PERFORMANCE ASSESSMENT FOR LLRW DISPOSAL IN A NEAR SURFACE REPOSITORY

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ABSTRACT

Performance assessment analysis is performed at AECL's Chalk River Laboratories (CRL) to support several low-level radioactive waste disposal concepts. This paper discusses the computer code developed at CRL in support of safety assessment calculations for LLRW disposal in near surface repositories. Various submodels in the code and the assumptions used are briefly described. Sample runs have been made and the vault roof performance function is shown to be a key parameter in the safety assessment.

INTRODUCTION

Atomic Energy of Canada Limited (AECL) is currently seeking a license to construct a prototype near surface repository for low-level radioactive waste (LLRW) disposal. The licensing procedure for a facility designed for the disposal of LLRW requires an assessment of its performance. The standard methodology for such assessments is pathways analysis, in which the rate of release of radionuclides and the resulting impact on human health are predicted. The principal tool for such calculations is a computer code containing a number of models that simulate the long-term mass transfer of radionuclides within the vault and surrounding geosphere, and their interactions with the surrounding biosphere. Waste Management Systems (WMS) at Chalk River Laboratories (CRL) developed the COSMOS (1) code to assess the performance of a LLRW disposal facility of the generic type represented by IRUS (Intrusion Resistant Underground Structure). However, during the last year and a half, the COSMOS models have been implemented under the Systems Variability Analysis Code (SYVAC) (2) executive, as the Near Surface Repository (NSURE) code. The SYVAC-NSURE code is now being used for the IRUS performance assessment where groundwater is the dominant pathway. This paper deals with the SYVAC-NSURE code and its application to IRUS.

IRUS

The design for a LLRW repository that has evolved at CRL consists of a concrete vault filled with waste packages and backfilled with sand. The top of the vault is covered with a 1 m thick reinforced concrete roof, with additional protective barriers designed for a service life of 500 years or more. Waste packages consist of a waste form (such as bitumen or concrete) sealed in drums or containers, and compacted bales. The IRUS prototype unit is 31.6 m long x 21.6 m wide x 8.6 m high from the base of the foundation to the underside of the concrete roof. The base and walls are made of 0.61 m thick reinforced concrete. The bottom of the vault is a permeable buffer layer (300 mm sand/clinoptilolite 90/10 wt.% and 300 mm sand/dochart clay 90/10 wt.%), which will permit drainage in the event of infiltration, thus avoiding the "bathtub effect". The buffer is located in the unsaturated zone above the water table. Figure 1 shows the schematic transverse section of an IRUS unit after closure.

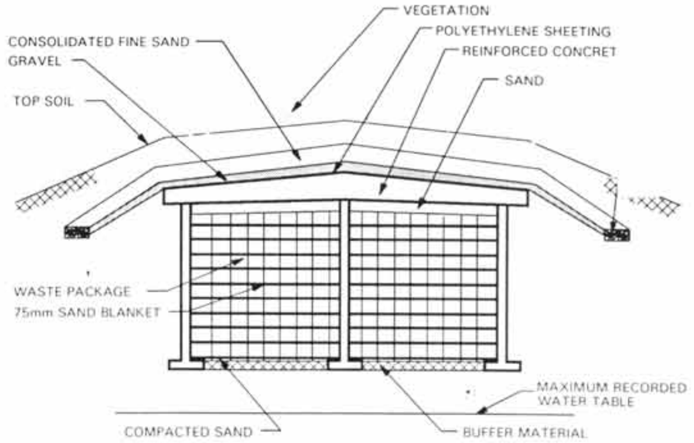

Fig. 1. A schematic transverse section of an IRUS unit after closure.

SYVAC-NSURE CODE

The SYVAC-NSURE code was developed under the SYVAC executive, based on the mathematical models developed by Selander et al. (3) and Rowat et al. (4). These include a vault model, models for transport through unsaturated layers and aquifers, and surface water transport, and a biosphere model. The NSURE code has been developed under SYVAC to take advantage of its time-series management package (TSMP) (2), and its features for probabilistic assessment. The code was written in standard FORTRAN-77, and is compatible with PC and mainframe platforms.

In its present form, the SYVAC-NSURE models: water infiltration through a leaking vault roof; the failure of containers and consequent leaching of radioactive contents, migration of the nuclides through unsaturated and saturated media such as buffer, backfill and layers of ground; dilution in groundwater and surface waters; and eventual dose rate to the critical individual. Figure 2 is a schematic flowchart for the NSURE model.

Vault Model

The present model treats the vault as a random array of waste forms (e.g., drums, bales) separated and surrounded by moist sand backfill. The vault model is designed so that, given the input parameters of the system, the nuclide flux leaving the bottom of the vault can be obtained from simple formulae.

For a given nuclide/waste form combination, the release rate can be categorized as "fast" or "slow". This distinction is

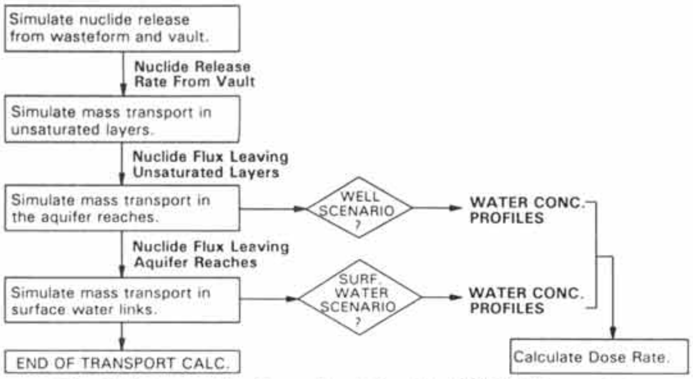

Fig. 2. Schematic flow chart for the NSURE model.

based on the relative values of the process time constants. The slow-release mechanism is a two-stage process: nuclides first diffuse out of the waste form and then migrate through the backfill and out of the vault. In general, if the release rate from the vault is limited by waste form leaching, then the slow-release mechanism is appropriate. The mathematical model for the slow-release system is that of a dispersion-advection equation for the vault, equipped with a driving term S(t), which represents nuclide leach rates. The release from the vault is then derived by solving the dispersion-advection equation with the driving term S(t), that is:

$$R_v \frac{\partial C_v}{\partial t} = D_v \frac{\partial^2 C_v}{\partial x^2} - U_v \frac{\partial C_v}{\partial x} + S(t) \qquad \text{(Eq. 1)}$$

The subscript v refers to the vault (the variables are defined in the Notation section). The interstitial or pore water velocity, U_v, governs advective transport and varies with transient rainfall episodes; however, in this model it is treated as a steady-state average (4).

The fast-release mechanism models nuclides that are poorly adsorbed by the waste form. Fast release is a one-stage process that assumes an instantaneous redistribution of the waste form nuclide inventory throughout the vault, at the instant of container failure. The nuclide release rates for the fast-release systems are limited by mass transfer properties of the vault as a whole, rather than by the waste form. The fast-release mechanism is conservative, because no credit is taken for the nuclide retention properties of the waste form. The governing equation for fast-release systems is obtained by replacing *S(t)* in Eq. (1) by an initial condition of constant concentration.

A major governing parameter in the vault model is the roof performance function, which determines the time and rate at which infiltrating water begins to penetrate the vault. This in turn changes the dominant transport mechanism from diffusion to advection, increasing the overall mass transfer rate in the process. Thus the two limiting mass transport regimes in the vault are "no flow" and "flow" (i.e., intact roof and leaking roof).

In the repository model, the container and roof degradation processes are characterized by performance functions. The containers, as long as they remain intact, delay the onset of waste form leaching. The vault roof, the concrete cap and protective barriers prevent the infiltration of precipitation. One of the features of SYVAC-NSURE is the ability to handle a gradual or sudden ingress of water into the vault brought on by roof leakage or failure. Similarly, the containers can fail suddenly or gradually. The user must first determine the appropriate performance functions, representing the container and roof failure rates.

Unsaturated Layer and Aquifer Models

The unsaturated layer model simulates the radionuclide transport through the buffer and soil layers leading to the aquifer, whereas a one-dimensional stream tube model is used for radionuclide migration through several aquifer reaches. The input flux for the unsaturated layers is the total flux leaving the vault under "no flow" and "flow" conditions. The governing equation for mass transfer in the multilayer system of buffer, overburden and aquifer is assumed to be the one-dimensional advection-dispersion equation for a saturated medium, with the following assumptions:

- the groundwater flow is uniform and one-dimensional,
- the aquifer is saturated, isotropic and homogeneous,
- in the aquifer the dispersivity is linear with respect to groundwater velocity, and has the form

$$D = \frac{D_0}{\tau^2} + \alpha U$$

- reversible linear adsorption (the K_d model) is assumed.

$$R = 1 + \frac{\rho(1-\varepsilon)}{\varepsilon} K_d$$

The governing equation is:

$$R \frac{\partial \Phi}{\partial t} = D \frac{\partial^2 \Phi}{\partial x^2} - U \frac{\partial \Phi}{\partial x} - \lambda R \Phi \qquad \text{(Eq. 2)}$$

with

$$\Phi = \phi(t) \quad at \quad x = 0$$

$$\Phi \rightarrow 0 \quad as \quad x \rightarrow \infty$$

This choice of transport equation for the unsaturated layers is conservative, because mass transfer rates in unsaturated media are usually less than those in saturated media. The solution to Eq. (2) can be expressed as a convolution integral (5):

$$\Phi(x,t) = \int_o^t \phi(\tau)\, G(x, t-\tau)\, d\tau \qquad \text{(Eq. 3)}$$

where

$$G(x,t) = \frac{x R^{1/2}}{(4\pi D t^3)^{1/2}} \exp\left[-\frac{(Rx - Ut)^2}{(4DRt)} - \lambda t \right] \qquad \text{(Eq. 4)}$$

is the Green's function for Eq. (2). In the development of Eq. (3) above, the medium is assumed to be semi-infinite, but the solution at the appropriate distance into the region is taken to represent the concentration at the outer edge of a finite region. This approximation, known as the semi-infinite medium approximation (6,7), is appropriate for the situation envisaged (1). Under the "no flow" condition in the unsaturated layers, the infiltration velocity term 'U' in Eq. (4) is identically zero, and therefore mass transport is via diffusion only.

Numerical integration of the convolution integral in Eq. (3), using the SYVAC's time-series management package, yields the time behaviour of radionuclide fluxes at the downstream face of a particular region. The radionuclide release rate at the output face of one region serves as the input source to the next region. At interfaces between different regions, contaminant flow may change due to changes in the parameters describing the groundwater/aquifer, or by removal of part of the aquifer flow by a well. The last aquifer reach is assumed to feed a surface water body, such as a lake or river. Figure 3 shows the graphical representation of the aquifer model and the well water scenario.

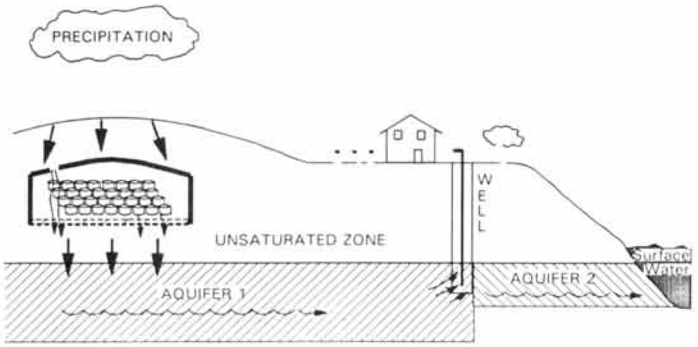

Fig. 3. Aquifer model and well water scenario.

In a well water scenario, a single well can be present at any one of the region interfaces. The groundwater is extracted through the well and used for domestic consumption and/or agricultural purposes. Contaminant concentration in well water is assumed to be equal to that in the groundwater plume, unless the demand on the well exceeds that available in the plume. In that case, clean water from outside the contaminant plume is also being drawn, resulting in a dilution of contaminant concentration.

Surface Water Transport Model

Surface waters are considered as a sequence of river reaches or lakes, called links. Mass transport of radionuclides takes place through a chain of links, and each link is modelled as a separate well-mixed compartment. Water can be drawn from any of these links for domestic or agricultural use. It is assumed that the water drawn is part of the total outflow from a compartment.

The amount of radionuclides in a compartment evolves according to the ordinary differential Eq. (9):

$$\frac{dA}{dt} = \Phi_o(t) - \left(\frac{q}{V} + \lambda + \sigma\right)A \qquad \text{(Eq. (5)}$$

with $A = 0$ at $t = 0$.

The main factor affecting radionuclide concentrations in this model is dilution (7), which increases successively with each lake or river reach. There are also two possible attenuation mechanisms: the first involves the sediment sorption of radionuclides settled at the bottom, and is modelled as an irreversible process; the second involves radioactive decay during the radionuclide resident time within the surface water body. It is assumed that contaminant disperses uniformly and instantly throughout the compartment volume. In general, the amount of radionuclide in the i^{th} compartment is given by the solution to Eq. (5),

$$A_i(t) = \int_o^t \Phi_{i-1}(\tau) e^{-\gamma_i(t-\tau)} d\tau \qquad \text{(Eq. 6)}$$

where, $\Phi_{i-1}(t)$, is radionuclide flux from the previous compartment. Knowing the amount A_I of radionuclide in the i^{th} compartment, the concentration of radionuclide in that compartment and radionuclide flux leaving the compartment can easily be calculated.

Biosphere Model

The biosphere model calculates the dose rate for a "standard infant" (10) or a "standard adult" (10), resulting from internal and external exposure to a given radionuclide. This is equal to the product of: radionuclide concentration in water; the nuclide pathway transfer factor (PTF); and the appropriate dose conversion factor (DCF). The products of PTFs and DCFs constitute the pathway dose conversion factors (PDCFs), which are based on the dose-to-concentration factors provided by the Canadian Standards Association (CSA) (10) and studies done at CRL (11). The types of dose calculated are:

a) effective dose equivalent (EDE), and
b) dose equivalent to skin and eight individual organs (12).

SAMPLE OUTPUT TYPICAL OF IRUS

Sample runs were made with the NSURE code to determine the impact of IRUS on the critical individual, in a typical IRUS scenario. This scenario assumes the individual is a subsistence farmer, living on the shore of Maskinonge Lake (at CRL) near the IRUS site. For this example H-3, Cl-36 and I-129 were selected because they are fast-release nuclides, whereas Cs-135 was chosen because it is a slow-release nuclide (i.e., relatively immobile). Performance functions for the containers and the roof are assumed to be ramp failure functions of zero to 100 years. and 500 to 1500 years., respectively. The peak EDE dose rates and the associated times are listed in Table I. The values are typical of IRUS results. Figure 4 depicts the dose rate profiles over a period of 5000 years. For Cl-36 and I-129, the behaviour between zero to 500 years is the diffusion-dominated domain. At the onset of infiltration there is a sharp rise in the mass transfer rate, due to the "washout flux" (these are nuclides that are present in the backfill and unsaturated layers, which with the onset of infiltration are subsequently washed out). The domain between

TABLE I

EDE Peak Dose Rates and associated times for
H-3, Cl-36, I-129 and Cs-135

Nuclide	EDE Peak Dose Rate (Sv/a)	Time (a)
H-3	2.4E-07	40
Cl-36	1.1E-08	520
I-129	5.5E-10	525
Cs-135	1.7E-11	3800

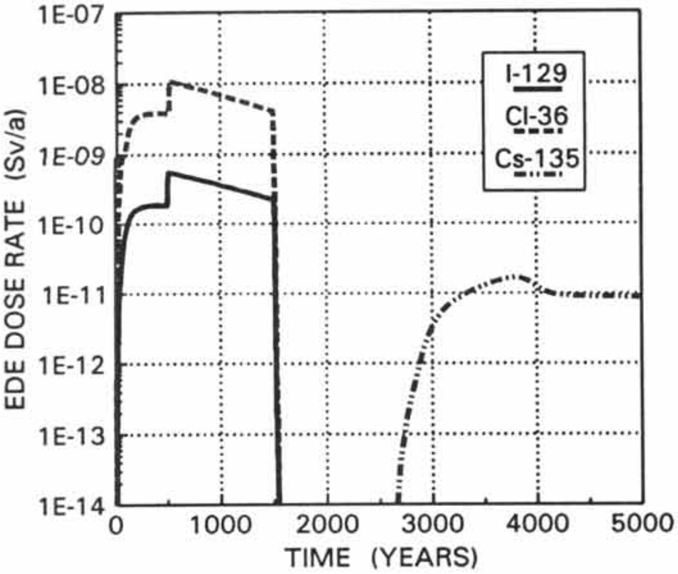

Fig. 4. EDE dose rate profile for Cl-36, I-129 and Cs-135.

500 and 1500 years is simply the effect of the roof failure function.

As mentioned earlier, the roof performance function is a major parameter in the vault model. To illustrate this sensitivity, NSURE was run for I-129 and Cs-135, with four different roof failure functions (RFFs); Table II lists the results from this exercise. Because Cs-135 is a slow release nuclide (i.e., adsorbed in the wasteform), the effect of RFFs is minimal. However, I-129 is highly sensitive to the roof failure rate (RFR) and somewhat sensitive to the initial time of roof failure. Higher RFR increases the mass transfer rate, whereas a delay in the onset of infiltration reduces the amount of "washout flux" due to the longer time in which diffusion can take place. Therefore, it is desirable to have a gradual roof failure over a long period of time, rather than a failure over a shorter period, even if it were to occur much later in time.

CONCLUSION

Performance assessment codes are needed in the design and safety assessment of LLRW disposal facilities. The SYVAC-NSURE code has been developed for the performance assessment of a near surface repository for LLRW disposal. The development of the NSURE model under the SYVAC executive has provided it with the efficiency of SYVAC's time-series management package as well as its features for probabilistic assessment. The SYVAC-NSURE code is being used for the safety assessment of LLRW disposal in IRUS. The roof failure performance function for IRUS has been shown to be a key parameter in the overall performance assessment.

TABLE II

EDE Peak Dose Rates and Associated Times for I-129 and Cs-135 with Different RFFs.

Roof Failure Function Type	Nuclide: I-129 EDE Peak Dose Rate(Sv/a)	Time(a)	Nuclide: Cs-135 EDE Peak Dose Rate(Sv/a)	Time(a)
Ramp 500 to 1500 a	5.5E-10	525	1.7E-11	3800
Ramp 500 to 1000 a	9.6E-10	525	1.8E-11	3340
Ramp 100 to 500 a	1.2E-09	150	1.2E-11	2900
Ramp 100 to 1000 a	6.2E-10	210	1.4E-11	3340

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NOTATION

A : Amount of radionuclide in compartment (Bq),
C : Concentration (mass of nuclide in the pore water per unit volume of porous medium) (Bq/m^3),
D : Pore Dispersion Coefficient (m^2/a),
D_o : Diffusivity of nuclide in water (m^2/a),
K_d : Distribution coefficient (m^3/kg),
q : Rate of water leaving compartment (m^3/a),
R : Retardation Factor (dimensionless),
t : Time (a),
U : Pore Velocity, the bulk or Darcy velocity divided by the porosity (m/a),
V : Volume of water in the compartment (m^3),
x : Distance (m),
α : Dispersion coefficient (m),
ε : Porosity (dimensionless),
λ : Radioactive decay constant (1/a),
ρ : Bulk density (kg/m^3),
σ : Sediment sorption removal constant (1/a),
τ : Mean tortuosity (dimensionless), and
$\phi(t)$: Source or Input Flux at $x = 0$ (Bq/a)
Φ : Radionuclide Release Rate or "flux" (Bq/a),
Φ_o : Radionuclide flux entering compartment (Bq/a),

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