EFFECT OF SALTSTONE VAULT ROOF CONFIGURATION ON THE RATE OF CONTAMINANT TRANSPORT

by

R. H. Hsu, A. D. Yu and P-S Lam

Savannah River Technology Center,
Westinghouse Savannah River Company
P.O. Box 616
Aiken, SC 29808

A paper for presentation at the
95 SIMULATION MULTICONFERENCES
Phoenix, AZ
April 9-13, 1995

and for publication in the Simulators XII Proceedings.

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EFFECT OF SALTSTONE VAULT ROOF CONFIGURATION ON THE RATE OF CONTAMINANT RELEASE

Robert H. Hsu
Andrew D. Yu
Poh-Sang Lam

Westinghouse Savannah River Company
P.O. Box 616
Aiken, SC 29802
USA

ABSTRACT

At the Savannah River Site, low-level radioactive decontaminated salt solution is mixed with slag, flyash, and cement to form a grout-like material called "Saltstone." The Saltstone is poured into concrete vaults constructed at the Saltstone Disposal Facility (SDF) [Langton 1988]. The impact of SDF on groundwater has been studied in a radiological performance assessment (PA) [Westinghouse 1992; Cook 1993]. Sophisticated groundwater models were used to predict the groundwater flow and contaminant transport problems [Yu 1993b]. The modeling effort was divided into two parts: the unsaturated-zone model and the saturated zone model. The unsaturated-zone model consists of the domain above the water table. The saturated-zone model comprises the aquifers and aquitards underlying the SDF. The unsaturated-zone model predicts mass flux rates (in units of grams/year or Curies/year) to the water table as a function of time. These flux rates are used as the source term for the saturated-zone model. The saturated-zone model predicts the spatial contaminant concentrations in the groundwater as a function of time.

This paper describes the unsaturated-zone modeling using the ECLIPSE code [Intera 1993] to evaluate the performance of three different roofing options: 1) the Worst Scenario, only 30 cm (1 ft) clean grout and no additional pour or roof; 2) a proposed New Design of a 1.33 percent slope concrete pour over the clean grout; and 3) the Original Design vault, with an engineered concrete roof of two percent slope. ECLIPSE is a finite-difference petroleum reservoir engineering code with an environmental tracer option. Nitrate was used as the "tracer" contaminant because it does not absorb or decay and is most abundant in the decontaminated salt solution. In this study, ECLIPSE solves the two-phase (air-water) two-dimensional (x-z vertical slice) flow and transport problem up to 10,000 years.

The properties of all materials are assumed to remain unchanged.

The predicted rate of nitrate released to the water table (g/yr) was divided by the total initial nitrate inventory in the modeling domain to obtain the fractional release rate (yr⁻¹). When the release rate histories were used as source terms for the saturated-zone model, the calculated peak groundwater nitrate concentrations at the compliance point are 1.01, 0.85, and 0.37 mg/liter, respectively, for the three cases. Because the maximum concentration limit (MCL) for nitrate is 45 mg/liter, we conclude that a configuration change from the Original Design to the New Design will not adversely impact the performance of the SDF for groundwater protection. Thus, the modeling results indicate that an engineered concrete roof originally proposed may be over-designed. Eliminating the roof and substituting it with a thin layer of concrete will reduce the project cost by approximately $2,000,000 per vault.

INTRODUCTION

The Saltstone Disposal Facility

The purpose of Saltstone Disposal Facility (SDF) is to protect human health, the environment, and the groundwater resources. It is designed for the release of contaminants in a slow, controlled manner over thousands of years. The impact of SDF on groundwater has been studied in a radiological performance assessment (PA) [Westinghouse 1992]. The PA addresses the performance requirements or objectives mandated by DOE Order 5820.2A [US DOE 1988]. One of the major performance objectives is to show that the impacted groundwater will be in compliance with the Safe Drinking Water Act [US DOE 1990].

The SDF will consist of 15 concrete vaults. The first vault (Phase I), completed in 1990, is 100-feet wide by
600-feet long by 25-feet high (30.5m x 182.9m x 7.6m). It contains six 100 ft x 100 ft cells. The Phase II vaults will be twice as wide (200 ft). Thickness of the Saltstone vault bottom slab is 61 cm (2 ft). The side walls are 46 cm (1.5 ft) thick. The vaults will be filled with Saltstone up to a height of 731 cm (24 ft). A layer of 30 cm (1 ft) clean grout is then poured above the Saltstone. The original design for the Saltstone roof is an engineered concrete cover with a two percent slope, approximately 3 feet thick at the center ridge and 2 feet at the edges. Prior to closure, the bottom of the vaults is at the ground level which is at least 20 feet above the historical high water table.

After all the vaults are filled, the SDF will undergo closure. The closure plan has not been completed. The current closure concept includes the placement, from the top of the vault to the ground surface, of two feet of clay, one foot of gravel, two feet of backfill soil, two feet of clay, one foot of gravel, and two feet of top soil. The purpose of the closure is to reduce infiltration, to prevent an inadvertent intruder from exposure to the waste, and to minimize the probability of waste exposure by erosion. A schematic diagram of the SDF is shown in Figure 1.

**Previous Modeling Results**

Groundwater models using PORFLOW computer code were used to predict the groundwater flow and contaminant transport [Yu 1993b]. PORFLOW [Runchal 1994] is a numerical code developed by the Analytic and Computational Research Inc. (Bel Air, CA). In the Saltstone PA [Westinghouse 1992], INEL also used PORFLOW to model a 600 ft x 200 ft x 25 ft vault (Phase II Vault). Saltstone was poured to a height of 24 ft from the bottom. One foot of clean grout was poured on top of the Saltstone. The concrete roof cover above the clean grout was assumed to be 3 ft thick and 0% slope. The clay cover was also horizontal. The effect of sloped roof and cover was modeled by tilting the gravitational field two percent. INEL did not include the post-closure clay cap in the conceptual model. They assigned a constant infiltration flow rate of 2 cm/yr as the top boundary condition. These conditions were used to represent an intact vault and an intact closure as the Baseline Scenario.

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![Schematic of the Saltstone Disposal Facility](image-url)
The INEL unsaturated zone model predicted a contaminant release rate history to the water table. This rate was normalized by the initial inventory, to get the fractional release rate. The fractional release history showed a peak of $3.75 \times 10^{-6}$ per year at about 7,000 years. The fractional release history was used as the source term for the saturated zone model that resulted in a peak nitrate concentration of 0.87 mg/L, compared to the MCL of 45 mg/L.

**CONCEPTUAL MODEL**

**Modeling Domain**

A two-dimensional vertical cross-section of a Saltstone vault was modeled. The closure cap was included in the simulation domain. The bottom of the simulation domain was set at the top of the water table. The elevation at this level was arbitrarily chosen to be zero. Only half of a vault was simulated to take advantage of the symmetry.

**Initial and Boundary Conditions**

The initial water saturation in the soil was obtained from an ECLIPSE modeling of the steady-state flow field under 40 cm/yr infiltration, the normal infiltration at SRS based on lysimeter tests and water balance calculations. The Saltstone vault was then superimposed on the modeling domain. The Saltstone and concrete vault were assumed to be initially saturated with water. The initial nitrate concentration in the Saltstone pore fluid was 0.16 g/cm³. There was no nitrate in the vault or the backfill soil.

The boundary conditions used for the simulation were: 1) constant water influx of 40 cm/yr at the top of the domain; 2) a 1-ft air layer at the top; 3) a 1-ft numerical aquifer layer at the bottom; 4) a vertical barrier and gravel drain to one side of the domain; and, 5) zero convective and diffusive fluxes at the vertical boundaries due to symmetry. The 40 cm/yr water influx was the average infiltration rate at the SRS. The air layer was maintained at 1.0 atmospheric pressure through the use of constant pressure air injection wells. The aquifer layer was connected to a relatively large aquifer to maintain a stable water table condition. The vertical barrier and gravel drain were an approximation that allowed the removal of run-off water without modeling the whole SDF.

**Transport Mechanism**

The dominant mechanisms for nitrate release from the Saltstone are convection and diffusion. Convection results from a very small amount of perched water flowing through the vault and leaching out nitrate. Diffusion results from the concentration gradient between the Saltstone and the model boundaries. Simultaneous transient flow and transport were simulated.

The relative importance between convection and diffusion is governed by the flow and transport properties of the porous media. It was assumed that the properties of the materials remain unchanged during the entire modeled period. For this study, the hydraulic conductivities of and the diffusivities for nitrate in Saltstone, concrete, backfill soil and clay were:

<table>
<thead>
<tr>
<th>Material</th>
<th>Conductivity (cm/sec)</th>
<th>Diffusivity (cm²/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saltstone</td>
<td>$1.0 \times 10^{-11}$</td>
<td>$5.0 \times 10^{-9}$</td>
</tr>
<tr>
<td>Concrete</td>
<td>$1.0 \times 10^{-10}$</td>
<td>$1.0 \times 10^{-8}$</td>
</tr>
<tr>
<td>Backfill Soil</td>
<td>$1.0 \times 10^{-5}$</td>
<td>$5.0 \times 10^{-6}$</td>
</tr>
<tr>
<td>Clay</td>
<td>$1.0 \times 10^{-7}$</td>
<td>$1.5 \times 10^{-6}$</td>
</tr>
</tbody>
</table>

The Saltstone, concrete, and soil characteristics (capillary pressure and relative permeability) could also affect the convective transport. However, their effects were not as important as the conductivities and diffusivities.

Other mechanisms that may affect contaminant transport are absorption, decay, chemical reactions, and solubility limits. They were believed to be unimportant for nitrate because nitrate is non-absorbing, non-decaying, non-reactive and highly soluble.

**MODELING METHODOLOGY**

The modeling effort was divided into two parts: the unsaturated-zone model and the saturated zone model. The unsaturated-zone model consists of the domain above the water table including, from bottom to top, the native soil, the Saltstone vault, a clay/gravel drain above the vault, backfill soil, a clay/gravel cap over the SDF, and the top soil. The conceptual model and simulation grid for Vault I (New PA) is depicted in Figure 2. The conceptual model and simulation grid for Phase II Vaults are not shown. For
those Vaults, the distance between the center of the vault and the center of the side wall is 100 feet. The height of the "Clean Pour" above the Saltstone is relatively higher as will be described later. The vertical drain removes water from the closure cap. The barrier prevents the run-off water from interfering with the flow around the vault. The saturated-zone model comprises the aquifers and aquitards underlying the SDF in three dimensions. Because of gravitation, contaminants released from a Saltstone vault migrate toward the water table. The unsaturated-zone model predicts mass flux rates (in units of grams/year or Curies/year) to the water table as a function of time and location. These flux rates are used as the source term for the saturated-zone model. The saturated-zone model predicts the spatial contaminant concentrations in the groundwater as a function of time. The compliance point is 100 meters from the facility boundary.

Fig. 2 Conceptual Model and Simulation Grid, Phase I Vaults

DESCRIPTION OF THE ECLIPSE RUNS

The ECLIPSE code [Intera 1994] was used for the simulation. ECLIPSE is a finite-difference petroleum reservoir engineering code with an environmental tracer option. We used ECLIPSE for this study because of its robust equation solver and the "corner point geometry" option. This option allows us to use non-rectangular grids for the sloped roof and closure. Only half a vault was used for the simulation model to take advantage of symmetry. Nitrate was chosen as the contaminant because it does not absorb or decay and is most abundant in the decontaminated salt solution. Nitrate was initially in the Saltstone and then migrated to the surroundings by advection and diffusion. In this study, ECLIPSE solves the two-phase (air-water) two-dimensional (x-z vertical slice) flow and transport problem up to 10,000 years. The properties of all materials are assumed to remain unchanged.

This study focuses on three options for the roof design: 1) the Worst Scenario, only 30 cm (1 ft) clean grout and no additional pour or roof, Phase I vault; 2) the New Design, a 1.33 percent slope concrete pour over the clean grout, Phase I vault; and 3) the Original Design, engi-
neered concrete roof, Phase II vault (New PA). Dimensions of the three roof configurations are depicted in Figure 3. We combined the clean grout and the clean concrete roof as "Clean Pour." We also conservatively assumed the physical properties of the clean grout to be those of the clean concrete even though the hydraulic conductivity and the nitrate diffusivity for the clean grout are smaller. This was also consistent with the INEL assumption. The parameters for the three cases are shown and compared in Table 1. The parameters for the INEL PA modeling efforts are shown under the “Old PA, INEL” case.

Because the surface of the grout is uneven during and after the pour, the height of the Clean Pour ranges between 1' to 1.5' at the edge. The ridge is approximately eight inches higher than the edge. In the New Design for Phase I Vaults, we assumed 28” Clean Pour at the ridge and 29” at the edge. These dimensions are thicker than the actual dimensions of a completed clean pour in a Vault I cell. In The Worst Scenario, we assumed a flat one foot Clean Pour. We also assumed the closure cap to be horizontal. This configuration is more conservative than the completed Vault I pour. Based on these assumptions, we expect that the performance of the actual pour configuration for Phase I vaults will be bracketed by the predictions of the Worst Scenario and the New Design.

RESULTS

Predicted nitrate peak fractional releases and peak groundwater concentrations at the compliance points are summarized in Table 2. The peak concentration for the INEL Old PA was predicted by the saturated zone model. They are estimated for the other three cases by:

$$C_{\max} = \frac{C_{\max, OPA} \times FR}{FR_{\max, OPA}}$$

where \( FR = \) fractional release, and \( OPA = \) Old PA.

Predicted nitrate fractional release curves are shown in Figure 4. For the New PA case, the curve did not peak until after 10,000 years. The value at 10,000 years (1.60E×10^8) is reported in Table 2. The peak concentration for the New PA (0.37 mg/L) is slightly less than half of that of the Old PA (0.87 mg/L). This is probably because 1) The Old PA predicted a 1.0×10^-11 cm/sec percolation rate through the vault that is the hydraulic conductivity of Saltstone. For the New PA, the thicker and steeper roof and sloped closure cap effectively reduced water percolation through the vault. 2) The soil saturation curves used for the Old PA showed high capillary pressure resulting in wet characteristics. The water saturation in the vadose zone for the native soil is above 88%. We feel this value is too high. Adjusted characteristic curves resulted in better water drainage around the vault which reduced head buildup above the vault and, therefore, reduced water percolation.

In the New Design, predicted nitrate peak fractional release is 3.67×10^-8 at 9,900 years. Calculated nitrate concentration is 0.85 mg/L. This increase in peak
concentration is because of the reduced Clean Pour thickness and the smaller size of the Phase I Vault; the smaller the vault, the higher the surface to volume ratio for diffusive contaminant release. In the Worst Scenario, we assumed a flat one foot Clean Pour. Predicted nitrate peak fractional release is $4.35 \times 10^{-6}$ at 6,900 years. The calculated peak groundwater concentration of nitrate is 1.01 mg/L. Since the groundwater MCL for nitrate is 45 mg/L, all predicted nitrate peak concentrations for an intact vault are well below the MCL.

<table>
<thead>
<tr>
<th>Cases</th>
<th>Maximum Fractional Release (per year)</th>
<th>$C_{\text{max}}$ (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Old PA</td>
<td>Value $3.75 \times 10^{-6}$ at 7,100</td>
<td>0.87</td>
</tr>
<tr>
<td>New PA</td>
<td>Value $1.60 \times 10^{-6}$ at &gt;10,000</td>
<td>0.37</td>
</tr>
<tr>
<td>New Design</td>
<td>Value $3.67 \times 10^{-6}$ at 9,900</td>
<td>0.85</td>
</tr>
<tr>
<td>Worst Scenario</td>
<td>Value $4.35 \times 10^{-6}$ at 6,900</td>
<td>1.01</td>
</tr>
<tr>
<td>Maximum Concentration Limit</td>
<td>Value 45.0</td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Predicted Maximum Nitrate Fractional Releases and Groundwater Concentrations.

DISCUSSION

The thickness, slope, and physical properties of the Clean Pour can all affect the performance of contaminant release. Among these properties, the physical properties have the greatest effect. The slope is also important. The thickness is probably least important because the Saltstone itself is less permeable than the Clean Pour. It was assumed that the clean grout has the same properties as the clean concrete. In reality, clean grout should have the same properties as the Saltstone ($K = 1.0 \times 10^{-11}$ cm/sec, $D = 5.0 \times 10^{-9}$ cm$^2$/sec). From groundwater concern, one foot of flat clean grout should result in a performance close to that predicted by the New PA case.

Based on the mechanisms of contaminant transport, the addition of an engineered roof above the current Clean Pour in a Phase I Vault cell appears to be unnecessary. Because water penetrates the vault in a downward direction, it will offset the upward contaminant diffusion. In contrast, contaminants are released through the bottom of the vault by diffusion and convection; and side of the vault by diffusion only. It is not necessary to have the Clean Pour thicker than the bottom slab or the side slab. The thicknesses for the concrete slabs are two feet at the bottom and 1.5 feet at the side. A Clean Pour of 1.5 feet will not result in more contaminant migration through the top than through the side walls, per unit area. Based on this reasoning, we believe the current pour on top of the Phase I Vault is adequate for groundwater protection. The only justification for considering an engineered roof or thicker pour is to delay the onset of vault cracking or to reduce the crack dimensions. These effects have to be quantified before we can conduct an ECLIPSE modeling study of the fractured scenarios.

When the saltstone vault is cracked, most of the contaminant release will be through the cracks. INEL used an analytical model to predict the fractional release from a fractured Saltstone vault. Predicted nitrate peak concentration was 53 mg/L (Cook 1993) compared to 0.87 mg/L for the intact case. Since INEL assumed that there was no contaminant transport through the external surfaces of the vault, there is no way to evaluate the effect of the design change on nitrate release using the analytical fractured model. WSRC is developing an ECLIPSE fractured model. Results of the fractured model will be reported later.
CONCLUSION

With the assumption of an intact Saltstone vault for 10,000 years, we can pour one foot of clean grout at 0% slope over the Saltstone and still meet the groundwater performance requirements. With the assumption of a fractured Saltstone vault, most of the contaminants are released through the fractures. Increasing or reducing the roof thickness will not significantly impact contaminant transport to the groundwater. These results support a design change to eliminate the concrete cover or additional pours over the current Phase I Vault configuration.

ACKNOWLEDGMENT

This work was sponsored by the U.S. Department of Energy Office of Environmental Restoration and Waste Management under DOE Savannah River Field Office Contract No. DE-AC09-89SR18035.

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AUTHORS' BIOGRAPHIES

Robert Hsu is a Fellow Engineer at the Savannah River Technology Center of Westinghouse Savannah River Company in Aiken, South Carolina. His current interests are in groundwater modeling, performance assessment, low-level and mixed waste disposal technology. He received D.E.S. and M.S. degrees in chemical engineering from Columbia University. Before joining the Savannah River Site in 1984, he worked for 3 years in the chemical processing industry with Du Pont.

Andy Yu is a Principal Engineer at the Savannah River Technology Center. His main interests are in groundwater modeling, performance assessment, low-level waste disposal technology, and environmental restoration. He received a Ph.D. in chemical engineering from the University of Wisconsin. Before he joined Du Pont at the Savannah River Site in 1988, he worked for 12 years in the petroleum industry with Chevron, Petroleum Recovery Research Center, and Texaco, on reservoir simulation and enhanced oil recovery.

Poh-Sang Lam is a Principal Engineer at the Savannah River Technology Center. His main interests are in groundwater modeling, fracture mechanics and structural integrity. He received a Ph.D. in Theoretical and Applied Mechanics from the University of Illinois. Before joining the Savannah River Site in 1990, he worked for 6 years with Goodyear Tire & Rubber Co.