Journal of the Korean Nuclear Society
Volume 34, Number 3, pp.232~241, June, 2002

A Case Study on the Safety Assessment for Groundwater Pathway in a Near-Surface Radioactive Waste Disposal Facility

JooWan Park, KeunMoo Chang, and ChangLak Kim
Nuclear Environment Technology Institute
150 Dukjin-dong, Yuseung-gu, Daejon, 305-353, Korea
p5j9w@khnp.co.kr

(Received October 24, 2001)

Abstract

A safety assessment is carried out for the near-surface radioactive waste disposal in the reference engineered vault facility. The analysis is mainly divided into two parts. One deals with the release and transport of radionuclide in the vault and unsaturated zone. The other deals with the transport of radionuclide in the saturated zone and radiological impacts to a human group under well drinking water scenario. The parameters for source-term, geosphere and biosphere models are mainly obtained from the site specific data. The results show that the annual effective doses are dominated by long lived, mobile radionuclides and their associated daughters. And it is found that the total effective dose for drinking water is far below the general criteria of regulatory limit for radioactive waste disposal facility.

Key Words : safety assessment, groundwater scenario, near-surface radioactive waste disposal facility

1. Introduction

It is generally accepted that eventually radionuclides in the radioactive wastes will be released and that these radionuclides will be transported to the accessible environment, initially through the groundwater system in the geosphere and subsequently through surface processes within the biosphere at the disposal site. Therefore, the long-term safety assessment of near-surface radioactive waste disposal should be described by modeling potential releases of radionuclides from vault, their movement through the geosphere, the resulting distribution of radiological contamination in the biosphere, and the consequent health risk to humans.

In this study, the radiological impact of radionuclides on a critical human group is evaluated for the reference near-surface radioactive waste disposal facility in Vaalputs, South Africa as a part of the IAEA coordinated research program on improvement of safety assessment methodologies (ISAM)[1,2]. This disposal facility is composed of 20 concrete vaults located above ground level and has a total of about 750,000 drums.

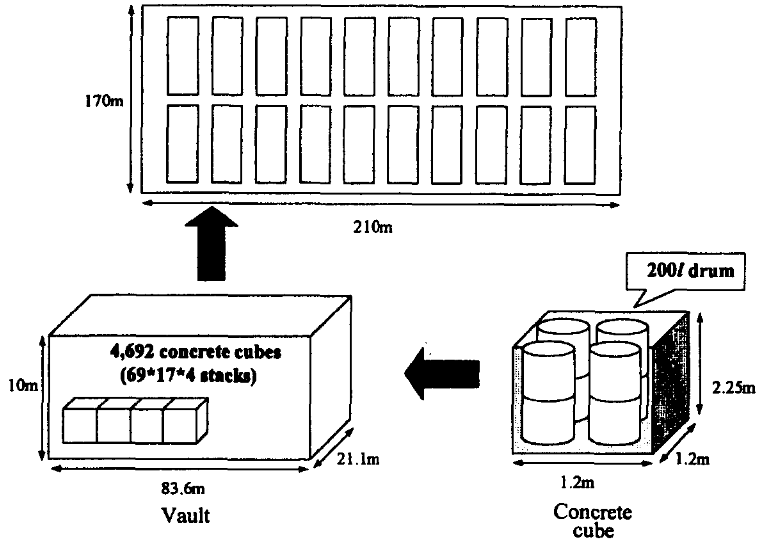

Fig.1. Layout of Disposal Vault and a Stack of Concrete Cube Containing 200 Liter Drums

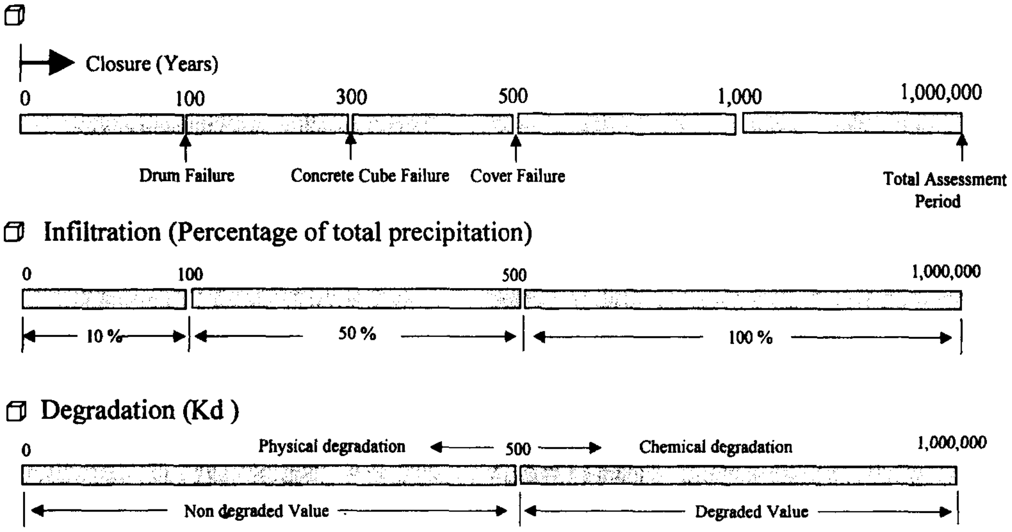

Fig.2. Time Frame to Reflect the Degradation of Near Field

The analysis deals with the drinking water scenario from a well, which is considered to provide the conservative results. The parameters for the modeling of source-term, geosphere and biosphere are mainly obtained from the site specific data. The release and transport of radionuclides in the vault and unsaturated zone are simulated by using DUST-MS[3]. GWSCREEN[4] is also used to model the transport of radionuclides in the saturated zone and radiological safety assessement. The analyses are coupled in such a way that the radionuclide mass flux at the bottom of the unsaturated zone by DUST-MS is used as input data for GWSCREEN. This approach provides the time variation of effective dose over long-term period after closure of disposal facility[5]. And the results from this approach is compared with those from a compartment modeling approach for the same facility and scenario.

2. Conceptual Model for Safety Assessment

2.1. Near-Field

The disposal facility is a set of 20 concrete vaults located above ground level. Figure 1 shows the spatial layout of vaults in disposal site and a stack of concrete cubes containing 200*l* drums within each vault. The waste disposal area contains two lines of 10 vaults. The approximate dimensions of the disposal area are 170 by 210 m giving a surface area of 35,700m^2.

150,000m^3 of grouted waste is disposed in standard 200*l* drums and placed into concrete cubes, and grout filled in between the drums. The facility has a total of about 750,000 drums (37,500 per vault). Each vault has internal dimensions of 9m high by 20.5m wide by 83m long allowing concrete cubes to be stacked 4 high ×17×69.

Figure 2 illustrates the time frame in safety assessment to represent the physical and chemical degradation of artificial barriers. It is assumed that the near-field barriers degrade with time. The drums are assumed to remain intact for 100 years and the concrete is assumed to physically fail after 300 years of closure and chemically degrade over a 1,000 year period from site closure. The cap is assumed to be maintained during the 100 year active institutional control period but then starts to degrade so that it allows the 50% of total precipitation until 500 years and it no longer limits the rate of water infiltration after 500 years. And the near field is assumed to be degraded chemically after 500 years so that the distribution coefficient for degraded vault is used for the safety assessment. Table 1 lists the radionuclide inventory at facility closure and decay chains considered in safety assessment.

2.2. Far-Field

It is assumed that water infiltrating through the near-field, flows vertically down through the

Table 1. Radionuclide Inventory at Facility Closure and Decay Chains Considered

Nuclide	Inventory(Bq)	Daughters
H-3	1E+15	
C-14	1E+13	
Ni-63	1E+10	
Sr-90	1E+15	
Tc-99	1E+14	
I-129	3E+10	
Cs-137	6E+09	
U-234	8E+15	Th-230→Ra-266→Pb-210
U-238	5E+10	U-234→Th-230→Ra-226→Ph-210→Po-210
Pu-238	2E+10	U-234→Th-230→Ra-226→Pb-210→Po-210
Pu-239	3E+10	U-235→Pa-231→Ac-227
Pu-241	6E+11	Am-241→Np-237→Pa-233→U-233→Th-229
Am-241	2E+10	Np-237→Pa-233→U-233→Th-229
Total	1E+16	

Table 2. Distribution Coefficients for Near-Field and Far-Field Media (m^3 kg^{-1})

Element	Degraded vault	Red sand/ Calcrete	Brown sand/ Gritty clay	White Kaolinite clay	Weathered granite
H	0.0E+0	0.0E+0	0.0E+0	0.0E+0	0.0E+0
C	2.0E-1	5.0E-3	5.0E-3	1.0E-3	5.0E-3
Ni	1.0E-2	4.0E-1	4.0E-1	6.0E-1	4.0E-1
Sr	1.0E-3	8.8E-3	7.1E-3	8.3E-3	5.5E-3
Tc	0.0E+0	1.0E-4	1.0E-4	1.0E-3	1.0E-4
I	1.0E-3	1.0E-3	1.0E-3	1.0E-3	1.0E-3
Cs	2.0E-2	5.4E-1	3.4E-1	2.2E-1	2.6E-1
Pb	5.0E-2	3.0E-1	3.0E-1	5.0E-1	3.0E-1
Po	0.0E+0	1.5E-1	1.5E-1	3.0E+0	1.5E-1
Ra	5.0E-2	5.0E-1	5.0E-1	9.0E+0	5.0E-1
Ac	2.0E-1	3.4E-1	3.4E-1	7.6E+0	3.4E-1
Th	1.0E+0	3.0E+0	3.0E+3	6.0E+0	3.0E+0
Pa	1.0E-1	3.4E-1	3.4E-1	7.6E+0	3.4E-1
U	1.0E-1	2.5E-3	6.8E-3	1.4E+3	3.0E-3
Np	1.0E-1	3.4E-1	3.4E-1	7.6E+0	3.4E-1
Pu	1.0E+0	3.4E-1	3.4E-1	7.6E+0	3.4E-1
Am	2.0E-1	3.4E-1	3.4E-1	7.6E+0	3.4E-1

Table 3. Physical and Hydraulic Properties of Geosphere

Lithology	Depth (m)	Hydraulic conductivity (m/y)	Bulk density (kg/m^3)	Total porosity (-)	Water filled porosity (-)	Longitudinal dispersivity (m)
Red sand/ Calcrete	2.7	0.91	1989	0.33	0.2	0.27
Brown sand/ Gritty clay	8.5	2.37	2230	0.41	0.2	0.85
White Kaolinite clay	8.0	1.86	2160	0.37	0.2	0.80
Weathered granite	35.8	2.37	1683	0.36	0.2	3.58

unsaturated zone and into the saturated zone. Consistent with site specific data, it is assumed that flow in the unsaturated and saturated zones is dominated by fracture flow. It is assumed that radionuclides can be sorbed onto the walls of the fractures. For flow in the unsaturated zone, it is assumed that there are a series of fractures below the disposal facility and that a porous medium approximation can be made to represent flow and transport in the zone. The unsaturated zone is made up of a sequence of four lithologies, starting with the red sand/calcrete at the surface.

In the saturated zone, it is assumed that the water that has percolated down from the

Table 4. Dose Coefficient for Ingestion

Radionuclide	Dose coefficients(adults)
	Ingestion(Sv/Bq)
H-3	1.8E-11
C-14	5.8E-10
Ni-59	6.3E-11
Ni-63	1.5E-11
Sr-90	3.1E-08
Tc-99	6.4E-10
I-129	1.1E-07
Cs-137	1.3E-08
Pb-210	6.9E-07
Po-210	1.2E-06
Ra-226	2.8E-07
Ac-227	1.2E-06
Th-229	6.1E-07
Th-230	2.1E-07
Pa-231	7.1E-07
Pa-233	8.7E-10
U-233	5.1E-08
U-234	4.9E-08
U-235	4.7E-08
U-238	4.8E-08
Np-237	1.1E-07
Pu-238	2.3E-07
Pu-239	2.5E-07
Pu-241	4.8E-09
Am-241	2.0E-07

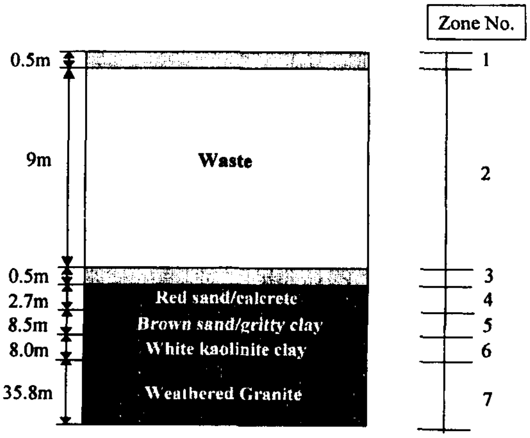

Fig. 3. Conceptual Model for DUST-MS Code

unsaturated zone is intercepted by a series of fractures. Groundwater is abstracted from a well that is 200 m away from the boundary of the disposal area. It is assumed that the series of fractures in the saturated zone that intercept the percolating water from the disposal facility can be represented by a single streamtube. The streamtube yields $2,160m^3y^{-1}$. Based on site specific data, a yield of $8,300m^3y^{-1}$ is assumed from the well. It is therefore assumed that the remaining $6,140m^3y^{-1}$ is derived from other fractures that carry uncontaminated water. And the consumption of drinking water is determined as $0.8m^3y^{-1}$ from the site specific data. Table 2 and 3 summarize site specific data such as distribution coefficients and hydraulic properties of geosphere. Ingestion dose conversion factor shown in Table 4 is taken from internationally recognized data collations[6].

3. Model Development and Governing Equations

3.1. Release and Transport in the Vault and Unsaturated Zone

The release of radionuclides from the vault and their transport through the unsaturated zone are simulated by using DUST-MS. Figure 3 illustrates the conceptual model for DUST-MS code. For source-term modeling, the concentration of radionuclides is homogenized for the whole volumes of repository by repository-averaging process. The diffusion release model is used for the release of radionuclides from the vault. The diffusion equation with radioactive decay is as follows.

$$\frac{\partial C_i(x,t)}{\partial t} = D_i \nabla^2 C_i(x,t) - \lambda C_i(x,t) \qquad (1)$$

where

$C(x,t)$: Concentration within the waste form (Bq/cm^3)

D_f : Waste form diffusion coefficient (cm^2/s)

λ : Radioactive decay constant (s^{-1})

x : Spatial location vector (cm)

t : Time since container failure (s)

One-dimensional finite difference approximation is used to model the transport of radionuclides in the unsaturated zone. The governing transport equation is :

$$\theta R_i \frac{\partial C_i}{\partial t} = \nabla \cdot \theta D_i \nabla C_i + \nabla \cdot V_d C_i - \lambda_i \theta R_i C_i + \sum_{j=i-N}^{i-i} f_{ij} \lambda_j R_j C_j + S_i \quad (2)$$

$$\theta D = a_t V_d + D_m \theta$$

where

C_i : Concentration of the i^{th} contaminant in the aqueous phase (Bq/cm^3)

t : Time (s)

θ : Volumetric moisture content (-)

R_i : Retardation coefficient for contaminant i ($R_i = 1 + \rho K_{d,i}/\theta$)

ρ : Bulk density of the soil (g/cm^3)

$K_{d,i}$: Distribution coefficient for i^{th} contaminant in the porous media (cm^3/g)

θD : Component of the dispersion-diffusion tensor (cm^2/s)

a_t : Transverse dispersion coefficient (cm)

V_d : Darcy velocity through the porous medium (cm/s)

D_m : Molecular diffusion coefficient corrected for tortuosity through the porous medium (cm^2/s)

λ_i : Radioactive decay constant of contaminant i (s^{-1})

f_{ij} : Fraction of decays of contaminant i that form contaminant j (–)

N : Number of contaminants in the simulation

S_i : External source injection rate per unit volume which includes release from the waste form (Bq/cm^3s^{-1})

For boundary conditions, the zero dispersive flux is applied at the top boundary. And zero concentration is applied at the bottom plane. This boundary condition would lead to the maximum flux out of the system under vertically downward flow model. And the infiltration rates into vault are used as the input data for the initial condition to estimate the mass release rate for each radionuclide.

3.2. Transport in the Saturated Zone and Radiological Impacts

For the transport of radionuclides through the saturated zone, GWSCREEN code is used. The modeling approach is based on the mass balance equation. The release rate from unsaturated zone (mass or activity per unit time) at time t is subsequently passed to the saturated zone model. It is assumed that main radioactive progeny travel at the same rate as the parent. The concentration of the i^{th} progeny in a decay chain at the receptor location is as follows.

$$C_i = C_{parent} \frac{DIF_i}{DIF_{parent}} \frac{R_{d\,parent}}{R_{di}} \quad (3)$$

where

C_{parent} : Groundwater concentration of the parent (Bq/cm^3)

DIF_i : Decay-ingrowth factor of the parent(-)

R_{di} : Retardation factor of the i^{th} progeny(-)

$R_{d\,parent}$: Retardation factor of the parent(-)

For radionuclides with a human health endpoint of committed effective dose, in Sv, radiological dose, D_c is given by

$$D_c = \left(\sum_{i=1}^{n} C_i \times DCF_i \right) WI \times EF \quad (4)$$

where

C_i : Groundwater concentration for the i^{th} decay chain number (Bq/cm^3)

WI : Water ingestion rate (cm^3/d)

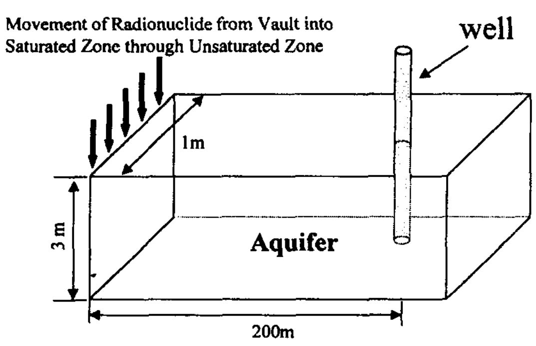

Fig.4. Conceptual Model for GWSCREEN Code

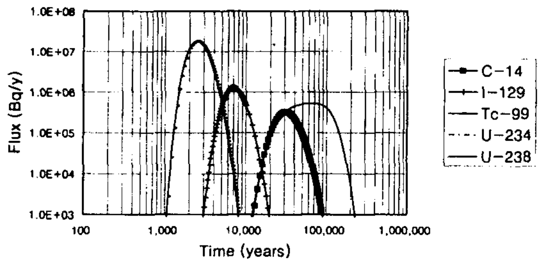

Fig.5. Flux of the Radionuclides at the Bottom of the Unsaturated Zone

DCF_i : Ingestion dose conversion factor for the i^{th} decay chain number (Sv/Bq)

EF : Exposure frequency (d/y)

n : Number of decay chain number(-)

GWSCREEN code is capable of simulating up to 3-dimensional transport of nuclides in the saturated zone. However, in this study, only longitudinal dispersion case is considered, which is to simulate the 1-dimensional streamtube flow. As commented earlier, the radionuclide flux as a function of time at the bottom layer of unsaturated zone calculated from DUST-MS are used as input data for GWSCREEN model. As shown in Figure 4, the radionuclides released from vault through the unsaturated zone are transported into source plane with $3m^2$ considering the assumption that the cross-sectional area of streamtube in the saturated zone is to be $3m^2$.

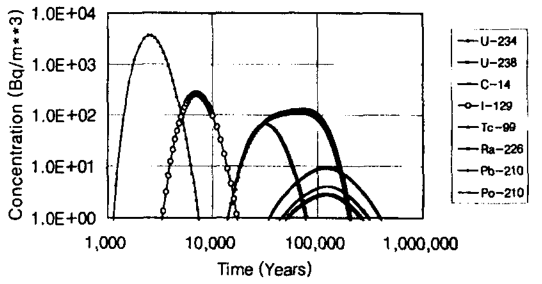

Fig.6. Radionuclide Concentration in Well Water as a Function of Time

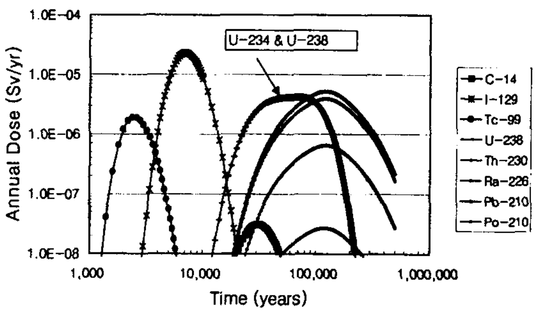

Fig.7. The Annual Effective Dose via Drinking Water Scenario

4. Results and Discussion

Figure 5 shows the flux of radionuclides at the bottom of the unsaturated zone. During their transport through the unsaturated zone, the radionuclides are retarded and decay to differing extents. The flux to the saturated zone is dominated by the longer lived, more mobile radionuclides such as C-14, I-129, Tc-99, U-234 and U-238. And it is found that the curve of U-234 overlaps that of U-238.

As shown in Figure 6, the same radionuclides give rise to the highest concentrations in the well water. And the daughters of U isotopes such as Ra-226, Pb-210 and Po-210 show less concentration values.

Figure 7 shows the annual effective dose to a

Table 5. Peak Dose and Concentration for Key Radionuclides

Radionuclide	Peak Time (yr)	Peak Concentration (Bq/m^3)	Peak Dose (Sv/yr)
C-14	31,000	66.9	3.1E-8
I-129	7,200	266.9	2.3E-5
Tc-99	2,400	3690.8	1.9E-6
U-234	60,000	123.2	4.2E-6
U-238	60,000	106.5	4.1E-6
Th-230	115,000	0.2	2.7E-8
Ra-226	122,000	5.7	6.4E-7
Pb-210	117,000	9.3	5.2E-6
Po-210	117,000	4.1	3.9E-6

Table 6. Comparison of Timing and Magnitude of Peak Dose and Concentration for Key Radionuclides

Radionuclide	This study			Another ISAM safety case study[7]		
	Peak time (yr)	Peak concentration (Bq/m^3)	Peak dose (Sv/yr)	Peak time (yr)	Peak concentration (Bq/m^3)	Peak dose (Sv/yr)
C-14	31,000	6.7E+1	3.1E-8	30,000	4.4E+1	2.1E-8
I-129	7,200	2.7E+2	2.3E-5	8,000	1.7E+2	1.5E-5
Tc-99	2,400	3.7E+3	1.9E-6	2,500	2.2E+3	1.2E-6
U-234 & U-238 chains combined	60,000	2.3E+2	8.3E-6	50,000	1.0E+2	4.7E-6
Total	7,200		2.3E-5	8,000		1.5E-5

human group for drinking water ingestion. Doses are dominated by the long lived, mobile radionuclides in the inventory and their associated daughters. The contribution of Tc-99 on total effective dose is weak though the concentration showed the highest value. This is because the dose conversion factor of Tc-99 is relatively low compared to other radionuclides such as I-129 or Po-210. The engineered and natural barriers ensure that the contribution from short lived, mobile radionuclides is negligible. There is an early peak (1.9E-6 Sv/y) at 2,400 years associated with Tc-99. The next peak (2.3E-5 Sv/y) occurs at around 7,200 years and is due to I-129. A further peak (4.2E-6 Sv/y) associated with the U-234 and U-238 occurs around 60,000 years. And their associate daughters such as Th-230, Ra-226, Pb-210 and Po-210 contribute to the total peak dose later on. Table 5 summarizes the results on peak concentration and dose for important radionuclides. It is found that the total effective dose for drinking water might be far below the general criteria of regulatory limit for radioactive waste disposal facility.

The results obtained from this study is compared to identify similarities and differences between our modeling approach and others'. As another participant in safety assessment of the reference vault disposal case, Little used a compartment modeling approach to represent the entire disposal system[7]. Table 6 gives the peak doses and their timing as calculated in this study and by Little. It can be seen that there is good agreement between the flux, concentration and dose results of both assessments in terms of the timing of the peak values and the important radionuclides and their decay chains. The peak value of total dose summed over all radionuclides in this study is in the same order of magnitude in comparison with the result of Little's. For the individual U-234 and U-238 daughters(i.e. Th-230, Ra-226, Pb-210 and Po-210), Little tracked the ingrowth of daughters from the disposed parent and distinguished the progeny from different decay chains. In our assessment, each progeny radionuclide is treated as a single member decay chain in groundwater pathway model, because the concentration of progeny radionuclides with relatively long half-lives considering the short groundwater travel time as given in this safety case, would not show reasonable results if secular equilibrium condition is adopted for such progeny radionuclides.

As a supplementary far-field model, 3-dimensional dispersion case in the saturated zone is assessed. Transverse dispersions are assumed to be one-tenth of longitudinal dispersion. The model considering 3-dimensional dispersion showed much lower peak radionuclide concentrations in well water than those from the model assuming only longitudinal dispersivity. This illustrates that the radionuclide concentrations could be influenced upon how to define dispersion condition in the saturated zone, and the one-dimensional stream tube approach in this study is conservative with respect to estimating concentrations of radionuclides in well water.

5. Conclusions

The radiological impact of radionuclides on a critical human group through well drinking water is evaluated for the reference engineered near-surface radioactive waste disposal facility. The release and transport of radionuclides in vault and unsaturated media are simulated by using DUST-MS code. And GWSCREEN code is used to model the transport of radionuclides in the saturated zone and the radiological safety assessment.

It is found that the annual effective doses are dominated by the radionuclides such as Tc-99, I-129, U-234, U-238, Th-230, Ra-226, Pb-210 and Po-210 which can be characterized by long lived, mobile radionuclides and their associated daughters. The contribution of I-129 to total effective dose is dominant among these radionuclides. U-234, U-238 and their associated daughters influence on total peak after 60,000 years. And the contribution of Tc-99 on total effective dose is relatively weak even though the concentration shows the highest value. The reason is that the dose conversion factor of Tc-99 is relatively low compared with other radionuclides.

It is concluded that total effective dose for drinking water would be far below the general criteria of regulatory limit for radioactive waste disposal facility.

Acknowledgement

This work has been carried out as a part of the Nuclear R&D program funded by the Ministry of Science and Technology.

References

1. IAEA, "ISAM, The International Programme for Improving Long Term Safety Assessment Methodologies for Near Surface Radioactive Waste Disposal Facilities: Objectives, Content and Work Programme. Final Version", International Atomic Energy Agency, Vienna (1997).
2. IAEA, "Vault Safety Case Data for the Liquid Release Calculations for the Design Scenario", ISAM Vault Safety Working Group, Vienna, December (2001).
3. T. M. Sullivan, "DUST-Disposal Unit Source Term : Data Input Guide", NUREC/ CR-6041, BNL-NUREG-52375 (1993).
4. A S. Rood, "GWSCREEN: A Semi-Analytical Model for Assessment of the Groundwater Pathway from Surface or Buried Contamination : Theory and Users Manual Version 2.5", INEEL/EXT-98-00750, Rev.1 (1999).
5. J. W. Park, K. Chang, and C. L. Kim, "Important Radionuclides and Their Sensitivity for Groundwater Pathway of a Hypothetical Near-Surface Disposal Facility" *Journal of the Korean Nuclear Society,* 33, 156-165 (2001).
6. IAEA, "International Basic Safety Standards for Protection Against Ionising Radiation and for the Safety of Radiation Sources", IAEA Safety Series 115, International Atomic Energy Agency, Vienna (1996).
7. R. H. Little, "Implementation of the Vault Safety Case Liquid Release Scenario in AMBER", IAEA ISAM Vault Safety Case Group- the 5th Working Group Meeting, Brussel, Belgium (2001).