Modeling Cs-137 Migration in Groundwater due to Low Probability Event of Leaching from Near Surface Disposal Facility for Low Level Solid Radioactive Waste

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Volume 1, Issue 5, October 2024
Received:18 September, 2024; Accepted: 03 October, 2024
DOI: https://doi.org/10.63015/7N-2440.1.5

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Abstract: In this paper, we present impact of Cesium-137 (Cs-137) disposal in a Near Surface Disposal Facility (NSDF) with respect to groundwater migration and its consumption for drinking. We employ the Multiple Area Source Model for simulating the fate of radionuclide in groundwater to evaluate its potential contamination due to extremely low probability event of leaching from the NSDF. The assessment conservatively assumes direct interaction between disposal trenches and the underlying aquifer neglecting the barrier provided by the unsaturated zone. Temporal profiles of concentration of Cs-137 at different down flow distances in groundwater are obtained over a period extending several years post-disposal. The results indicate that even under such a worst-case conservative scenario and for an annual disposal rate of 3 TBq/y for a period of 50y, the maximum Cs-137 concentration in groundwater remains significantly below the safe drinking water threshold of 10 Bq/L recommended by the World Health Organization. It is found that amount of Cs-137 generally disposed in NSDF is significantly lower than the allowable disposal limit corresponding to concentration defined for safe drinking water limit.

Keywords: Near surface disposal facility, Leaching, Groundwater contamination, Radionuclide transport, Multiple area source model.

1. Introduction: The operation and maintenance of nuclear facilities generate low level solid radioactive waste, which poses environmental and radiological hazards [1]. Among the radionuclides present in such waste, Cs-137 is of particular concern due to its long half-life of 30.1 years and its high fission yield of approximately 6.1% [2]. Low-level radioactive waste containing Cs-137 is typically disposed of in engineered structures such as stone-lined trenches, reinforced concrete trenches, and tile holes in Near Surface Disposal Facilities (NSDFs) [3]. Due to the low-level of radioactivity and employed engineered safety features in NSDFs, the probability of leaching of radioactivity from these facilities into groundwater due to ingress of water from precipitation etc. is negligible [4]. However, the impact assessment even of such a low probability event is required according to the regulations applicable for such facilities, particularly given that the World Health Organization (WHO) recommends a maximum safe level of 10 Bq/l for Cs-137 in drinking water [5].

To ensure safety of the public, migration of Cs-137 in groundwater is modelled to ensure compliance with regulatory guidelines, both during the operational phase and post-closure phase of the disposal facilities. Groundwater modeling is a key tool in these assessments, enabling the prediction of radionuclide transport and dispersion within aquifers [6]. Analytical models offer exact solutions to simplified versions of the groundwater flow and solute transport equations [7]. On the other hand, numerical models such as MODFLOW and FEFLOW solve the more complex, multi-dimensional flow and transport equations

through numerical approximations [8]. While numerical models can account for more realistic scenarios, they require extensive input data and are computationally really intensive. That is why for regulatory assessments, despite their limitations related to simplifications, analytical models are valuable tools and a more practical alternative for predicting contaminant fate and evaluating their impact by employing conservatism in the simplified assumptions [9]. In this study, we employ the Multiple Area Source Model (MASOM), an analytical model developed by Sunny et al. (2006) [10], to model Cs-137 leaching from a typical NSDF and further migration in groundwater. Brief details of the model and the corresponding results are discussed in the following sections.

2. Contaminant Transport Model: Multiple Area Source Model (MASOM) is designed to simulate the dispersion and dilution processes of contaminants as they migrate through groundwater, taking into account the key physical and chemical processes involved. The release rate ψ(t) from the disposal facility into groundwater is mathematically expressed as [10]

$$\boldsymbol{\Psi(t) = \frac{QK_L}{K_L+\lambda}[1 - \exp(-(K_L + \lambda)t)]} \quad (1)$$

where Q represents the disposal rate of the radionuclide (in Bq/s), K_L denotes the leach rate coefficient (in s^{-1}), λ is the radioactive decay constant (in s^{-1}) and t is the time (s). The leaching of radionuclides is affected by several factors including the structural integrity of the disposal modules, the radionuclide's distribution coefficient, and the rate at which water infiltrates through the disposal module. The leach rate coefficient K_L can be expressed as a function of the infiltration velocity, as described in the following formula.

$$\boldsymbol{K_L = \frac{v_L}{D\theta R_d}} \quad (2)$$

where D represents the depth of the disposal module, θ is the porosity of the aquifer and R_d is the retardation factor given by:

$$\boldsymbol{R_d = 1 + \frac{\rho K_d}{\theta}} \quad (3)$$

where K_d is the distribution coefficient (ml/g) and ρ is the soil density (g/ml).

Eq. (2) provides the fundamental basis for estimating the rate at which radionuclides may enter groundwater systems from disposal facilities. The transport of radionuclides through groundwater is governed by several key processes including advection, molecular and turbulent diffusion, interaction with soil, radioactive decay, and chemical removal rates. For unidirectional flow primarily in the x-direction, and for homogeneous groundwater velocity and dispersion coefficients, these processes are translated into 3D mathematical equation known as advection dispersion equation as given below [10]:

$$\frac{\partial C}{\partial t} = \frac{D_x}{R_d}\frac{\partial^2 C}{\partial x^2} + \frac{D_y}{R_d}\frac{\partial^2 C}{\partial y^2} + \frac{D_z}{R_d}\frac{\partial^2 C}{\partial z^2} - \frac{u}{R_d}\frac{\partial C}{\partial x} - \lambda C \quad (4)$$

where D_x, D_y and D_z are the dispersion coefficients along the x, y, and z axis respectively, u denotes the groundwater velocity along x-direction, λ is the decay constant, and C represents the concentration of radionuclides within the pore space (Bq/L).

Eq. (4) is solved under a set of assumptions for initial and boundary conditions viz. C is zero at initial time and at infinite distances from the source. Analytical solution for the concentration due to an instantaneous point source extended to account for an area source by integrating over the source dimensions is given as a convolution integral [10]:

$$\boldsymbol{C(x, y, T) = \int_0^T \psi(T - \tau) C_i(x, y, \tau) d\tau} \quad (5)$$

Where T is the period of disposal operation, τ is the running variable, and C_i is the radionuclide concentration in the groundwater due to instantaneous release of unit radioactivity [13]. Eq. (5) estimates the concentration profile up to the disposal period 'T'. The radionuclide concentration following the termination of the disposal operation can be assessed using the expression given below:

$$\mathbf{C(x,y,t) = \int_0^T \psi(T-\tau) C_i(x,y,T+\tau) d\tau + \psi(T) \int_0^t \exp[-\lambda_1 (t-\tau) C_i(x,y,\tau) d\tau} \quad (6)$$

Where $\lambda_1 = \lambda + K_L$ and t is the post disposal period with the origin at the termination time T. The first integral in Eq. 6 accounts for the radionuclide concentration in groundwater during the post- disposal reflecting the activity leached during the disposal period. The second integral represents the additional radioactivity in groundwater resulting from leaching that occurs after the termination of disposal. These integrals are evaluated using the Simpson's 1/3 method.

3. Parameters: Site-specific hydrogeological parameters play a crucial role in determining the extent of radionuclide migration. For present work, we utilized the data for a typical NSDF site as reported by Shelly et al. [11] where they conducted field and laboratory studies in and around NSDF to determine the site specific hydrogeological parameters such as porosity, hydraulic conductivity, groundwater velocity, and the K_d. These hydrogeological data is used as input to simulate migration of Cs-137 in groundwater and the corresponding radiological impact through drinking water pathway. As the data had a range of values, the values selected for the deterministic estimation are based on the conservative assumptions to get the maximum potential radionuclide concentration in groundwater (Table 1). For modeling radionuclide leaching from disposal modules, the infiltration velocity for stone-lined trenches (SLT) was assumed to be equal to the design basis value generally used for uranium tailings ponds [12] i.e. 1×10^{-9} m/s,. Infiltration velocities for reinforced concrete trenches (RCCT) and tile holes (THs) were assumed to be one and two orders of magnitude lower, respectively considering their better integrity. We assumed a continuous disposal rate of 1 TBq/year of Cs-137 into each of the three modules over a 50-year period, resulting in a total inventory of 150 TBq, with 50 TBq allocated to each module.

Table 1: Parameters used in the modelling

Parameter	Value
K_d of Cs-137 (ml/g)	116.7
θ of the waste matrix/aquifer	0.29
ρ_b of the waste matrix/aquifer (g/cc)	1.6
u (m/d)	3.22
Aquifer thickness (m)	2
Longitudinal dispersivity (m)	1
Transverse dispersivity (m)	1
Infiltration Velocity (SLT, m/s)	$1x10^{-9}$
Infiltration Velocity (RCCT, m/s)	$1x10^{-10}$
Infiltration Velocity (TH, m/s)	$1x10^{-11}$

4. Results and Discussion: Modelling Cs-137 migration in groundwater from the NSDF incorporates several conservative assumptions to ensure the safety of the public. Although groundwater mapping indicates the flow direction towards the sea [11], for conservative estimation it is considered towards the population center. Figure 1 shows the temporal profiles of Cs-137 concentration at three distances along the centerline i.e. 500 m, 600 m and 1000 m. The maximum Cs-137 concentration in groundwater at 500 m is calculated to be 1.62×10^{-2} Bq/L, occurring 300 years after disposal (Table 2). At 600 and 1000 m, the concentrations are 4.5×10^{-3} Bq/L and 2.72×10^{-5} Bq/L, occurring 350 and 570 years after disposal respectively (Table 2, Figure 1). The concentration values estimated are significantly below the World Health Organization's (WHO) safe drinking water limit of 10 Bq/L for Cs-137 [5], demonstrating that the estimated concentrations are more than 600 times lower than the WHO recommendations. Based on the concentration at 500m distance and for concentration corresponding to WHO's safe limit for drinking of 10 Bq/L, the allowable activity for Cs-137 disposal is estimated to be 1852 TBq/y which is orders of magnitude higher than the activity generally disposed of in NSDFs [13, 14].

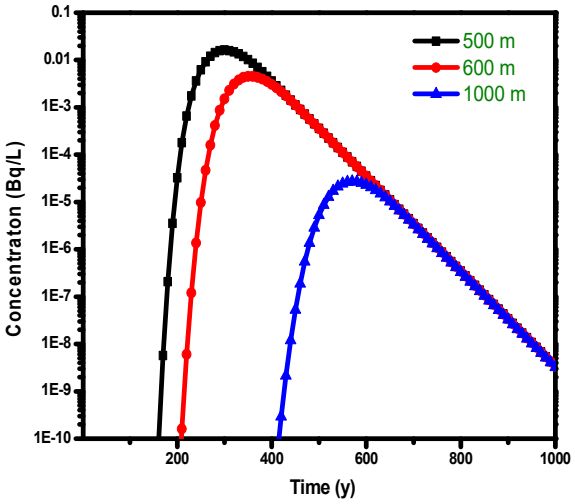

Figure 1: Concentration of Cs-137 in groundwater at three distances from SWDF

Table 2: Peak concentration of Cs-137 at different distances from NSDF and peaking time

Distance (m)	Peak conc. (Bq/L)	Time (years)
500	1.62×10^{-2}	300
600	4.5×10^{-3}	350
1000	2.72×10^{-5}	570

5. Conclusions: Modeling of leaching of Cs-137 disposed at a typical NSDF and its migration with groundwater is carried out by utilizing site-specifc hydrogeological data. Despite the conservative assumptions made in the modeling the radionucldie leaching and transport, the predicted Cs-137 concentrations at various distances from the disposal site remain well below the World Health Organization's safe drinking water limit of 10 Bq/L. Moreover, it is concluded that the activity of Cs-137 generally disposed of in the NSDFs is significantly lower than the allowable activity estimated corresoponding to safe drinking water limit of WHO. These findings suggest that the risk of Cs-137 migration into groundwater from NSDF is minimal.

Acknowledgements:
The authors express their sincere gratitude to Dr. S.K. Jha, Head, Radiation Protection Section (Nuclear Fuels), Shri Probal Chaudhury, Head, RSSD, and Dr. D.K. Aswal, Director, HS&E Group of Bhabha Atomic Research Centre (BARC), Mumbai, India, for their invaluable support. The authors also extend their gratefulness to Dr. P. Ashokkumar, Head, Health Safety Section (Radiological Laboratories), and Dr. Faby Sunny, formerly of BARC, Mumbai, India, for their encouragement, support, and guidance.

Conflict of Interest: Authors declare No conflicts of interest.

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