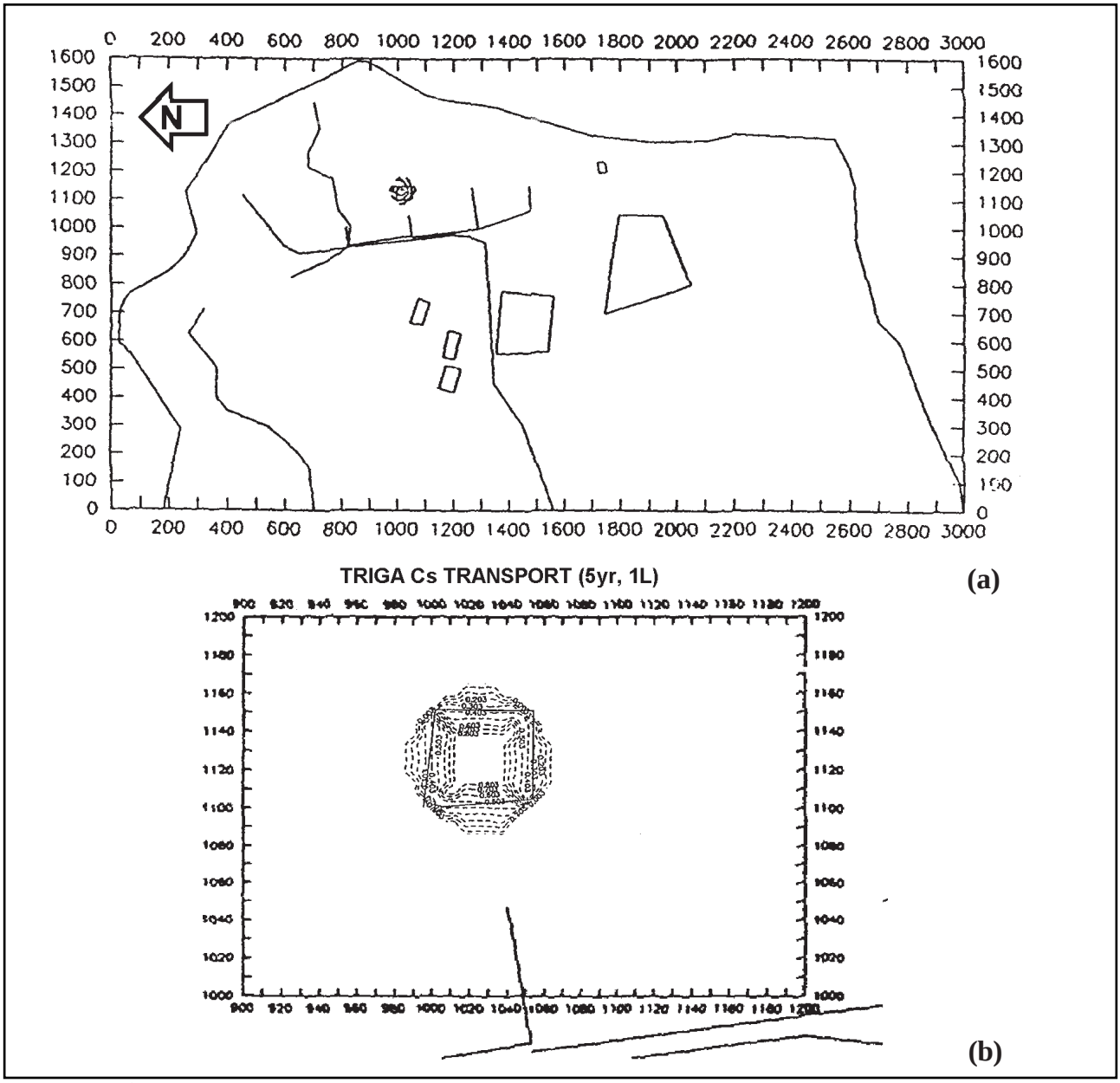

Figure 7. ^{137}Cs concentration in first layer of the study area after 5 years.

Figure 8 is the concentration distribution chart of ^{137}Cs in each layer over time. First, the first layer shows an average concentration at the boundaries after 5 years of about 0.39 mg/l, and after 10, 20 and 30 years 0.31, 0.23 and 0.14 mg/l respectively. The concentrations at points about 15 m away from the boundary lines of the reactor are about 0.003 mg/l for all time steps. The second layer shows an average concentration at the boundary lines after 5 years at about 0.011 mg/l. After 10, 20 and 30 years the values are 0.018, 0.026, and 0.026 mg/l respectively. The concentrations at points about 10 m away from the boundary lines are about 0.01 mg/l for all time steps. Meanwhile, the concentrations at the reactor circumference in the third and fourth layers are below 0.001 mg/l.

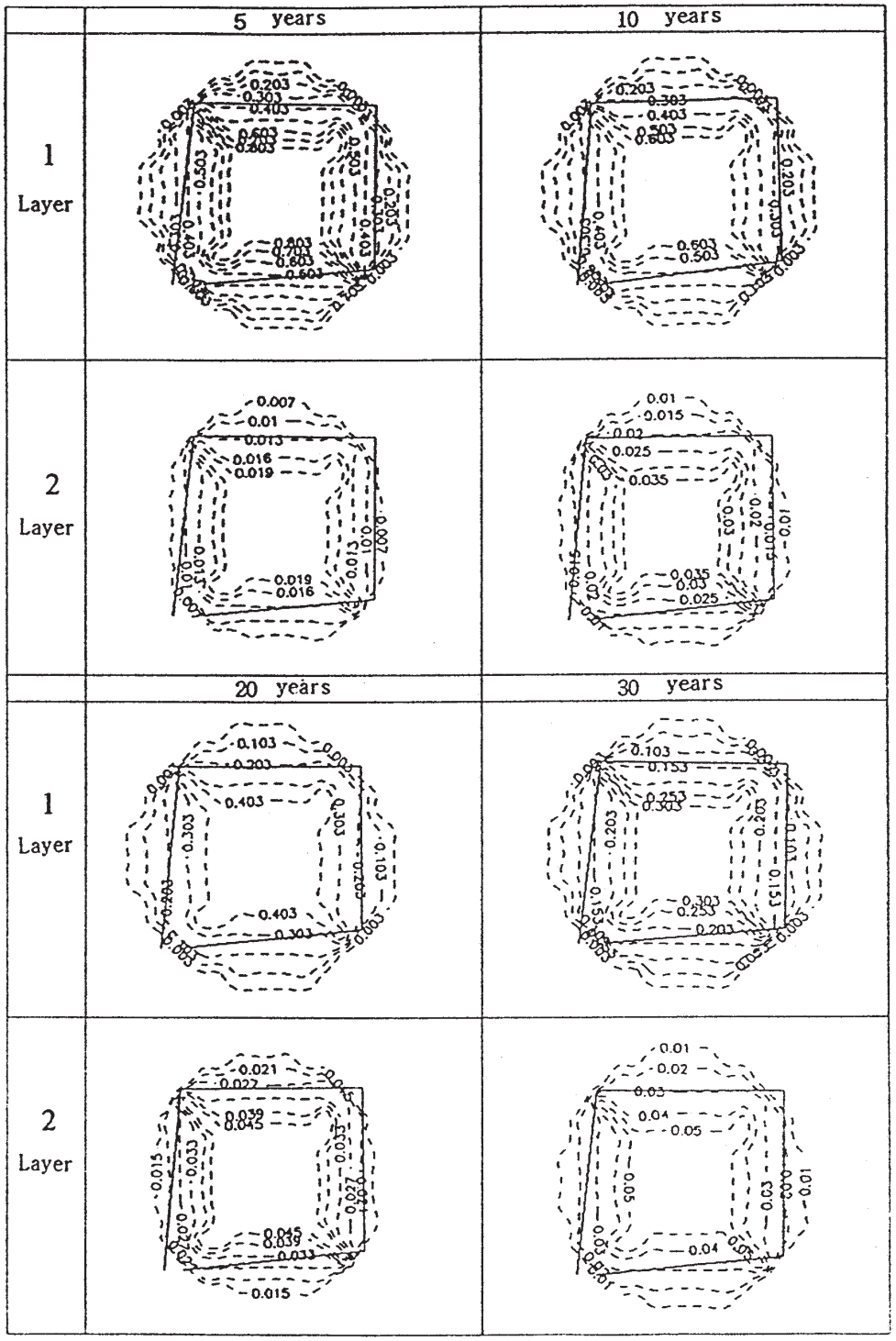

Figure 8. ^{137}Cs concentration near the TRIGA reactor along time.

Figure 9 is the concentration distribution chart of ^{97}Sr in each layer over time. The first layer shows that an average concentration at the boundary lines of the TRIGA reactor after 5, 10, 20 and 30 years is 0.38, 0.30, 0.21, and 0.13 mg/l respectively. The concentrations at points about 15 m away from the boundary lines of the reactor are 0.003 mg/l for all time steps. The second layer shows that an average concentrations at the boundary lines after 5, 10, 20 and 30 years are 0.011, 0.018, 0.025,

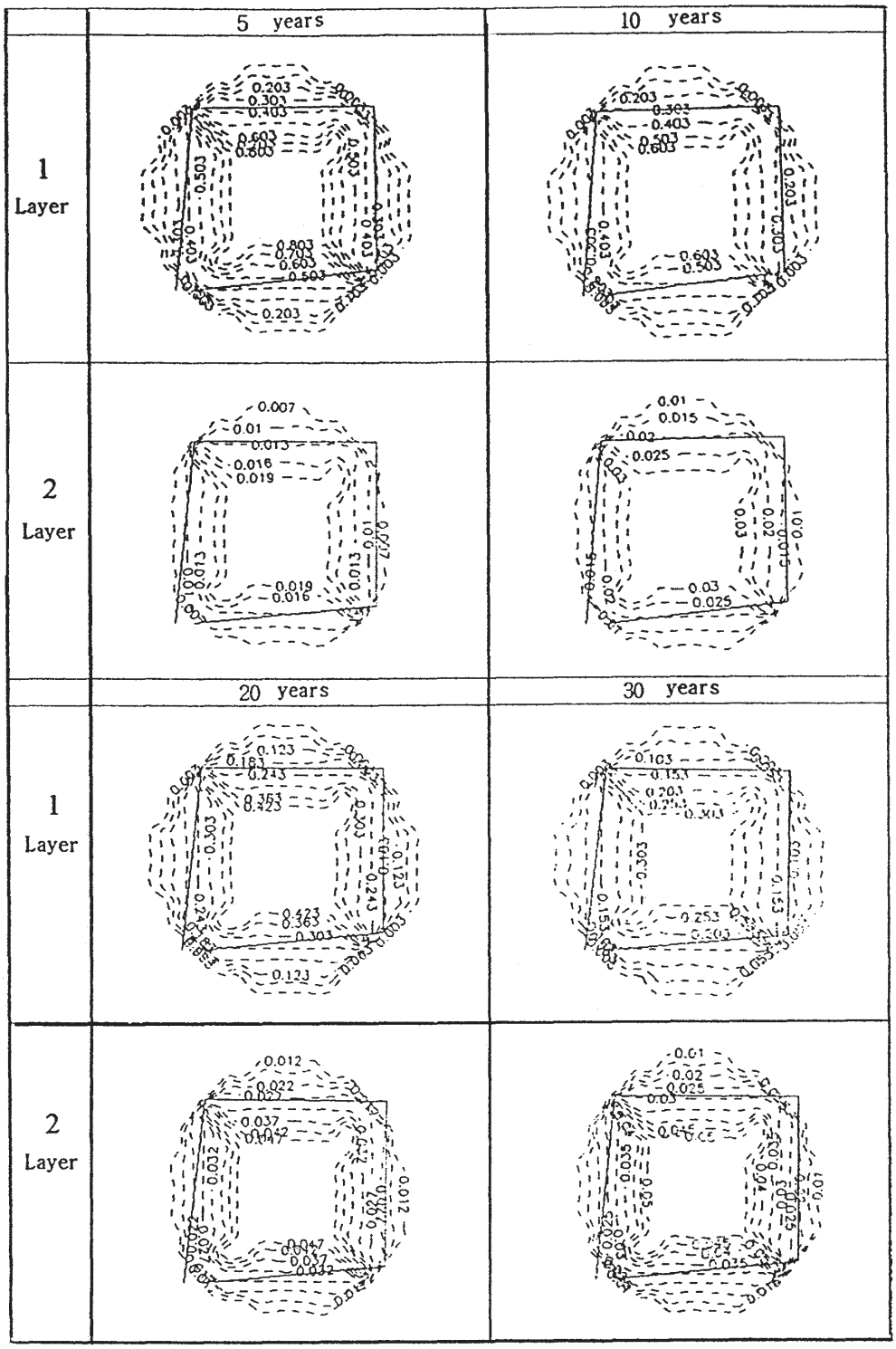

Figure 9. ^{90}Sr concentration distribution near the TRIGA reactor along time.

and 0.026 mg/l, respectively. The concentrations at points about 10 m away from the boundary lines are about 0.01 mg/l for all time steps. Meanwhile, the concentrations in the third and fourth layers are below 0.001 mg/l.

Figure 10 shows the concentration distribution chart of ^{60}Co in each layer along time. Firstly, the first layer shows that an average concentrations at the boundary lines of the reactor after 5, 10, 20 and

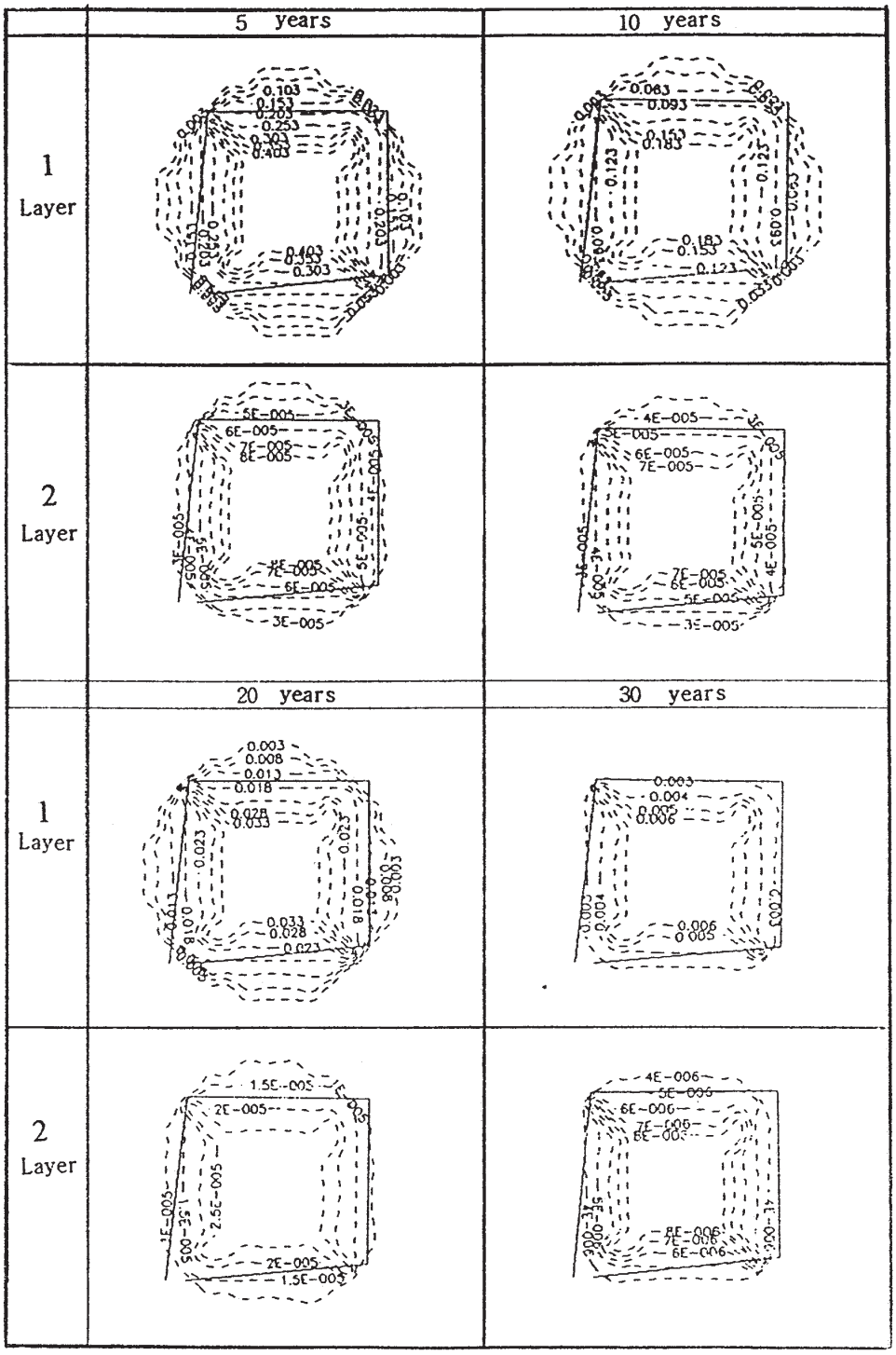

Figure 10. ^{60}Co concentration distribution near the TRIGA reactor along time.

30 years are 0.19, 0.09, 0.02, and 0.003 mg/l, respectively. The concentrations at points about 15 m away from the boundary lines of the reactor stay about 0.003 mg/l up to 20 years but are reduced to below 0.001 mg/l after 30 years. The second layer shows that an average concentration at the boundary lines after 5, 10, 20 and 30 years are 0.000045, 0.00004, 0.000015, and 0.000004 mg/l, respectively. The concentrations at points about 7 m away from the boundary lines are below 0.00003

mg/l. The concentration in the third and fourth layers are below 0.00001 mg/l.

CONCLUSIONS

The groundwater under the TRIGA reactor is mixed with the groundwater flow from a mountain near the reactor, and then flows to a stream in a westerly direction. The groundwater pathway that could inflict the most critical damage with radionuclide contamination is assumed to be the 150 m section from the reactor to the stream in a westerly direction. The average flow velocity of groundwater under the reactor is analyzed to be 0.6-1.8 m/year.

The concentration distributions of ^{137}Cs and ^{90}Sr were similar. The concentrations in the first layer under the TRIGA reactor decreased over time, and the concentrations at points about 15 m away from the boundary lines of the TRIGA reactor are about 0.003 mg/l, The concentrations in the second layer under the TRIGA reactor increased over time, and the concentration levels at points about 10 m away from the boundary lines of the TRIGA reactor are about 0.003 mg/l.

The ^{60}Co concentrations in the first layer under the TRIGA reactor decreased over time and the concentration at points about 13 m away from the boundary lines of the TRIGA reactor are about 0.03 mg/l. The ^{60}Co concentrations in the second layer decreased over time, and the concentrations at points about 7 m away from the boundary lines of the TRIGA reactor are about 0.00003 mg/l.

As mentioned above, the radionuclides concentrations after decommissioning are reduced to 0.003 mg/l in less than 15 m from the boundary lines of the reactor site. Thus, the stream, which is located about 150-200 m away from reactor site is not influenced by the radionuclides. It is concluded that radionuclides that leaked from the TRIGA reactor after decommissioning have not had significant environmental impact in the area around the TRIGA reactor.

ACKNOWLEDGMENT

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