MODELING THE FLOW OF WATER IN AND AROUND SHALLOW BURIAL TRENCHES*

C. J. Suen
Brookhaven National Laboratory
Upton, New York 11973

ABSTRACT

Water flow through a generic low-level waste burial trench has been modeled for a vertical cross-section perpendicular to the longitudinal axis of an elongated trench, using the finite element code, FEMWATER, in two-dimensional vertical mode. The grid consists of 513 nodes and 468 variable-size quadrilateral elements, and the simulation domain is about 56 m (H) x 34 m (V). The trench, which is situated in the unsaturated zone, measures approximately 28 m wide and 10 m deep in cross-section, and is composed of three types of soil a high-conductivity gravel cap on top, a low-conductivity clay layer beneath it, and backfill soil in the waste burial region. The rest of the domain is made up of undisturbed soil. Different cases have been simulated by varying boundary conditions, geometry and hydraulic properties. These results are used in radionuclide transport calculations to determine the "source term" (4). In addition, numerical experiments provide valuable information in trench design, such as, the geometry of the moisture barrier. Results from these experiments indicate that a moderate extension (8 m) of the clay layer beyond the sides of the trench can significantly reduce the net water flow (by 42%). They also show that sparsely distributed waste packages have minimal effect on the net flow through the trench.

INTRODUCTION

The objective in modeling shallow-land burial trenches for low-level wastes is to predict the release rates of radioactive nuclides into the environment. It has long been recognized that advection is the major mechanism in the transport of chemical species through the soil (1), and therefore, in order to calculate the amount of radioactivity released with time, the flow of water into and out of these trenches must first be modeled. In addition to transport, water also plays an important role in the processes of leaching and container corrosion, which likewise control the release of radionuclides into the soil from waste forms (2,3). Hence, the flow rate and the moisture content of the soil are essential information in determining the "source term". This paper is part of the overall effort at Brookhaven National Laboratory in the determination of the "source term" for low-level waste burial trenches. Results from this work have been used to calculate radionuclide release rates using the solute transport model discussed in a separate paper presented in this meeting (4).

The flow of water in the unsaturated (vadose) zone, where shallow trenches are located, can be conveniently simulated by computer models applying finite element, finite difference and other related techniques. One of the main advantages of using a computer model is that variables, such as geometry, external conditions (rainfall etc.) and hydraulic properties, can easily be changed, and their effects on the behavior of the system can be separated and studied individually without much difficulty. The finite element method also has the additional ability to handle irregular-shape geometry and complex heterogeneities. Computer codes which can be used to predict the environmental effects of hazardous and nuclear waste disposal sites have been reviewed by several NRC and EPRI contractors (5,6). This paper reports the findings of two-dimensional water flow simulations in the vertical mode using the recently revised version of the finite element computer code FEMWATER (7,8). These output data are then used for calculating radionuclide releases with the companion computer code FEMWASTE (9), reported by a separate paper given at this meeting (4). These Fortran codes have been compiled and executed with either a DEC/VAX or IBM-PC/AT computer. Identical cases show no significant discrepancies in the results between outputs from the two different systems.

MODEL DESCRIPTIONS

This model is non-site specific. It is designed to represent a general situation but can be easily modified to accommodate for site specific data. It primarily simulates a uniform vertical cross-section (in the x-z plane) of a shallow trench perpendicular to its longitudinal axis (y-direction). It is further assumed that the groundwater velocity vectors are parallel to such a cross-section for the major portion of the trench, except close to the two ends. Therefore, a

---

* This work was performed under the auspices of the United States Nuclear Regulatory Commission.

two-dimensional representation is sufficient for the purpose, and the results would be most applicable to the central portion. Because of complete bilateral symmetry in the geometry considered, the actual simulation has been carried out only on half of the vertical cross-section. The left half has been arbitrarily chosen, with the plane of symmetry on the right, and the origin of the x-z coordinate system at the lower left corner of the domain of simulation. The elements and nodes are conveniently numbered from bottom to top and from left to right (Fig. 1). The trench area is located at the upper right. This is the principal area of interest where detailed groundwater flow rate, pressure head and moisture content are sought.

The entire domain is divided into a total of 468 quadrilateral elements and 513 nodes. The variable-size elements are the smallest within the trench area where a higher resolution is required, while their size increases with the distance from the trench. The overall dimensions of the simulation domain are 56 meters wide and 34 meters deep, with the trench measuring approximately 28 meters wide by 10 meters deep (in a complete cross-section).

The purpose for using an extended domain with boundaries far from the trench area is to ensure that the simulated groundwater flow through the burial trench is independent of the artificially imposed boundary conditions (B.C.). These artificial B.C. are necessary, because, for generic cases, conditions at or near the trench boundary cannot be measured or predetermined. Therefore, arbitrary conditions are imposed at some distances from the trench such that they have minimal effects on the water flow in the region of interest. The minimum distances for these boundaries can only be determined for each individual case by a trial-and-error process. On the contrary, to simulate site-specific cases, the boundary conditions should be prescribed according to field conditions whenever possible.

The top boundary is the ground surface, and, hence, designated as a rainfall-seepage type boundary. The rainfall-seepage boundary is a variable type boundary condition which is treated as either a prescribed head (also known as Dirichlet or the first type boundary value problem) or a prescribed flux (also known as Neumann or the second type boundary value problem) boundary condition, depending on water saturation at the surface to be determined by an iterative loop. Rainwater is allowed to infiltrate into the ground at a net rate equal to rainfall minus evapotranspiration. Under the condition of time-averaged rainfall, no ponding occurs, and therefore, the prescribed flux condition normally prevails. The right boundary of the simulation domain, which is the axial plane of the trench, can be accurately treated as an impervious (or no-flow) boundary because it is the plane of symmetry. In contrast, the left boundary is an artificially imposed boundary, and is arbitrarily taken also as an impervious boundary for convenience. It is placed far enough from the trench, so that its presence would not have any effect on the water flow around the trench region. Similarly, another impervious boundary is placed at the bottom. A near-horizontal phreatic surface (water table) is artificially created close to the bottom boundary by specifying constant heads (Dirichlet B.C.) for the bottom two nodes of the left and the right boundaries (Node nos. 1, 2, 495, 496 in Fig. 1). For some specific cases in which the effect of the water table is important, this arrangement allows the formation of a somewhat "free" phreatic surface and imposes less arbitrary constraint to the solution of water flow in the region of interest, i.e., the trench area. The prescribed heads at the Dirichlet boundary nodes can also be adjusted by an iterative process. Alternatively, a fixed horizontal phreatic surface can be produced by specifying head values of the bottom row of nodes, but this does not allow for the effects of the rise and fall of the water table, hence, changing saturation profile, resulting from varying rainfall rates.

The domain is made up of four materials of different hydraulic properties: 1) the undisturbed soil outside the trench area (assuming a sandy soil with a saturated hydraulic conductivity, $K_{sat} = 10^{-4}$ cm/s), 2) the backfill soil inside the waste burial region ($K_{sat} = 10^{-3}$ cm/s), 3) the clay layer designed as a rainwater barrier ($K_{sat} = 10^{-8}$ cm/s), and 4) the gravel cap used to prevent excessive erosion ($K_{sat} = 5.0$ cm/s). All of their properties are taken to be isotropic, and the values used in the simulations are listed in Table I. Because the actual field values for these soil types vary considerably with their localities and depositional histories, the values used for this modeling work were chosen arbi-trarily to reflect their relative differences, and they are non-site specific.

A number of numerical experiments have been carried out using this finite element setup, with varying amounts of rainfall and changing bottom B.C. The results and the conditions of some representative cases are discussed in the following section.

RESULTS AND DISCUSSIONS

Steady-State Simulation with Time-Averaged Rainfall

A number of steady-state cases have been simulated using the finite element grid described. Because these are time-invariant solutions, time-averaged rainfall rates must be used. The bottom boundary condition (Dirichlet B.C. on both sides near the bottom boundary) is *adjusted slightly* by iteration to accommodate different rainfall rates, so as to produce a near-horizontal phreatic surface near the bottom of the domain of simulation. Although the solutions, resulting from varying rain-fall and boundary conditions, lead, as expected, to different values of hydraulic head, pressure head, saturation and darcy velocity, the basic results from these simulations are quite similar. Therefore, only one typical case is presented here. This case corresponds to a

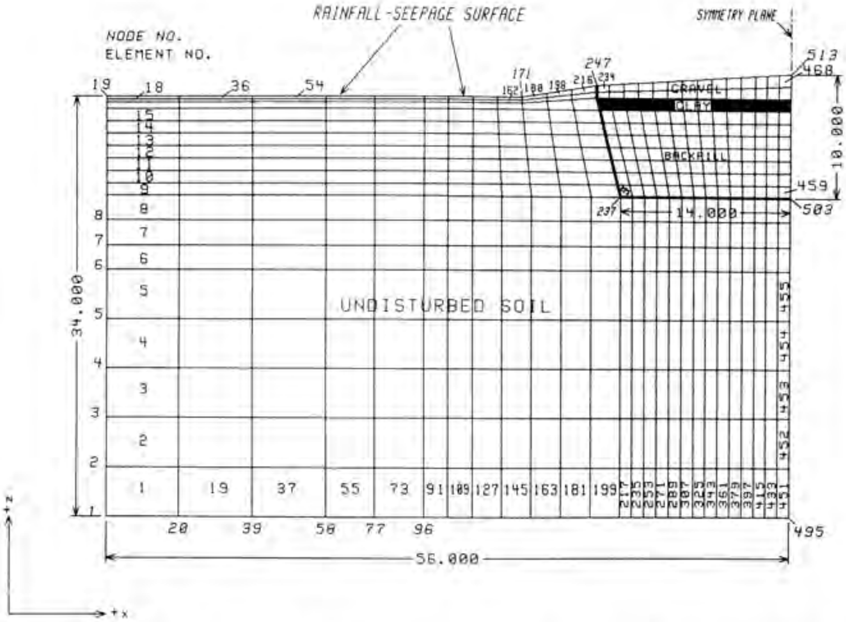

Fig. 1. The Finite Element Grid. Node Numbers are Slanted; Element Numbers are Not. Dimensions Shown are Given in Meters.

TABLE I

Soil Properties Used

	Porosity (%)	Hyraulic Conductivity (cm/sec)
Undisturbed soil	30	10^{-4}
Backfill	40	10^{-3}
Clay layer	50	10^{-8}
Gravel cap	30	5.0

Pressure Head (cm)	Moisture Content (Volumetric)				Relative Conductivity	
	(1)	(2)	(3)	(4)	(1) (2) (3)	(4)
- 800.0	0.024	0.032	0.040	0.0024	0.0758	0.00758
- 200.0	0.0425	0.0567	0.0708	0.00425	0.1120	0.01120
- 100.0	0.09	0.12	0.15	0.009	0.2758	0.02758
- 25.0	0.285	0.380	0.475	0.0285	0.9483	0.0948
- 12.5	0.290	0.387	0.483	0.029	0.9655	0.0965
0.0	0.2925	0.390	0.4875	0.2999	0.9655	0.965
100.0	0.2995	0.3993	0.4992	0.30	0.9999	0.999
2000.0	0.30	0.40	0.50	0.30	0.9999	0.999

Column (1): undisturbed soil
(2): backfill
(3): clay layer
(4): gravel cap

rainfall rate of 127 cm/year, approximately equal to the average annual precipitation of South Carolina without evapotranspiration.

Fig. 2a and Fig. 2b show the hydraulic (or total) head and pressure head distributions, respectively, in the entire domain under steady-state condition. From the pressure head contours (Fig. 2b), the phreatic surface (or water table) can be located where the solution of pressure head equals zero, and, thus, coincides with the zero contour near the bottom boundary. It is about 20 meters from the bottom of the trench, and it bulges slightly upwards in the middle. This sym-metrical shape is produced by the two identical Dirichlet B.C. at both the lower left and lower right corners. Above the water table, the pressure head contours between the trench and the water table are nearly horizontal and uniformly spaced, indicating that neither the artificial bottom B.C. nor the presence of the burial trench has any significant effect on water saturation of this region. Therefore, the pressure head solution within the trench area, which is higher up in the cross-section, is practically neutral to the artificial boundary at the bottom, and it is mainly controlled by the soil properties and the geometry of the region. In Fig. 2b, it can be easily seen that the effect of an almost impervious clay layer dominates the pressure head distribution in the trench.

Similar observations can be made from the hydraulic head distribution in Fig. 2a. The bottom contours are symmetrical, showing water flow towards the two bottom corners where "outlets" are created by the Dirichlet nodes. The contours in the mid-section are nearly horizontal and uniformly spaced, and so are those near the ground surface at only a short distance (>10 m) away from the trench region. These again reflect that the arbitrary conditions at the bottom have minimal effect on water flow in the upper half of the domain of simulation, and the existence of the trench only affects water flow immediately adjacent to it.

The water flow pattern is shown in more detail in the plot of darcy velocity vectors originating from the corresponding nodal points (Fig. 3). As expected from the head solutions, the vectors become essentially vertical at a short distance away from the trench, as indicated by the vertical-line pattern in Fig. 3. Again, this reflects that the water flow in most of the domain is practically neutral to the trench and the bottom B.C. Velocity vectors within the trench area show that rain water infiltrates into the high-conductivity gravel cap, but it cannot penetrate the clay layer below. As a result, water flows horizontally away from the trench axis towards the edge. A very thin zone of water saturation exists just above and below the gravel/clay interface. (The details of this region are lost by the contour algorithm used and cannot be observed in Fig. 2a and 2b.) From Fig. 3, it is also evident that, although the clay layer forms an effective moisture barrier by pre-venting rainwater from flowing into the waste burial regionfrom above, water can still bypass this barrier and enter through the sides at a significantly high rate due to capillary pressure in the backfill. This is indicated by the velocity vectors of relatively large magnitudes. The obvious solution to this problem could be either: 1) extending the clay barrier horizontally to an optimum distance, or 2) constructing another moisture barrier vertically along the sides of the trench. The first possibility has been investigated numerically using the existing model, and the results are discussed in the following section.

The Effect of Extending the Trench Cap

The effect on water flow through the trench area, resulting from extending the moisture barrier beyond the area immediately above it, has been simulated by changing the soil properties of the appropriate elements. The trench cap (consisting both gravel and clay layers) has been extended 4, 8 and 12 meters as shown in Fig. 4. The results of these cases can be compared with the "standard" configuration in Fig. 4a. All boundary conditions and the rainfall rate have been kept identical, as described previously. An average rainfall of 127 cm/yr has been used for all these cases.

Fig. 3 shows most of the water enters through the side and exits from the bottom. Hence, the reduction of water flow through the trench area can be measured by comparing the total water flux through the trench bottom. This can be evaluated by plotting the darcy velocity components normal to the trench bottom from Node 237 to Node 503 as shown in Fig. 5. The areas under the curves have been integrated simply by Simpson's rule, and are given in Table II. Evidently, the amount of water flowing through the trench can be significantly reduced by extending the moisture barrier by only a few meters. Specifically, a 25% reduction can be achieved by a 4-meter extension on each side. The reduction will be approximately doubled (to 53%), if the extension is tripled to 12 meters. However, this may be impractical, since it would make the horizontal area of the cap about twice that of the trench itself. A similar finding was reported by Dennehy and McMahon (10), whose simulation results showed that a 3-meter wide compacted clayey-sand barrier around the perimeter of their experimental trench greatly inhibited water from entering it. The optimal amount of extension and the most desirable geometry of the moisture barrier would be controlled by a combination of factors, such as the soil properties and the dimensions of the trench, as well as operational practicality. Nonetheless, it can be conveniently determined by numerical simulation models as exemplified here.

The Effect of Waste Packages

In practice, the waste packages are placed inside the trench region which is subsequently backfilled with soil. Most of these packages, e.g., carbon steel drums and high-integrity containers (HICs), initially have very low or practically zero hydraulic conductivities. In order to simulate the

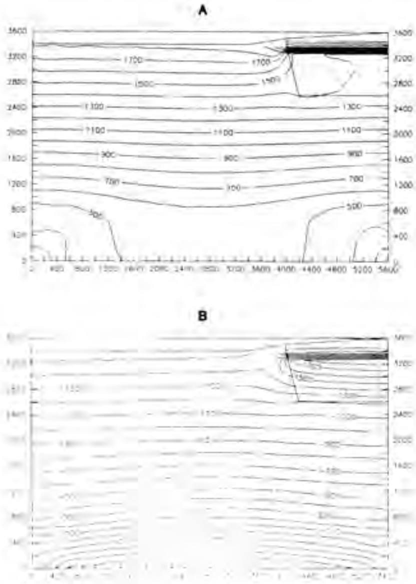

Fig. 2. (A) Hydraulic Head Distribution; (B) Pressure Head Distribution for a "Standard" Case, Under Steady-State Condition, Corresponding to an Average Rainfall of 127 cm/yr. Both Units for the Contour Lines and for the Distance Tic Marks (On Borders) are Centimerters.

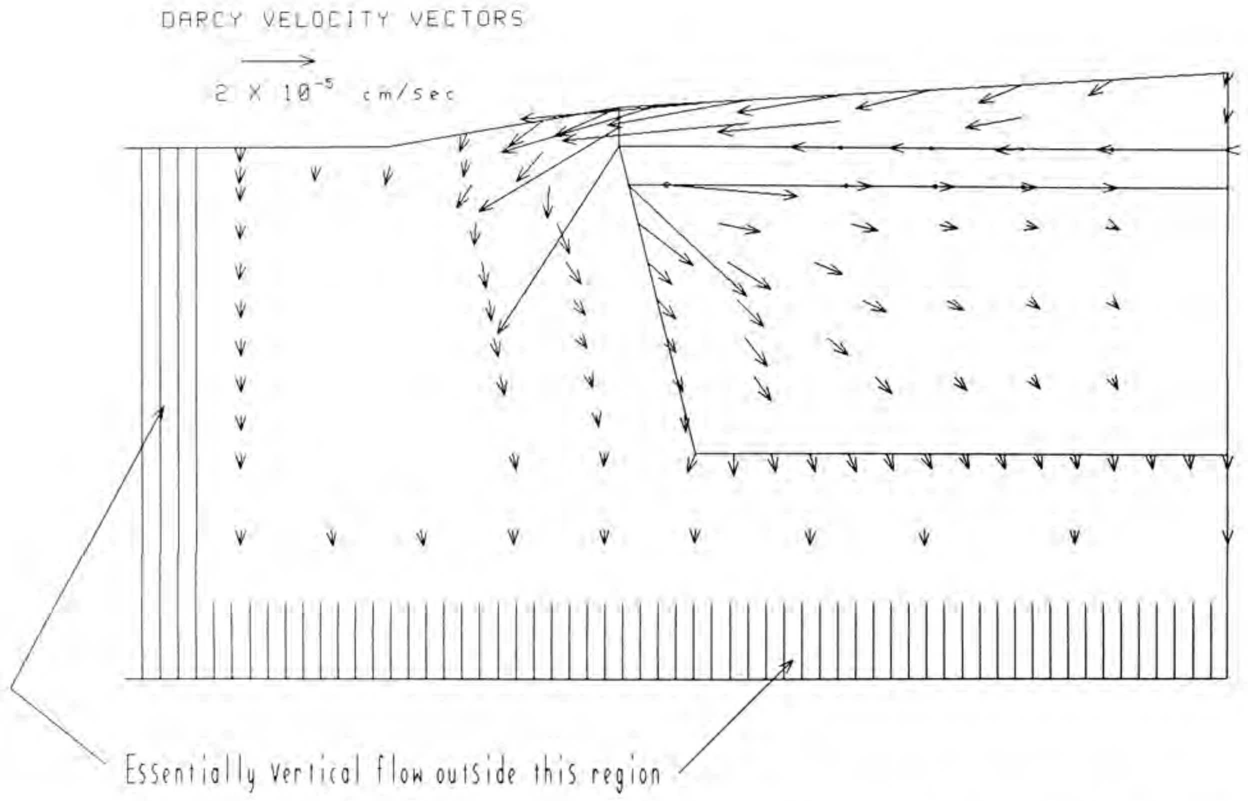

Fig. 3. Darcy Velocity Vectors of the Trench Region. Magnitude of Vectors can be Approximated by Comparing With an Example Given in the Upper Left Corner.

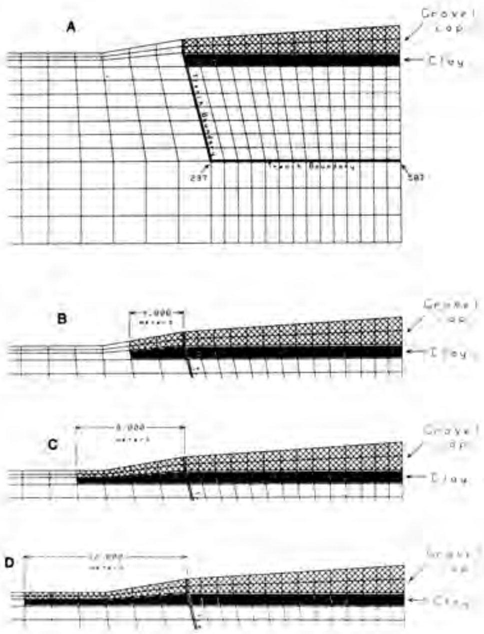

Fig. 4. Extension of the Trench Cap Beyond the Trench Boundary. (A) The Standard Case; (B) 4-Meter Extension; (C) 8-Meter Extension; (D) 12-Meter Extension.

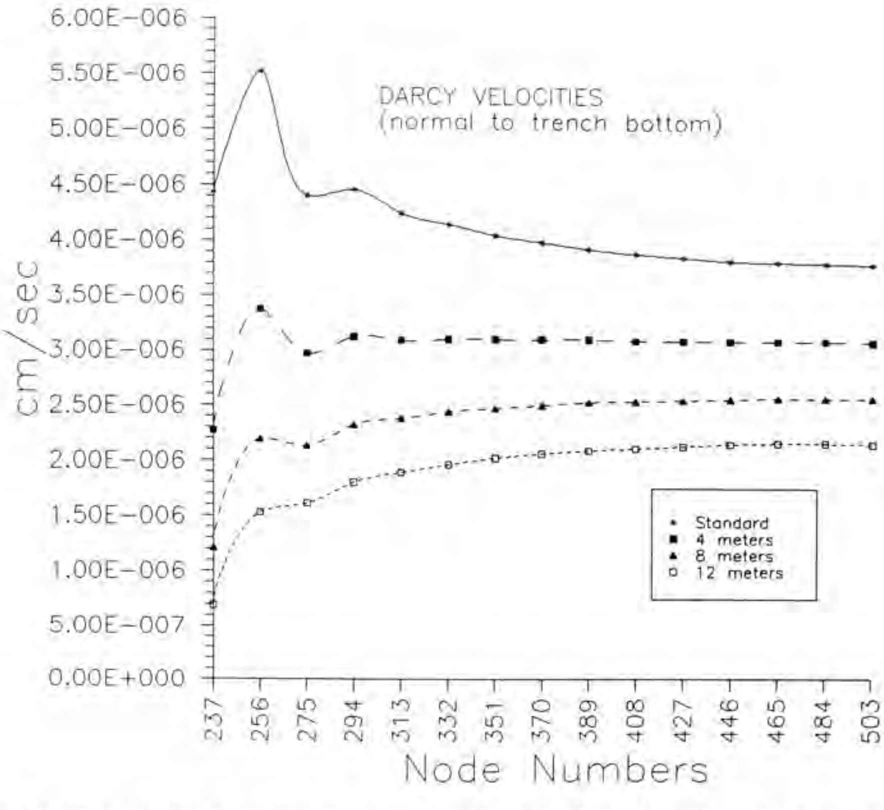

Fig. 5. Profiles of Darcy Velocity Components Normal to the Trench Bottom (from Node No. 237 to Node No. 503) for the Different Cases Shown in Fig. 4.

TABLE II

Calculated Net Water Fluxes Normal to the Trench Bottom for Different Extensions of the Clay Barrier

	Total Flux (cm^3/sec/cm)	Percent Reduction
Standard Case	5.84×10^{-3}	-
4-meter extension	4.34×10^{-3}	25.7%
8-meter extension	3.38×10^{-3}	42.0%
12-meter extension	2.72×10^{-3}	53.3%

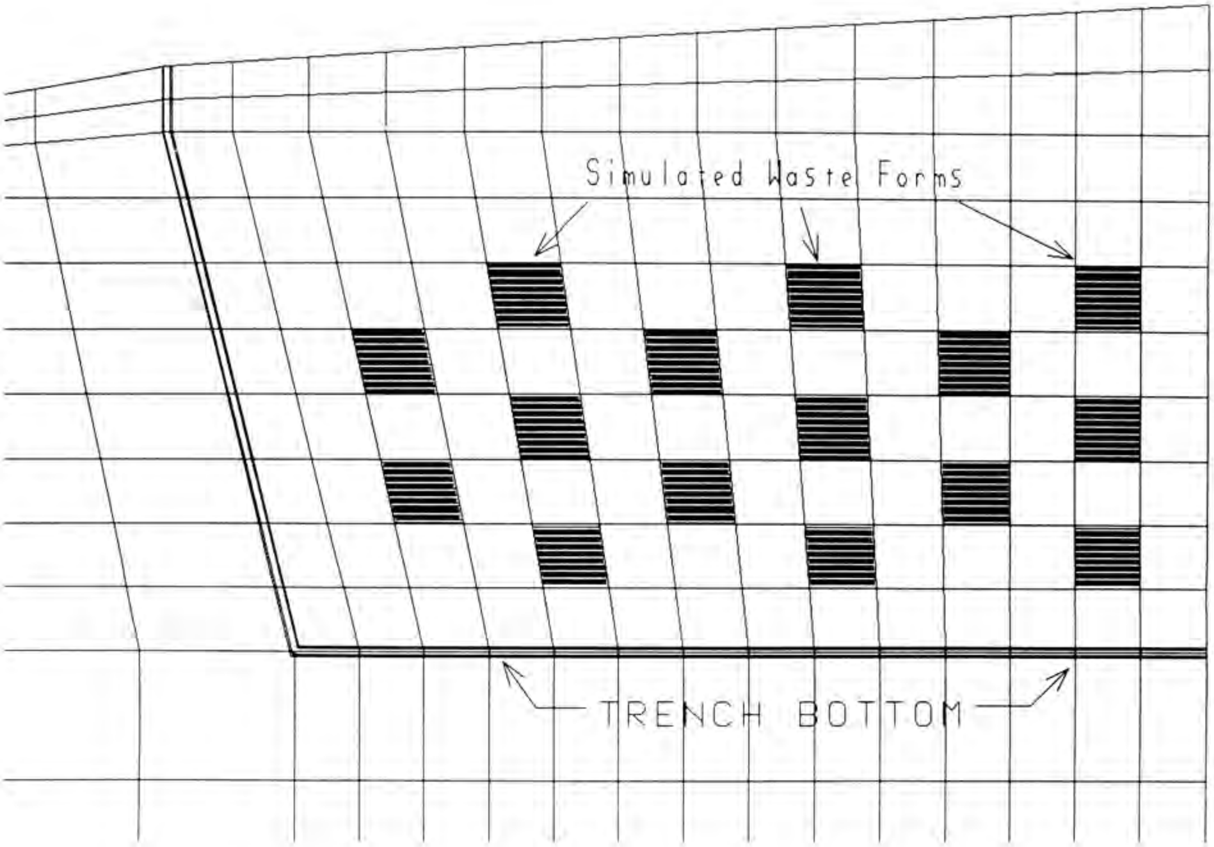

Fig. 6. Elements Used to Represent Waste Packages in the Trench.

overall effect on water flow through the trench due to the presence of such waste packages, selected elements within the waste burial region have been assigned a different set of hydraulic properties. These elements are shown in Fig. 6. With this regular pattern, 1 out of every 4 elements (or 25%) in the interior b of the burial region is used to represent a waste package. In practice, this number may be higher (<25%). Also in reality, the waste packages are not continuous in the third dimension (along the y-axis), and water must also flow around them in the y-direction. However, because water flow is restricted artificially to two dimensions (the x-z plane) in the present model, the results from this 2-D model would lead to the over-estimation of the net effect of flow inhibition by impervious packages. This would, therefore, tend to offset the low volume percentage of waste packages used in the simulation. To accurately predict these opposing effects, a three dimensional model must be used. Nevertheless, a rough estimate can be gained from simulated results using the current 2-D model.

In addition to simulating the effect of almost impervious (very low hydraulic conductivity) waste packages, it is important to investigate the opposite effect of highly permeable packages. From the two extreme cases, some ideas on the complete range of variations due to different hydraulic properties can be obtained. For convenience, hydraulic properties identical to the clay layer have been used to represent the impervious waste packages, and those of the gravel cap have been used for the high-conductivity packages.

As in the numerical experiments described in the last section, the overall water flow through the burial trench can be estimated by plotting the darcy velocity components normal to the trench bottom as shown in Fig. 7a & 7b. Again, the velocity profile with the waste packages is compared to a standard case without the waste packages. Fig. 7a indicates the perturbation of simulated flow velocities at the trench bottom by the presence of impervious waste packages. It can be seen that, although in some sections, the flow velocity is reduced relative to the standard case, the flow velocity in other sections increases. This is because in the unsaturated zone, water readily channels through the area of relatively higher conductivity (and less resistance) bypassing the low-conductivity obstacles. In addition, the effective conductivity in the channel area further increases because of higher saturation. This same phenomenon is observed in the case of very high conductivity waste packages (Fig. 7b), with the exact opposite effect.

In the unsaturated zone, this channeling phenomenon minimizes the impact on the net flow-through rate across the total area. As before, the net water flux across the trench bottom can be evaluated by integrating the area under the curves in Fig. 7a and 7b, simply by using Simpson's rule. The calculated results are listed in Table III. The net effect due to the impervious waste packages is a 1.78% reduction in net flux, while that due to the very high conductivity packages is a 2.22% increase. Despite the over-estimation of the effect resulting from 2-D modeling, it can be concluded that the presence of waste packages in the trench has only minimal effect on the overall water flow rate through the trench area, provided that enough space between the packages is left for the backfill. This tentative conclusion is based on very rough approximations. If more details are needed, they must be obtained by using a finite element mesh with a higher-resolution, and, possibly, 3-D modeling.

CONCLUSIONS

A finite element model has been used, in the 2-D vertical mode, to simulate groundwater flow through a generic burial trench under different conditions and geometry. Based on the results of these simulations, the following conclusions can be drawn:

1) Steady-state simulations show that the low-conductivity clay layer is aneffective moisture barrier by preventing rainwater from infiltratingdirectly into the burial trench, but water in the gravel cap flows towardsthe edge and enters the trench from the sides due to capillary suction.Therefore, in order to optimize its performance, the moisture barriershould be extended beyond the sides of the trench. Modelingresults show that a 42% reduction in overall flow through rate can beachieved by an extension equal to 25% of the trench width (about 8 meters).
2) The net water flow through the trench is not significantly affected bysparsely distributed waste packages with wide spaces between them.However, the effect of tightly packed waste packages warrants more detailedstudy.
3) Without any knowledge of the boundary conditions in the proximity of aspecific trench location, a generic trench can be modeled with artificiallycreated boundary conditions placed far away from the trench region. Thesimulated flow through this trench would be free from the effects of theartificial boundaries provided they are at reasonable distances away fromthe region of interest.

This paper is part of the on-going project at Brookhaven National Laboratory in the determination of the "source term" for low-level waste burial trenches, performed under the auspices of the U.S. Nuclear Regulatory Commission. The data generated from these water flow simulations have been used to model transport of radionuclides. The results are discussed in a complementary paper presented in this meeting (4).

REFERENCES

1. General Research Corporation, "Study of Chemical Toxicity of Low-Level Wastes," Vol. 1., NUREG/CR-1793, (1980).

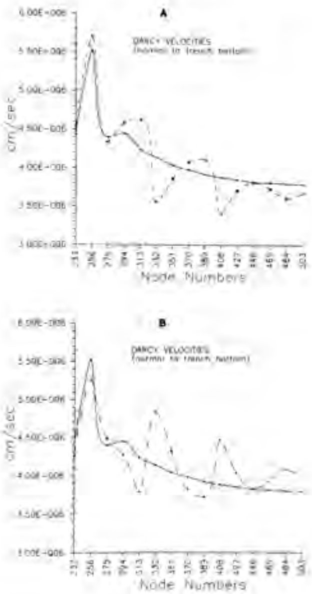

Fig. 7. Comparing Profiles of Darcy Velocity Components Normal to the Trench Bottom for: (A) a Case of Almost Impervious Waste Packages (Dashed Line) With the "Standard" Case (Solid Line); (B) a Case of High-Conductivity

TABLE III

Comparison of Net Water Fluxes Normal to the Trench Bottom for the Cases With Impervious and Very High Conductivity Packages

	Total Flux ($cm^3/sec/cm$)	Percent Change
Standard Case	5.84×10^{-3}	-
Low-K Waste Packages	5.73×10^{-3}	-1.78%
High-K Waste Packages	5.97×10^{-3}	+2.22%

2. S. M. Mughabghab and T. M. Sullivan, "Investigation of the Pitting Corrosion of Low-Carbon Steel Containers," Waste Management '88, (1988).

3. C. R. Kempf, "A Mechanistic Model for Leaching from Low-Level Radioactive Waste Packages," Waste Management '88, (1988).

4. T. M. Sullivan, "Prediction of the Migration of Radionuclides to the Boundary of a Shallow Land Burial Trench," Waste Management '88, (1988).

5. C. A. Oster, "Review of Ground-Water Flow and Transport Models in the Unsaturated Zone," NUREG/CR-2917, PNL-4427, (1982).

6. C. T. Kincaid, J. R. Morrey, and J. E. Rogers, "Geohydrochemical Models for Solute Migration. Volume 1: Process Description and Computer Code Selection," EPRI EA-3417, Vol. 1, (1984).

7. G. T. Yeh and D. S. Ward, "FEMWATER: A Finite-Element Model of WATER Flow Through Saturated-Unsaturated Porous Media," ORNL-5567, (1980).

8. G. T. Yeh, "FEMWATER: A Finite-Element Model of Water Flow Through Saturated-Unsaturated Porous Media First Revision," ORNL-5567/R1, (1987).

9. G. T. Yeh and D. S. Ward, "FEMWASTE: A Finite-Element Model of WASTE Transport through Saturated-Unsaturated Porous Media," ORNL-5601, (1981).

10. K. F. Dennehy and P. B. McMahon, "Effects of Trench Design and Infiltration Fluxes in Soil-Moisture Migration into Burial Trenches at Barnwell, South Carolina," Proc, Eighth Annual DOE Low-Level Waste Management Forum, Denver, Colorado, September, 1986, Technical Session 1, 99, (1987).