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ABSTRACT

The Network Flow and Transport (NWFT) model has been developed at Sandia to supplement the groundwater flow and radionuclide transport capability provided by the Sandia Waste Isolation Flow and Transport (SWIFT) model. NWFT requires only a small fraction of the computer time required by SWIFT. However, transport calculations in NWFT are presently limited to decay chains of up to three isotopes which must have the same distribution coefficients. It is anticipated that NWFT will be used jointly with SWIFT. SWIFT will be used to establish the fluid flow field for different depository breachment scenarios. SWIFT will also provide pressure boundary conditions for NWFT and will be used to check selected NWFT radionuclide discharge results. NWFT will be used in sensitivity and risk analysis to examine the effects of variables which alter the radionuclide source rate and migration time.

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## 1. Introduction

The Fuel Cycle Risk Analysis Division at Sandia Laboratories is funded by the Nuclear Regulatory Commission to develop a methodology for risk assessment of radioactive waste disposal in geologic media (Ref. 1). As part of this program, the SWIFT model for transport of radionuclides dissolved in groundwater has been developed (Ref. 2). SWIFT is a three-dimensional, finite difference model which solves equations describing fluid flow, conservation of energy, conservation of non-trace solute mass (e.g., dissolved salt) and radioactive trace component transport. The sophistication and flexibility which make the SWIFT program very powerful for the study of physical processes also make it somewhat unwieldy when one needs a simple, efficient means for calculating radionuclide transport without concern for thermal effects, brine transport, or some of the other, additional capabilities of the SWIFT program. The Network Flow and Transport model (NWFT) was developed to help meet the need for a simple, efficient model of radionuclide transport for use in risk assessment.

Groundwater flow calculations are performed in NWFT by first describing the flow system as a network of one-dimensional segments. Fluid discharge and velocity are determined by requiring conservation of mass at the segment junctions. Once the flow system is established, the radionuclide migration pathway from the depository to the discharge point is determined. Radionuclide discharge is then calculated by assuming that transport occurs along a single, one-dimensional path having length equal the total migration path length and using the average isotope velocity. In spite of its obvious simplicity, the single path assumption can be applied to a large class of depository breachment scenarios. Use of an average velocity is, we believe, adequate in most cases for risk assessment as it preserves the total radionuclide migration time.

In its present form, NWFT allows different values of hydraulic conductivity, porosity, and distribution coefficient to be used for each flow segment. A radionuclide chain of no more than three isotopes can be transported and, at the present time, all isotopes in the chain must have the same distribution coefficient. Other limitations of the model in its present form include: (1) it does not account for the effects of brine on flow, (2) waste form solubility limits cannot be taken into account and (3) the model represents a two-dimensional flow system as a network of one-dimensional segments and thus cannot adequately treat some two-dimensional problems. An example where the third limitation applies is the withdrawal of contaminated water by a water well. In this case, lateral dispersion (which is not accounted for in NWFT) reduces the contaminant concentration in the water withdrawn from the well.

One further important caution needs to be stated here. A simplified model such as NWFT should be used only in conjunction with a model such as SWIFT which provides a realistic description of the fluid flow field. SWIFT can be used to determine the radionuclide migration path for any particular depository breachment scenario. NWFT can then be applied to reproduce the migration path and to evaluate the effects on radionuclide discharge of variables which alter the radionuclide source rate or migration time.

In Chapter 2, the physical content of NWFT is described in some detail including a brief discussion of the Reference Site (Ref. 1) which motivates the form of the flow network used in NWFT. Chapter 3 contains a description of input to NWFT. Chapter 4 provides brief descriptions of the individual subroutines in NWFT. Comparisons between NWFT and SWIFT are presented in Chapter 5 along with sample problems.

## 2. Physical Content of NWFT

### 2.1 The Reference Site

The construction of the flow network in NWFT is loosely based on a hypothetical flow system which serves as a reference site for the risk methodology development program. The reference site is described in detail in Reference 1 and will only be discussed briefly here.

The site is located in a symmetrical upland valley, half of which is shown in Figure 2.1. The crest of the ridge surrounding the valley is at an elevation of 6000 feet. The crest is a surface and groundwater divide so that the only water moving in the valley is water that falls in the valley. The valley is drained by a major river, River L, which is at an

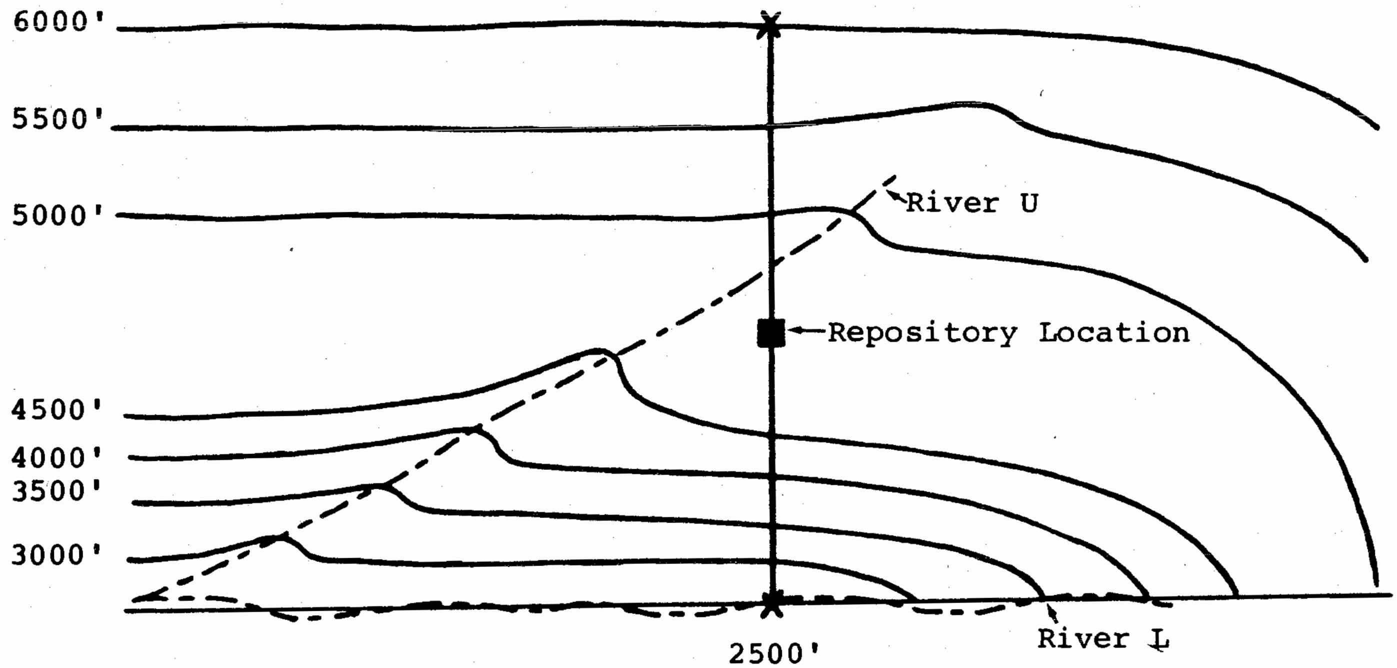



Figure 2.1. Physiographic Setting of the Reference Site

elevation of 2500 feet opposite the surface structures of the repository.

The geology of the area near the site is shown in cross-section in Figure 2.2. The valley is underlain by crystalline bedrock which crops out over a narrow strip lying at the ridge crest surrounding the valley. The bedrock is assumed impermeable to groundwater flow. The bedrock is overlain by a sequence of sedimentary rocks as shown in Figure 2.2.

Groundwater flow at the reference site is shown schematically in Figure 2.3. Flow in the upper sand and gravel aquifer is not shown here as it is hydraulically isolated from the middle sandstone by the upper shale. Barring disruptive events, the permeability of the shale and salt is sufficiently low that flow through these layers is generally insignificant.

A reduced representation of the reference site (the outlined portion in Figure 2.2) was used in the SWIFT model to calculate pressures. The resultant pressure head distribution is shown in Figure 2.4.

## 2.2 The Network Flow Model

Both Figures 2.3 and 2.4 suggest that flow in the middle and lower sandstone aquifers (or some portion of them) can be adequately represented by one-dimensional flow systems. Thus the network representation shown in Figure 2.5 was developed. Legs, pressures and positive flow directions are identified in Figure 2.6. Legs 1, 2, and 3 are used to represent the middle sandstone aquifer. Legs 4, 5, and 6 represent the lower aquifer

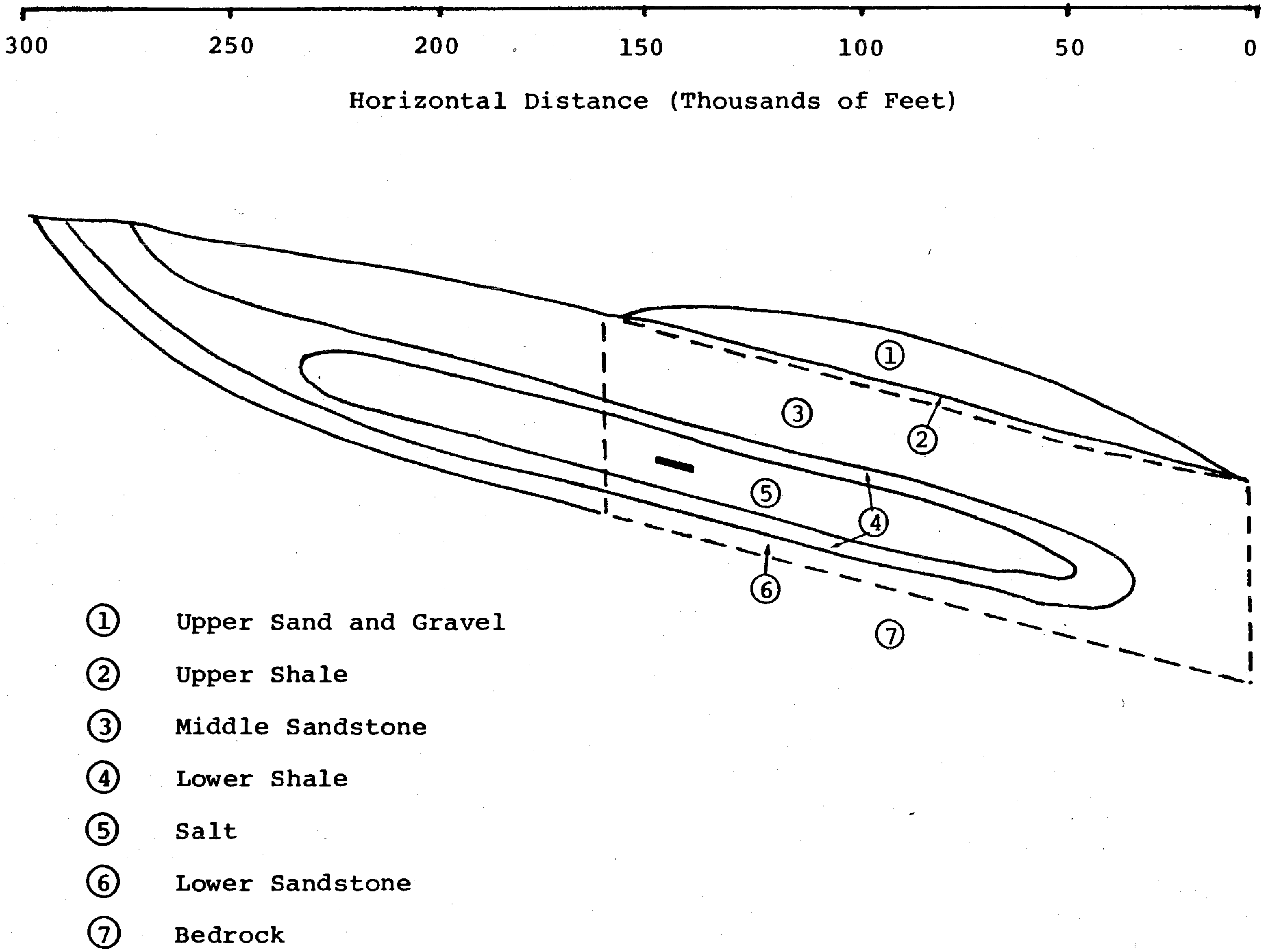



Figure 2.2. Reference Site Geology

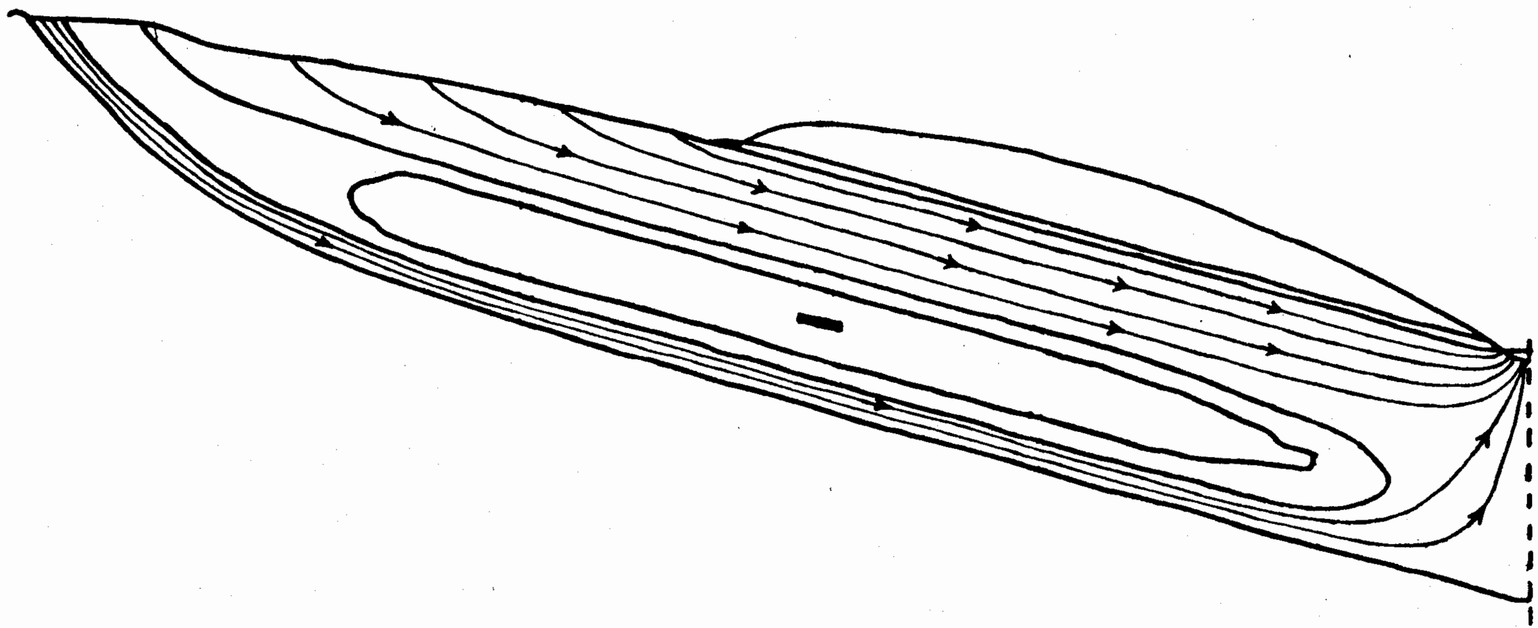


Figure 2.3. Groundwater Flow at the Reference Site

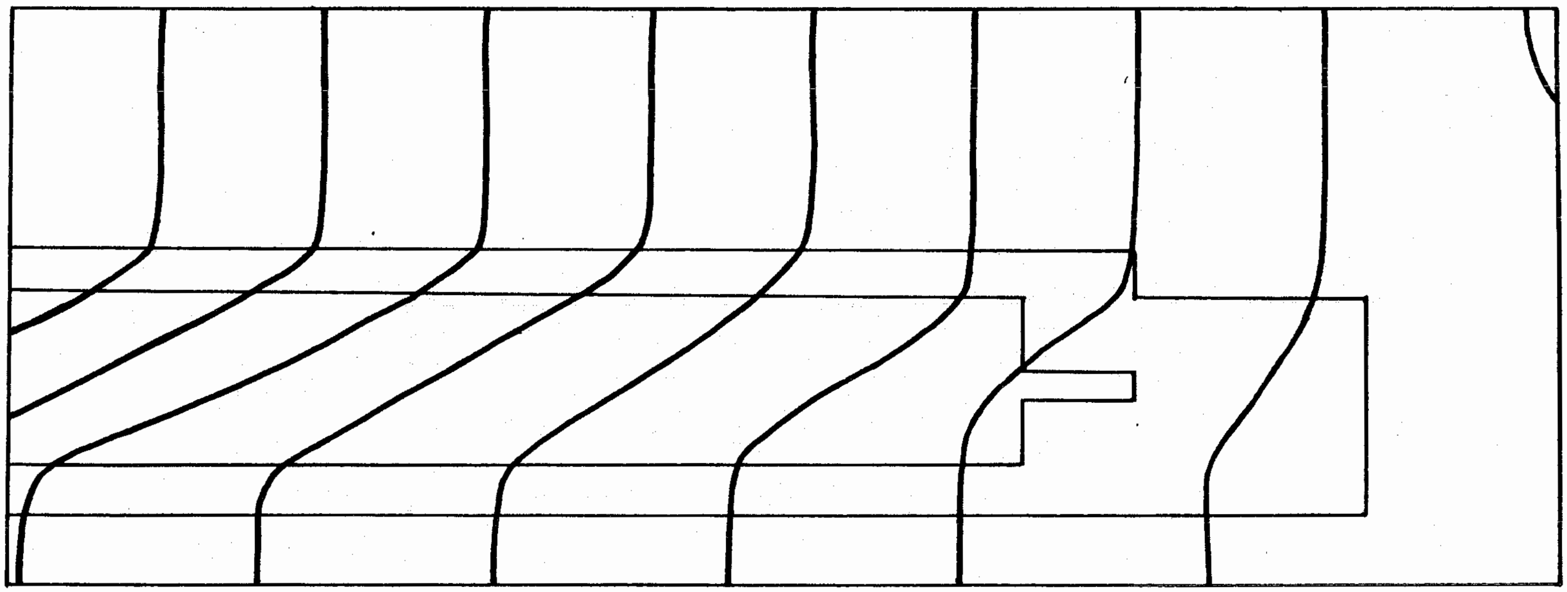


Figure 2.4. Hydraulic Head Distribution at the Reference Site.

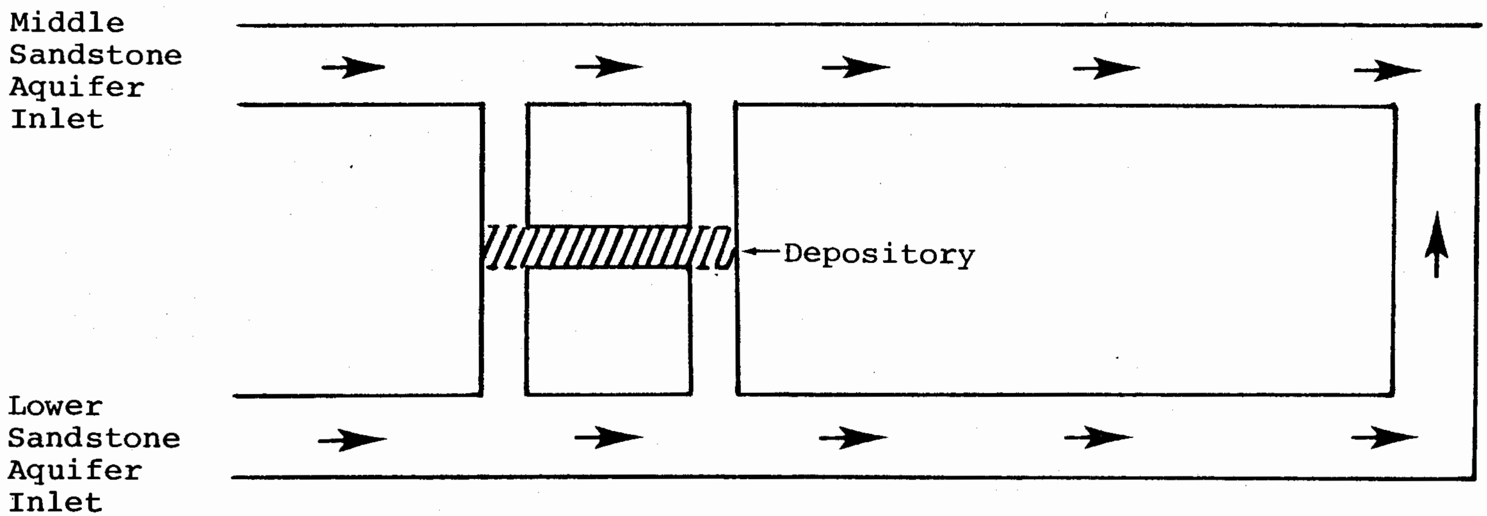



Figure 2.5. Network Representation of Reference Site Flow System.

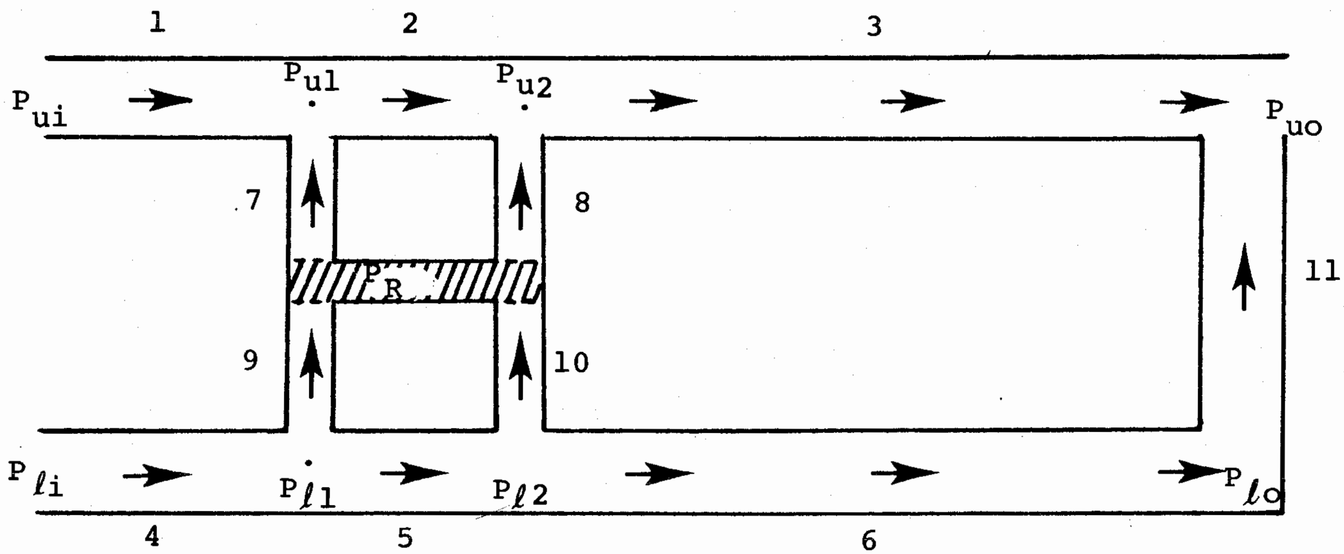



Figure 2.6. Identification of Legs and Leg Junctions used in NWFT. Arrows Indicate Positive Flow Directions.

and leg 11 represents discharge from the lower aquifer to River L. Legs, 7, 8, 9 and 10 are used to represent various disruptive features which affect the salt and shale layers near the depository. Several types of disruptive features which could potentially establish flow paths through the depository can be represented by assigning appropriate properties to legs 7 through 10. Some examples of the types of paths which can be represented are shown in Figure 2.7.

The following properties are assumed known for the flow calculations (Figure 2.6).

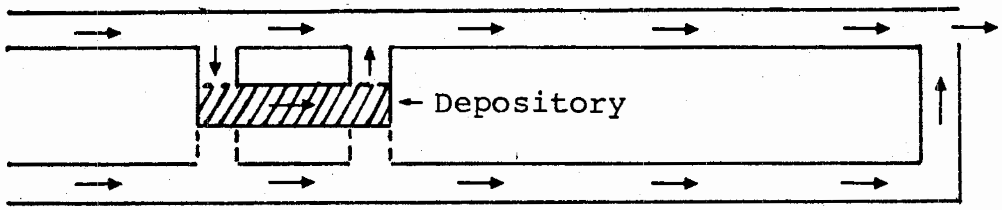
| | | |
|---|---|---|
| 1. | $P_{ui}$, $P_{\ell i}$, $P_{uo}$ | pressure head boundary conditions |
| 2. | $K_1$, $K_2$, ... $K_{11}$ | hydraulic conductivity for legs 1 to 11 |
| 3. | $A_1$, $A_2$, ... $A_{11}$ | cross-sectional area for legs 1 to 11 |
| 4. | $L_1$, $L_2$, ... $L_{11}$ | lengths of legs 1 to 11 |
| 5. | $\phi_1$, $\phi_2$, ... $\phi_{11}$ | porosity in legs 1 to 11 |
| 6. | $d_{ui}$, $d_{u1}$, $d_{u2}$, $d_{uo}$<br>$d_{\ell i}$, $d_{\ell 1}$, $d_{\ell 2}$, $d_{\ell o}$<br>$d_r$ | elevation of leg junctions measured from datum |

The values of fluid discharge in legs 1 to 11 are given by

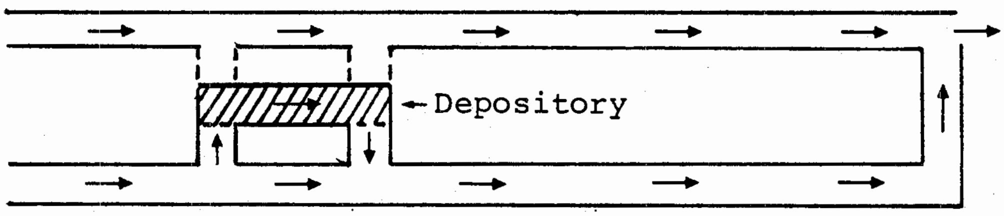
$$q_1 = \frac{K_1 A_1}{L_1} (P_{ui} + d_{ui} - P_{u1} - d_{u1}) \qquad 2.1$$

$$q_2 = \frac{K_2 A_2}{L_2} (P_{u1} + d_{u1} - P_{u2} - d_{u2}) \qquad 2.2$$

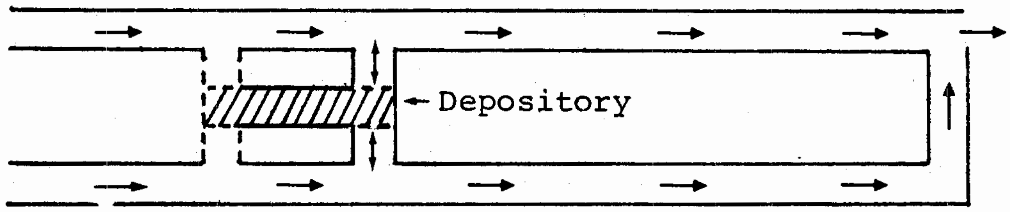
$$q_3 = \frac{K_3 A_3}{L_3} (P_{u2} + d_{u2} - P_{uo} - d_{uo}) \qquad 2.3$$




U-Tube to Overlying Aquifer




U-Tube to Underlying Aquifer




Connection Through Depository
From Underlying to Overlying
Aquifer

Figure 2.7. Examples of disruptive events that can be treated in NWFT.

$$q_4 = \frac{K_4 A_4}{L_4} (P_{\ell i} + d_{\ell i} - P_{\ell 1} - d_{\ell 1}) \quad 2.4$$

$$q_5 = \frac{K_5 A_5}{L_5} (P_{\ell 1} + d_{\ell 1} - P_{\ell 2} - d_{\ell 2}) \quad 2.5$$

$$q_6 = \frac{K_6 A_6}{L_6} (P_{\ell 2} + d_{\ell 2} - P_{\ell o} - d_{\ell o}) \quad 2.6$$

$$q_7 = \frac{K_7 A_7}{L_7} (P_R + d_r - P_{u1} - d_{u1}) \quad 2.7$$

$$q_8 = \frac{K_8 A_8}{L_8} (P_R + d_r - P_{u2} - d_{u2}) \quad 2.8$$

$$q_9 = \frac{K_9 A_9}{L_9} (P_{\ell 1} + d_{\ell 1} - P_R - d_r) \quad 2.9$$

$$q_{10} = \frac{K_{10} A_{10}}{L_{10}} (P_{\ell 2} + d_{\ell 2} - P_R - d_r) \quad 2.10$$

$$q_{11} = \frac{K_{11} A_{11}}{L_{11}} (P_{\ell o} + d_{\ell o} - P_{uo} - d_{uo}) \quad 2.11$$

Conservation of mass at each leg junction gives the following equations

$$q_1 + q_7 = q_2 \quad 2.12$$

$$q_2 + q_8 = q_3 \quad 2.13$$

$$q_4 = q_9 + q_5 \quad 2.14$$

$$q_5 = q_{10} + q_6 \quad 2.15$$

$$q_9 + q_{10} = q_7 + q_8 \quad 2.16$$

$$q_{11} = q_6 \quad 2.17$$

In the equations above, it is assumed that the depository itself offers negligible resistance to flow. Such a situation might exist if salt dissolution created flow channels through the depository.

In NWFT, equations 2.12 through 2.17 are solved to determine the unknown pressures

$$P_{u1},\ P_{u2},\ P_{\ell 1},\ P_{\ell 2},\ P_R,\ P_{\ell o}$$

Darcy velocities in each leg are given by

$$U_i = \frac{q_i}{A_i} \qquad i = 1, 11 \qquad 2.18$$

and interstitial velocities are

$$V_i = \frac{U_i}{\phi_i} \qquad i = 1, 11 \qquad 2.19$$

2.3 Radionuclide Transport

The exit leg for waste to leave the depository is determined as the leg with maximum interstitial velocity away from the depository. Possible migration paths are (see Figure 2.6):

legs 7, 2, 3

legs 8,3

legs 9, 5, 6, 11

legs 10, 6, 11

The total migration path length is the sum of the lengths of the individual legs. The average isotope velocity is given by the total path length divided by the total migration time.

Radionuclide discharge for a chain of three isotopes having the same distribution coefficient is given by the following equations for a decaying band release (Ref. 3).

$$N_1(t) = \frac{N_1(0)}{2T} e^{-\lambda t} \left[G(t) - G(t - T)\ S(t - T)\right] \qquad 2.20$$

$$N_2(t) = \left[\frac{N_2(0)\ e^{-\lambda_2 t}}{2T} + \frac{N_1(0)}{2T}\left(\frac{\lambda_1}{\lambda_2 - \lambda_1}\right)\left(e^{-\lambda_1 t} - e^{-\lambda_2 t}\right)\right] \cdot \left[G(t) - G(t - T)\ S(t - T)\right] \qquad 2.21$$

$$N_3(t) = \left[\frac{N_3(0)}{2T} e^{-\lambda_3 t} + \frac{N_2(0)}{2T}\left(\frac{\lambda_2}{\lambda_3 - \lambda_2}\right)\left(e^{-\lambda_2 t} - e^{-\lambda_3 t}\right) + \frac{N_1(0)}{2T}\lambda_1\lambda_2\left(\frac{e^{-\lambda_1 t}}{(\lambda_2 - \lambda_1)(\lambda_3 - \lambda_1)} + \frac{e^{-\lambda_2 t}}{(\lambda_1 - \lambda_2)(\lambda_3 - \lambda_2)} + \frac{e^{-\lambda_3 t}}{(\lambda_1 - \lambda_3)(\lambda_2 - \lambda_3)}\right)\right] \cdot \left[G(t) - G(t - T)\ S(t - T)\right]$$

where $t$ = time (days)

$N_i(0)$ = inventory of isotope i at time t = 0 (Ci)

$\lambda_i$ = decay constant of isotope i (days$^{-1}$)

$T$ = leach time (days)

$S(x) = 0 \qquad x < 0$

$S(x) = 1 \qquad x \geq 0$

and the function G(t) is given by

$$G(t) = \text{erfc}\left(\frac{x - \bar{u}t}{\sqrt{4\alpha t\bar{u}}}\right) + e^{\frac{x}{\alpha}}\,\text{erfc}\left(\frac{x + \bar{u}t}{\sqrt{4\alpha t\bar{u}}}\right)$$

where $\alpha$ = dispersivity (ft)

$\bar{u}$ = average isotope velocity accounting for retardation (ft/day)

$x$ = distance from source to discharge point (ft)

erfc = complementary error function.

### 3. Flow Model Input

Attempting to keep the input flexible, requesting no more input than necessary, and keeping the input simple represent conflicting goals. In this model we reached compromise solution with the concept of a "base case," and modifications to the base case. The base case is the latest set of data that has been read. The modifications may range from no change to an entire new base case.

## 3.1 The Input Option Case (20I1)

Input flexibility is not achieved without a price which is the addition of a card of input option flags. Because an entire base case is required for the first problem set, no input option card is required, but for all problem sets after the first, this option card is required. On this Input Option Card, as with the Problem Option Card (section 3.2), a blank card column (or zero punch), causes the default to occur. A non-zero numeric punch causes the non-default action to occur. There are currently eleven input options, explained in detail in 3.15. The input option variable is INP(I).

## 3.2 The Problem Option Card (20I1, 1 card)

The problem option card is the first card required in the base case. It is required for the first problem set, and is required in later problem sets only if INP(1)≠ 0. The variable into which this array is read is IOPT(I). The first ten problem options are used for program control, the remaining ten are debug print options. Because of the format, the subscript is the card column for the flag, i.e., IOPT(5) is card column 5.

The options list below indicates subroutines in which the options are exercised and the action taken for IOPT ≠ 0.

IOPT(1) - <u>DRIVIS</u> - Delete printout of radionuclide discharge as a function of time.

IOPT(2) - <u>ANAMOD</u> - Create an output file (Tape 20) of peak discharge or total (integrated) discharge.

IOPT(3) - ANAMOD - Read a file of input vectors from Tape 10.

IOPT(4) - FLOWIN - Read rock densities for each leg. Otherwise the rock density is estimated from the porosity for each leg using an assumed particle density of 170 $lb/ft^3$ ($2.7\ g/cm^3$).

IOPT(5) - ANAMOD - Used in conjunction with IOPT(2). If EQ 0, print integrated discharge to Tape 20. If NE 0, print peak discharge.

IOPT(6) - PATHLEN - Delete printout of Darcy velocity, interstitial velocity, and fluid discharge by leg.

IOPT(7) - USEINP - Delete output of network flow schematic and leg properties.

IOPT(8) - PATHLEN - Delete printout of pressure heads at leg junctions.

IOPT(9) - IOPT(10) - Not used at present.

The following options provide debug printout.

IOPT(11) - ANAMOD - Print the output of AVINT (a library subroutine used to determine the integrated discharge).

IOPT(12) - GETRV - Print the input vectors from Tape 10.

IOPT(13) - PATHLEN - Print information for the migration path.

IOPT(14) - Not used

IOPT(15) - BAND - Print information related to solution of the discharge equation.

IOPT(16) - GIT - Print information for the G(t) function.

IOPT(17) - COEFF - Print coefficients in linear equations for unknown pressures.

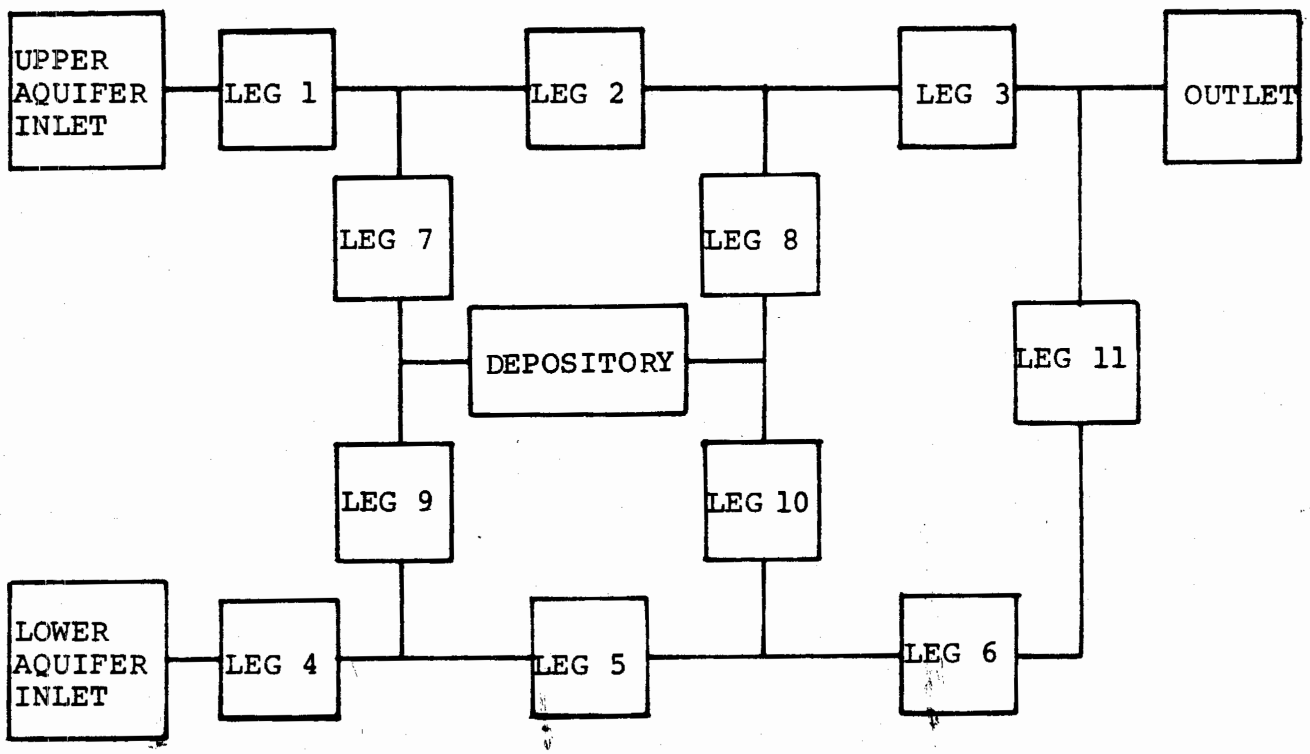
IOPT(18) - Not used

IOPT(19) - Not used

IOPT(20) - USEINP - Print theta values (theta = conductivity * area/path length).

## 3.3 Schematic

The following picture provides a useful schematic of the network flow system as well as nomenclature for input descriptions.



3.4 Inlet and Outlet Heads (8E10.3, 1 card)

This card contains the inlet and outlet heads in feet. There are three values required. For the second and subsequent cases, these boundary conditions are input only if INP(2) ≠ 0.

| Field | Card Column | Variable Name | Description |
|---|---|---|---|
| 1 | 1-10 | PUIN | Upper Aquifer Input Head |
| 2 | 11-20 | PLIN | Lower Aquifer Input Head |
| 3 | 21-30 | PUOUT | Upper Aquifer Output Head |

3.5 Hydraulic Conductivities (8E10.3)

These two data cards contain 11 values of hydraulic conductivity in feet/day. For the second and subsequent cases, the conductivities are input only if INP(3) ≠ 0.

| Field | Card Column | Variable Name | Description |
|---|---|---|---|
| 1 | 1-10/1 | COND1 | Hydraulic Conductivity for Leg 1 |
| 2 | 11-20/1 | COND2 | Hydraulic Conductivity for Leg 2 |
| . | . | . | . |
| . | . | . | . |
| . | . | . | . |
| 11 | 21-30/2 | COND11 | Hydraulic Conductivity for Leg 11 |

3.6 Cross-Sectional Areas (8E10.3)

These two data cards contain 11 values of cross-sectional areas in square feet. For the second and subsequent cases, the areas are input only if INP(4) ≠ 0.

| Field | Card Column | Variable Name | Description |
| --- | --- | --- | --- |
| 1 | 1-10/1 | AREA1 | Cross-sectional area of leg 1 |
| 2 | 11-20/1 | AREA2 | Cross-sectional area of leg 2 |
| ⋮ | ⋮ | ⋮ | ⋮ |
| 11 | 21-30/2 | AREA11 | Cross-sectional area of leg 11 |

3.7 Leg Lengths (8E10.3)

These two data cards contain the lengths of each leg in the network flow system in feet. For the second and subsequent cases, the leg lengths are input only if INP(5) $\neq$ 0.

| Field | Card Column | Variable Name | Description |
| --- | --- | --- | --- |
| 1 | 1-10/1 | PATH(1) | Length of leg 1 |
| 2 | 11-20/1 | PATH(2) | Length of leg 2 |
| ⋮ | ⋮ | ⋮ | ⋮ |
| 11 | 21-30/2 | PATH(11) | Length of leg 11 |

3.8 Elevations (8E10.3)

The next two data cards contain leg junction elevations (in feet) measured from an arbitrary datum. For the second and subsequent cases, the elevations are input only if INP(6) $\neq$ 0.

| Field | Card Column | Variable Name | Description |
|---|---|---|---|
| 1 | 1-10/1 | VPATH(1) | Elevation of the upper aquifer input, the input side of leg 1. |
| 2 | 11-20/1 | VPATH(2) | Elevation of the junction of legs 1, 2 and 7. |
| 3 | 21-30/1 | VPATH(3) | Elevation of the junction of legs 2, 8, and 3. |
| 4 | 31-40/1 | VPATH(4) | Elevation of the junction of legs* 7 and 9 at the depository. |
| 5 | 41-50/1 | VPATH(5) | Elevation of the junction of legs* 8 and 10 at the depository. |
| 6 | 51-60/1 | VPATH(6) | Elevation of the input to the lower aquifer, leg 4. |
| 7 | 61-70/1 | VPATH(7) | Elevation of the junction of legs 4, 9, and 5. |
| 8 | 71-80/1 | VPATH(8) | Elevation of the junction of legs 5, 10, and 6. |
| 9 | 1-10/2 | VPATH(9) | Elevation of the junction of legs 6 and 11. |
| 10 | 11-20/2 | VPATH(10) | Elevation of the upper aquifer outlet, junction of legs 3 and 11. |

3.9 Porosities (8E10.3)

These two data cards contain 11 values of porosity. For the second and subsequent cases, porosities are input only if INP(7) ≠ 0.

| Field | Card Column | Variable Name | Description |
|---|---|---|---|
| 1 | 1-10/1 | PHI1 | Porosity in leg 1 |
| 2 | 11-20/1 | PHI2 | Porosity in leg 2 |
| . | . | . | . |
| . | . | . | . |
| . | . | . | . |
| 11 | 21-30/2 | PHI11 | Porosity in leg 11 |

*In the present version, these two elevations must be equal.

### 3.10 Isotope Data (I5/A6, 4X,2E10.4)

The next two to four cards contain isotope data. The first card contains the number of isotopes, NOISO. The remaining NOISO cards describe each isotope in the chain. On the second and subsequent cases, these data are input only if INP(8) ≠ 0.

| Field | Card Column | Variable Name | Description |
|---|---|---|---|
| 1 | 1-5/1 | NOISO | Number of isotopes in this decay chain (NOISO ≤ 3). |

The following NOISO data cards are identical in format

| | | | |
|---|---|---|---|
| 2 | 1-6/2 | ISONAME | Name of this isotope in a form XXYYY where XX is the chemical symbol and YYY is the mass number. |
| 3 | 7-10/2 | ignored | |
| 4 | 11-20/2 | THALF | Half life in years |
| 5 | 21-30/2 | CURZ | Initial inventory in curies of this isotope. |

### 3.11 Leach Time and Dispersivity (2E10.3)

The next data card contains the leach time in years and the dispersivity in feet. On the second and subsequent cases, these data are input only if INP(9) ≠ 0.

| Field | Card Column | Variable Name | Description |
|---|---|---|---|
| 1 | 1-10 | LEACH | Leach time |
| 2 | 11-20 | ALPHA | Dispersivity |

3.12 Density (8E10.3)

If IOPT(4) ≠ 0, the leg densities are input here. The units are lb/ft$^3$. The input of these values on the second and subsequent cases is controlled by INP(10) ≠ 0 as well as IOPT(4) ≠ 0. If the densities are not input, they are calculated from

RHO(I) = 170.0 * (1.0 - PHI(I)).

| Field | Card Column | Variable Name | Description |
|---|---|---|---|
| 1 | 1-10/1 | RHO(1) | Density in leg 1 |
| 2 | 11-20/1 | RHO(2) | Density in leg 2 |
| . | . | . | . |
| . | . | . | . |
| . | . | . | . |
| 11 | 21-30/2 | RHO(11) | Density in leg 11 |

3.13 Distribution Coefficients

The next two cards contain 11 values of distribution coefficients in ft$^3$/lb. For the second and subsequent cases, distribution coefficients are input only if INP(11) ≠ 0. Note that in the present version of NWFT, KD(1) and KD(4) are never used.

| Field | Card Column | Variable Name | Description |
|---|---|---|---|
| 1 | 1-10/1 | KD(1) | Distribution coefficient for leg 1 |
| 2 | 11-20/1 | KD(2) | Distribution coefficient for leg 2 |
| . | . | . | . |
| . | . | . | . |
| . | . | . | . |
| 11 | 21-30/2 | KD(11) | Distribution coefficient for leg 11 |

### 3.14 Additional Input (I10, E10.1, I10)

For each case, totally independent of the INP vector, one data card is always required. This card is used when input vectors are to be read from Tape 10.

| Field | Card Column | Variable Name | Description |
|---|---|---|---|
| 1 | 1-10 | NOVEC | The number of consecutive vectors to be read from the file Tape 10. |
| 2 | 11-20 | TUB | The maximum time for the discharge calculations. |
| 3 | 21-30 | NOSKIP | The number of vectors on file Tape 10 to skip over before starting the sequence of NOVEC vectors. |

Use of other than blank, 0, or 1 for NOVEC, and blank or 0 for NOSKIP assumes that a file called TAPE 10 is available, and that its use has been enabled by setting IOPT(3) ≠ 0. This is not checked, and if IOPT(3) = 0, then NOVEC identical runs will be made.

### 3.15 Reducing Input for Cases Other than the First

For all cases other than the first one, one additional data card is required. This card directs the various inputs for a case, specifying which to read and which to omit. Omitted values remain as they were, unchanged from the last values input. The values read on this data card are binary values, a blank, or zero field meaning do not read this input, and a non-zero value indicates a read.

| Field | Card Column | Variable Name | Description |
|---|---|---|---|
| 1 | 1 | INP(1) | Controls input of the problem option card. See 3.2. |
| 2 | 2 | INP(2) | Controls input of Inlet and Outlet Heads. See 3.4. |
| 3 | 3 | INP(3) | Controls input of hydraulic conductivities. See 3.5. |
| 4 | 4 | INP(4) | Controls input of cross-sectional areas. See 3.6. |
| 5 | 5 | INP(5) | Controls input of path lengths. See 3.7. |
| 6 | 6 | INP(6) | Controls input of elevations. See 3.8. |
| 7 | 7 | INP(7) | Controls input of porosities. See 3.9. |
| 8 | 8 | INP(8) | Controls input of isotope data. See 3.10. |
| 9 | 9 | INP(9) | Controls input of leach time and dispersivity. See 3.11. |
| 10 | 10 | INP(10) | Controls input of rock density if and only if IOPT(4) ≠ 0, otherwise has no effect. See 3.2 and 3.12. |
| 11 | 11 | INP(11) | Controls input of distribution coefficients. See 3.13. |
| 12 | 12 | INP(12) | Not currently used. |
| | | ... INP(20) | |

# 4. Subroutine Descriptions

## 4.1 BAND

| Called From | Calls |
|---|---|
| DRIVIS | GIT |

Error Messages

STOP 10 - Number of isotopes less than 1 or greater than 3.

BAND computes the discharge rate of a decay chain of up to 3 isotopes at a distance x from the source and at time T. The source function is assumed to be a decaying band.

## 4.2 COEFF

Called From

ANAMOD

Error Messages

None

The flow equations (Section 2.2, equation 2.12 to 2.17) are six equations in six unknowns. COEFF evaluates the 6 x 6 matrix of coefficients and the 6 x 1 matrix of constant terms.

## 4.3 DRIVIS

| Called From | Calls |
|---|---|
| ANAMOD | BAND |

Error Messages

Stop 32 - Upper time bound (TUB) is smaller than the time required for radionuclides to reach the discharge point.

This subprogram is the driver for the discharge rate solution. It chooses a time to start the solution, a time to end the solution, and the number of time points at which to evaluate a solution.

The time interval from beginning of solution, TBEGIN, to end of solution, TEND, is divided into a number of points NTP $\leq$ 201. TRA is the radionuclide migration time; i.e., the time required for the radionuclide to travel from the source to the discharge point assuming no dispersion. LEACH is the source leach time. Because dispersion is accounted for, radionuclides will begin to discharge before time TRA and will continue to discharge after time TRA + LEACH. Therefore, TBEGIN and TEND are defined as follows:

$$\text{TBEGIN} = (1 - f) \cdot \text{TRA}$$

$$\text{TEND} = (1 + f) \cdot \text{TRA} + \text{LEACH}$$

where $f = 0.9$ currently.

In the case where the leach time is long compared to the migration time, the time from TBEGIN to TEND is divided into three parts. The time from TBEGIN to 2 * TRA, while the discharge rate is building up, is divided into NUMB(1) intervals. The time from 2 * TRA to LEACH, while the discharge rate can be expected to be relatively constant, is divided into NUMB(2) intervals. The time from LEACH to TEND, while the discharge rate is declining, is divided into NUMB(3) intervals.

If TRA > 0.1 · LEACH, the time from TBEGIN to TEND is divided into NTP intervals.

## 4.4 FLOWIN

Called From

ANAMOD

Error Messages

| | |
|---|---|
| Stop 2 | End-of-file encountered reading hydraulic conductivities. |
| Stop 3 | End-of-file encountered reading cross-sectional areas |
| Stop 4 | End-of-file encountered reading leg lengths |
| Stop 5 | End-of-file encountered reading porosities |
| Stop 6 | End-of-file encountered reading input hydraulic heads |
| Stop 7 | End-of-file encountered reading leg junction elevations |
| Stop 11 | End-of-file encountered readin NOISO |
| Stop 12 | End-of-file encountered reading isotope data |
| Stop 13 | End-of-file encountered reading leach time, dispersivity |
| Stop 23 | End-of-file encountered reading distribution coefficients |
| Stop 24 | End-of-file encountered reading densities |
| Stop 26 | End-of-file encountered reading problem option card |
| Stop 30 | Present version requires no elevation change across depository |

This subroutine reads all card input except the vector card (Section 3.14). For computation, hydraulic conductivities are converted from ft/day to ft/year.

## 4.5 GETPATH

Called From

PATHLEN

Error Messages

| | |
|---|---|
| Stop 14 | All the flow velocities are directed into or out of the depository |

Stop 15 There is no outflow in leg 3 or legs 6 and 11

Stop 16 There are no flows greater than CUTOFF * FLOWMAX

Stop 17 Flow is out in leg 7 but not leg 2

Stop 20 Flow is out in leg 7 or leg 8 but not in leg 3

Stop 21 Flow is out in leg 9 but not in leg 5

Stop 22 Flow is out in leg 9 or leg 10 but not in leg 6

Consider the network flow in the vicinity of the depository (Figure 2.6). GETPATH finds the vertical leg with the greatest flow velocity. GETPATH then supplies the flow path to PATHLEN to enable it to compute the total path length.

## 4.6 GETRV

<u>Called From</u>

ANAMOD

<u>Error Messages</u>

Stop 25 End of file reading TAPE 10.

GETRV is called only if IOPT(3) is not 0 (see 3.2), and reads an array of new input values from the file TAPE 10. GETRV is used primarily as an input medium for statistical studies. The subprogram is easily rewritten for other input formats.

## 4.7 GIT

<u>Called From</u>

BAND

GIT evaluates the function G(t) (equation 2.2). G(t) has two terms. The first term is a complementary error function. The term contains an exponential times the complementary error function. The exponential term typically becomes very large while the complementary error function is typically quite small. The error functions are evaluated using an approximation from Reference 6.

## 4.8 PATHLEN

Called From

ANAMOD

Calls

GETPATH

PATHLEN computes the flow volumes, the Darcy and pore velocities. It calls GETPATH to determine the radionuclide migration path. PATHLEN determines the total path length from depository to outlet, the isotope velocity, and travel time.

## 4.9 SCHEMA

Called From

USEINP

SCHEMA prints a schematic network diagram similar to Figure 2.6 to aid in checking program input.

## 4.10 SKIPRV

Called From

ANAMOD

Error Messages

Stop 27 End-of-file encountered reading TAPE 10

Skips NOSKIP records forward from present positon on file NOFILE. Used to position the alternate input file used for sensitivity analysis.

### 4.11 USEINP

Called From

ANAMOD

Calls

SCHEMA (4.9)

All the input, having been read in, and possibly modified by GETRV, is expanded in USEINP to the form used in the remaining calculations. The input values are not changed (except for unit conversions) and are thus available for reuse.

## 5. Results and Sample Problems

### 5.1 Comparison with SWIFT

To check the accuracy of NWFT results, calculations have been performed to compare NWFT with SWIFT. The disruptive feature which was modeled is a U-tube connecting the depository to the overlying aquifer as shown in Figure 5.1. Two SWIFT calculations were performed to provide the needed results. The first calculation represented the reference site, including the U-tube, as shown in Figure 5.2. The purpose of this calculation was to establish the pressure head distribution and to determine interstitial velocities throughout the reference site. A second representation (Figure 5.3) of the reference site was then used for radionuclide transport calculations. Boundary pressures at the

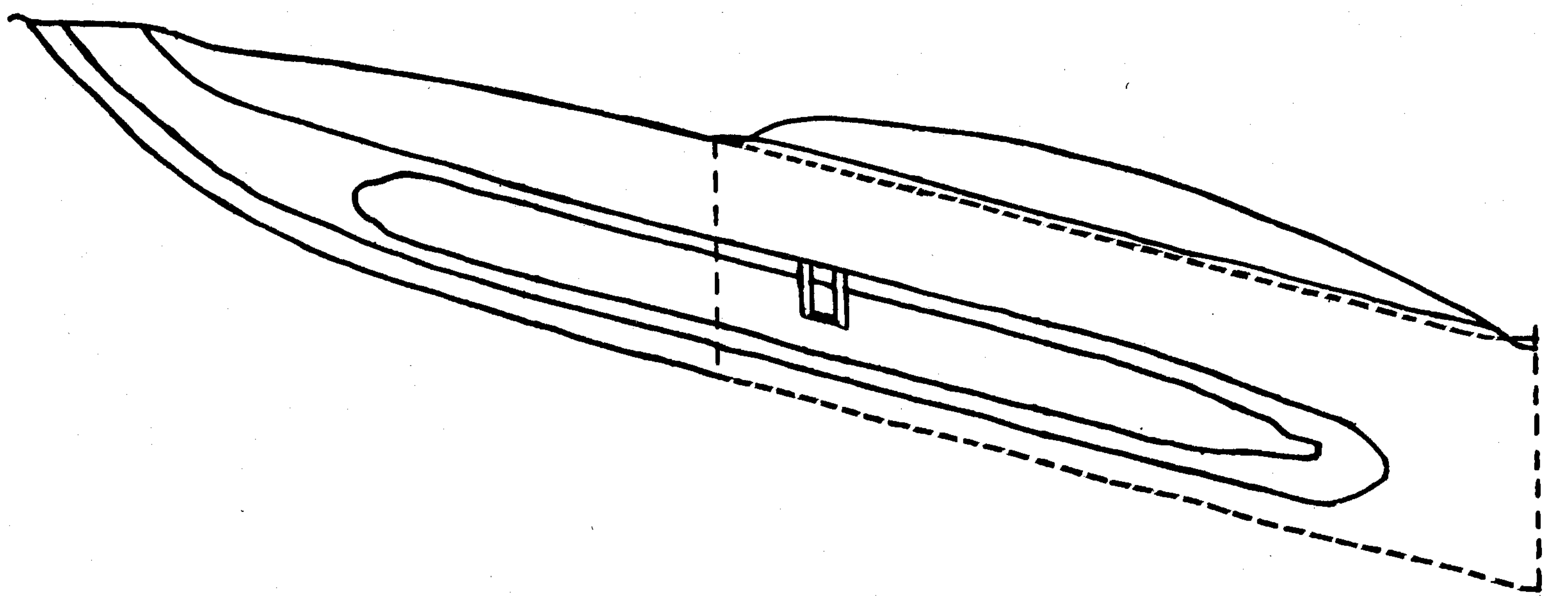


Figure 5.1. U-Tube Formed Through Depository

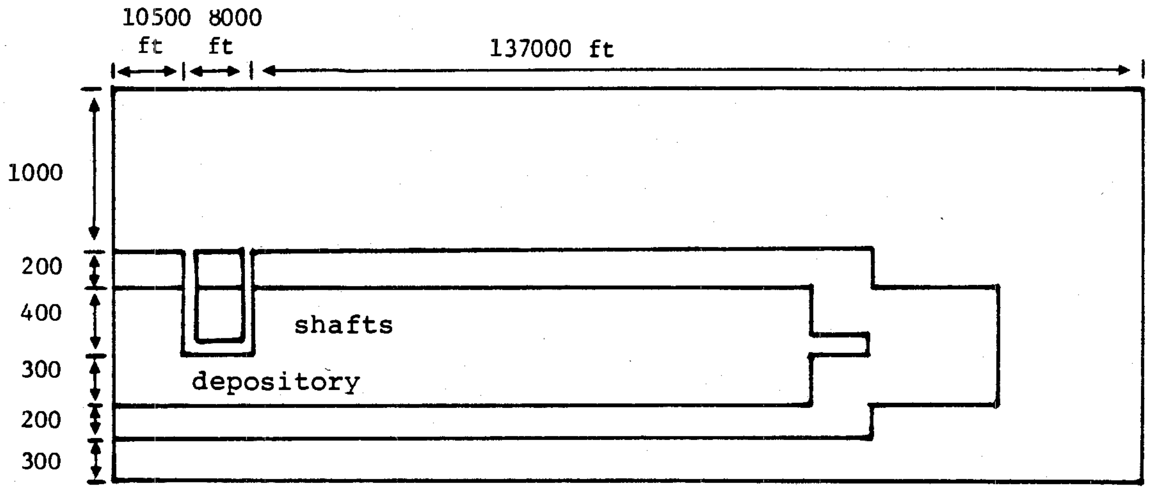



Figure 5.2. Representation of Reference Site with U-Tube used in SWIFT for Pressure Calculations

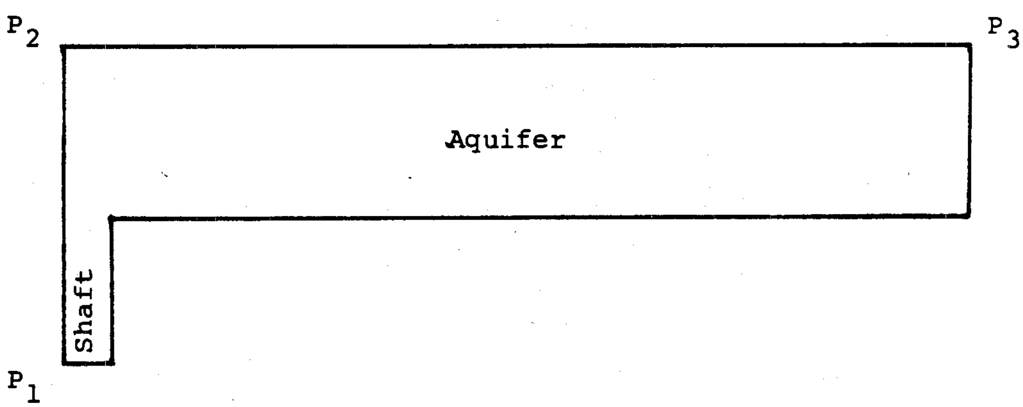



Figure 5.3 Representation of Reference Site with U-Tube used in SWIFT for Radionuclide Transport Calculations

points indicated in Figure 5.3 were taken from the earlier SWIFT calculation. Two calculations were necessary because the grid block size required for accurate radionuclide transport calculations is too small to permit such calculations in the reference site representation of Figure 5.2 whereas considerably larger grid blocks can be used for pressure calculations.

The physical characteristics of the reference site which were used as input to SWIFT and NWFT are listed in Table 5.1. Radionuclide source data used in the comparison are listed in Table 5.2. Other input to NWFT for this comparison are given in Sample Problem 1 (Section 5.2).

Results of the radionuclide discharge calculations are shown in Figures 5.4 and 5.5. As these figures indicate, the comparison between the two models is quite good. The relatively narrow pulse and low peak discharge rate of Pu 240 results from the fact that the half life of Pu 240 is short ($6.76 \times 10^3$ years) compared to the migration time. The discharge pulse for U 236 shows the expected plateau as its half life is considerably longer than the migration time. Had we compared radionuclide concentrations at some intermediate location (e.g., in the aquifer immediately above the depository), the comparisons would probably not have been as good. The reason is that the one dimensional path assumption in NWFT does not account for the dilution which occurs when the dissolved radioactive material enters the aquifer. However, NWFT does properly maintain the total migration time so that the radionuclide discharge, which is the important result, is adequately represented.

Table 5.1. Assumed Reference Site Properties for NWFT/SWIFT Comparison

| | Horizontal Hydraulic Conductivity (ft/day) | Vertical Hydraulic Conductivity (ft/day) | Porosity |
|---|---|---|---|
| Middle Sandstone | 50.0 | 1.4 | 0.30 |
| Lower Shale | $10^{-2}$ | $10^{-3}$ | 0.30 |
| Salt | $10^{-5}$ | $10^{-6}$ | 0.03 |
| Lower Sandstone | 40.0 | 1.4 | 0.30 |
| Borehole Properties | - | 10.0 | 0.15 |

Table 5.2. Radionuclide Data for NWFT/SWIFT Comparison

| Isotope Name | Half Life (Years) | Initial Amount (Ci) |
|---|---|---|
| Pu 240 | $6.76 \times 10^3$ | 1000 |
| U 236 | $2.39 \times 10^7$ | 1000 |

Leach Time = $10^5$ years

Dispersivity = 500 feet

Distribution Coefficient (shaft) = 0.0

Distribution Coefficient (aquifer) = 1.6 $ft^3/lb$ = 100 $cm^3/gm$

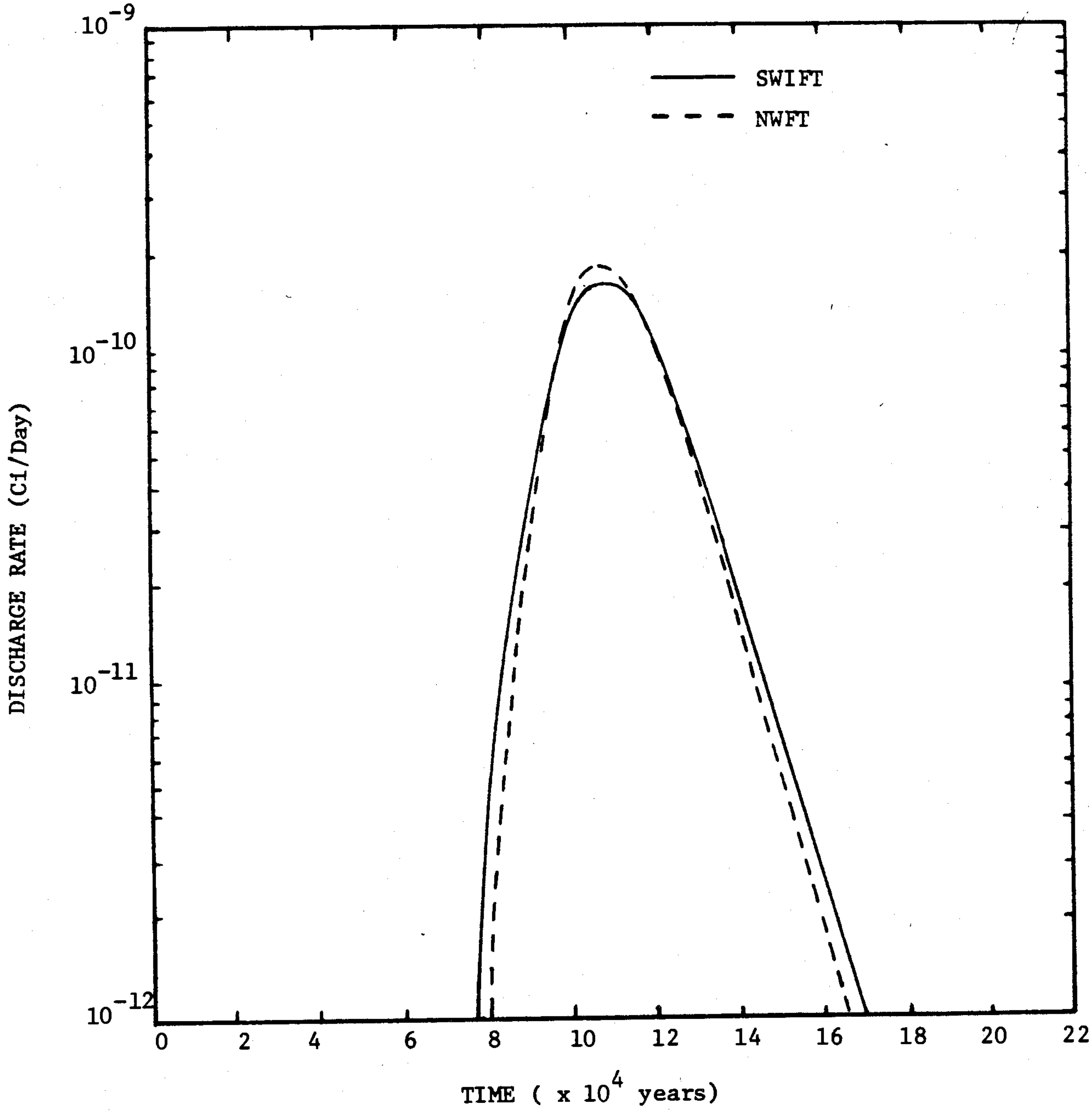



Figure 5.4. Discharge Rate for Pu 240

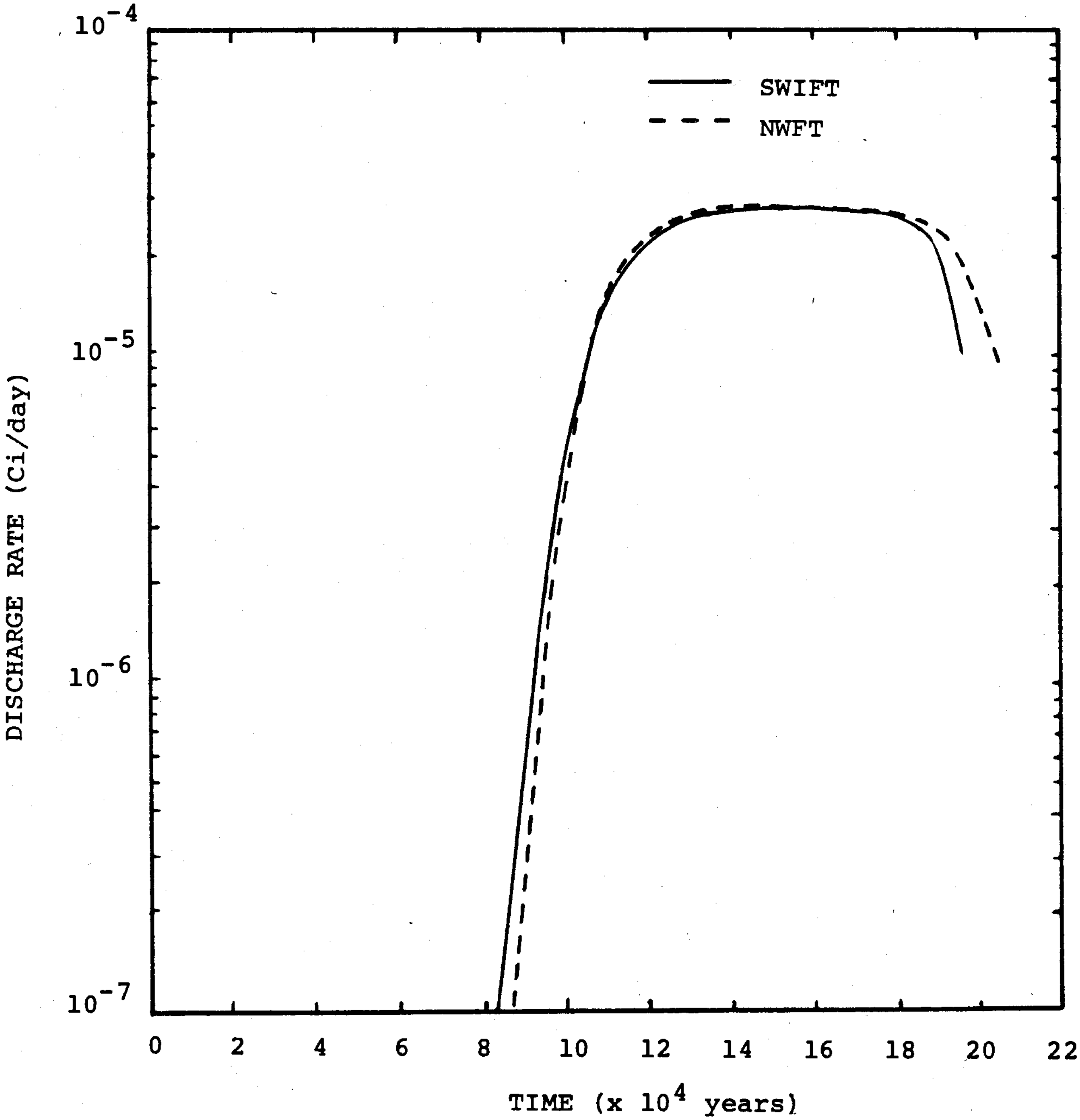



Figure 5.5. Discharge Rate for U 236

## 5.2 Sample Problems

### 5.2.1 Input

Two NWFT sample problems are included in this section. The two problems model the dashed portion of Figure 2.2 but represent different disruptive events.

Sample problem 1 is the SWIFT/NWFT comparison problem of the preceding section which includes a U-tube disruptive event. The input values are listed in Tables 5.3A and 5.3B. The inlet and ou' let pressure heads were obtained as described in Section 5.1. The leg junction elevations listed in Table 5.3 are included in Figure 5.6 in parentheses. These elevations were chosen to assure that tl vertical leg lengths only represent radionuclide movement through the salt and shale layers. The elevations from left to right (with the exception of the depository which is assumed to be horizontal) reflect the dip angle of the strata. The remainder of the values in Table 5.3 are leg properties. The cross-sectional areas listed are the areas through which fluid flows. The upper sandstone, legs 1, 2 and 3, is 1000 feet thick and is modeled as 1000 feet wide. The lower sandstone, legs 4, 5 and 6 is 300 feet thick and is modeled as 1000 feet wide. Leg 11 is 21000 feet x 1000 feet The width of 1000 feet was chosen in these legs to assure that the disruptive feature in legs 8 and 10 has a small perturbing effect on the large sandstone aquifers. Legs 8 and 10 are 25 x 25 feet. Legs 7 and 10 are essentially closed. No significant flow should occur through these legs; therefore the assigned area of these legs is small - 1 x 1 feet. Porosity and hydraulic conductivity values for the salt and sandstone were chosen from appropriate values

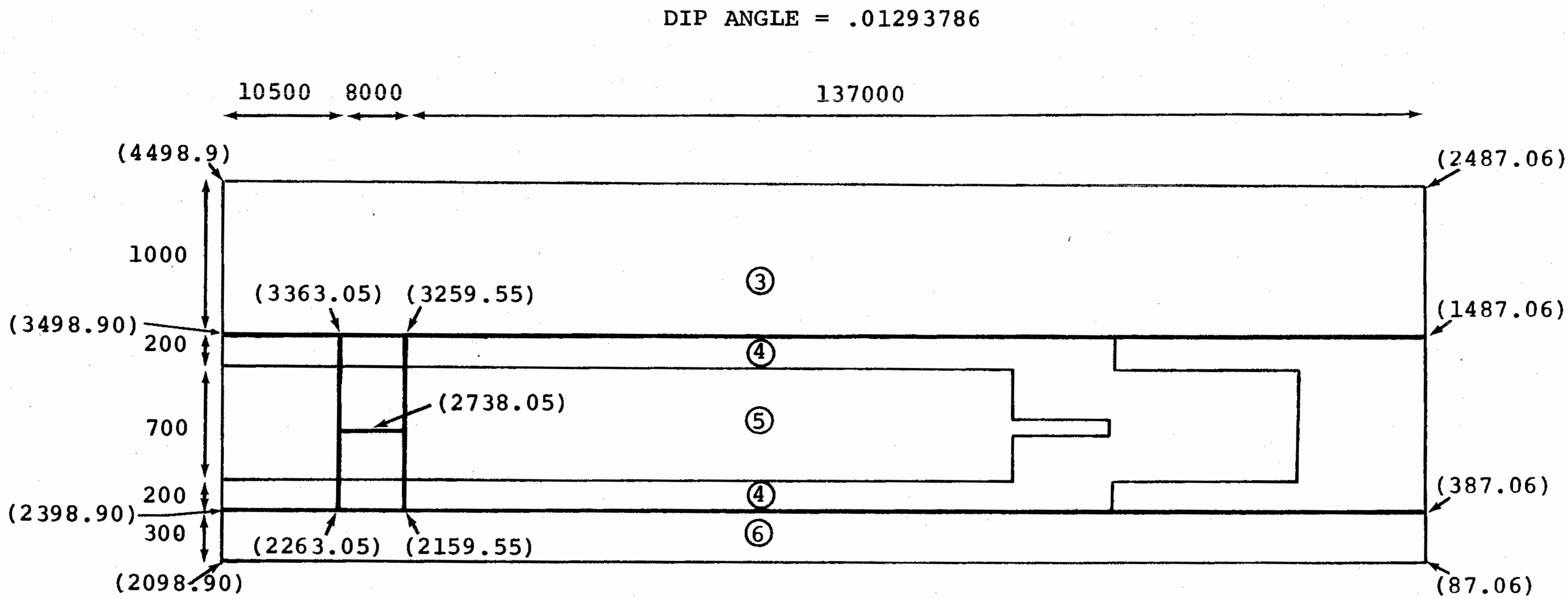
Table 5.3A Leg Properties for Sample Problem 1

| Leg Number | Cross-Sectional Area ($ft^2$) | Length (ft) | Hydraulic Conductivity (ft/day) | Porosity | Distribution Coefficient ($ft^3$/lb) |
|---|---|---|---|---|---|
| 1 | $1 \times 10^6$ | 10500 | 50 | .3 | 1.6 |
| 2 | $1 \times 10^6$ | 8000 | 50 | .3 | 1.6 |
| 3 | $1 \times 10^6$ | 137000 | 50 | .3 | 1.6 |
| 4 | $3 \times 10^5$ | 10500 | 40 | .3 | 1.6 |
| 5 | $3 \times 10^5$ | 8000 | 40 | .3 | 1.6 |
| 6 | $3 \times 10^5$ | 13700 | 40 | .3 | 1.6 |
| 7 | 625 | 625 | 10 | .15 | 0 |
| 8 | 625 | 521.5 | 10 | .15 | 0 |
| 9 | 1.0 | 475 | 1.0E-6 | .15 | 0 |
| 10 | 1.0 | 578.5 | 1.0E-6 | .15 | 0 |
| 11 | $2.1 \times 10^7$ | 1100 | 1.4 | .3 | 1.6 |

Table 5.3B Boundary Conditions and Leg Junction Elevations for Sample Problem 1

| Leg Junction | Boundary Condition (ft) | Elevation (ft) |
|---|---|---|
| Upper Aquifer Inlet | 1000.00 | 3498.90 |
| Lower Aquifer Inlet | 1505.00 | 2398.90 |
| Outlet | 1000.00 | 1487.06 |
| 1-7-2 | | 3363.05 |
| 2-8-3 | | 3259.55 |
| 4-9-5 | | 2263.05 |
| 5-10-6 | | 2159.55 |
| 7-9-Depository | | 2738.05 |
| 8-10-Depository | | 2738.05 |
| 6-11 | | 387.06 |

3




③ Middle Sandstone
④ Lower Shale
⑤ Salt
⑥ Lower Sandstone

Figure 5.6. Heavy lines are those modeled by 1-D NWFT Model. Elevations are shown in parentheses. All distances are in feet.

listed in Table 5.1 Distribution coefficient values for Pu and U in the sandstone legs were assigned from the lower end of known values (Ref. 4 and 5). The presence of brine along the radionuclide migration path could justify the use of a relatively low distribution coefficient. Distribution coefficient values for legs 7, 8, 9 and 10 are zero to account for salt in and surrounding the legs. Although Kd values were assigned to all the legs, only the Kd values in legs 8 and 3 (the travel path of the radionuclides) are used in this sample problem.

Sample problem 2 represents a disruptive event which is a connection through the depository from the underlying to overlying sandstone. The input values are listed in Tables 5.4A and 5.4B. Only the property values input in legs 7, 8, 9 and 10 differ from those input in sample problem 1. Legs 8 and 10 are 25 x 25 feet and have a hydraulic conductivity of 10 ft/day. Legs 7 and 9 are essentially closed. They are 1 x 1 feet and have a hydraulic conductivity of $10^{-6}$ ft/day. In this problem, the flow path is along legs 10, 6, 11 (i.e., through the lower aquifer).

The output resulting from the NWFT model for sample problems 1 and 2 is shown in Tables 5.4 and 5.5.

## 6. Conclusions

The Network Flow and Transport (NWFT) model has been developed to supplement the capability provided by the Sandia Waste Isolation Flow and Transport (SWIFT) model. SWIFT will be used to establish the fluid flow field and possible radionuclide migration paths for depository breachment scenarios. SWIFT will also

Table 5.4A Leg Properties for Sample Problem 2

| Leg Number | Cross-Sectional Area ($ft^2$) | Length (ft) | Hydraulic Conductivity (ft/day) | Porosity | Distribution Coefficient ($ft^3$/lb) |
|---|---|---|---|---|---|
| 1 | $1 \times 10^6$ | 10500 | 50 | .3 | 1.6 |
| 2 | $1 \times 10^6$ | 8000 | 50 | .3 | 1.6 |
| 3 | $1 \times 10^6$ | 137000 | 50 | .3 | 1.6 |
| 4 | $3 \times 10^5$ | 10500 | 40 | .3 | 1.6 |
| 5 | $3 \times 10^5$ | 8000 | 40 | .3 | 1.6 |
| 6 | $3 \times 10^5$ | 137000 | 40 | .3 | 1.6 |
| 7 | 1.0 | 625 | 1.0E-6 | .15 | 0 |
| 8 | 625 | 521.5 | 10 | .15 | 0 |
| 9 | 1.0 | 475 | 1.0E-6 | .15 | 0 |
| 10 | 625 | 578.5 | 10 | .15 | 0 |
| 11 | $2.1 \times 10^7$ | 1100 | 1.4 | .3 | 1.6 |

Table 5.4B Boundary Conditions and Leg Junction Elevations for Sample Problem 2

| Leg Junction | Boundary Condition (ft) | Elevation (ft) |
|---|---|---|
| Upper Aquifer Inlet | 1000.00 | 3498.90 |
| Lower Aquifer Inlet | 1505.00 | 2398.90 |
| Outlet | 1000.00 | 1487.06 |
| 1-7-2 | | 3363.05 |
| 2-8-3 | | 3259.55 |
| 4-9-5 | | 2263.05 |
| 5-10-6 | | 2159.55 |
| 7-9-Depository | | 2738.05 |
| 8-10-Depository | | 2738.05 |
| 6-11 | | 387.06 |

provide pressure boundary conditions for NWFT. For a given scenario, NWFT will be used in sensitivity and risk analysis to evaluate the effects of variables which alter the radionuclide source rate and migration time. NWFT requires only a small fraction of the computer time required by SWIFT and can, if properly used, adequately reproduce radionuclide discharge rates predicted by SWIFT.

NWFT transport calculations are presently limited to decay chains of no more than three isotopes which are required to have the same distribution coefficients. NWFT does not account for the effects of brine on flow or waste form solubility limits. NWFT also cannot adequately represent scenarios in which lateral dispersion is important. Additional development work is presently under way to remove several of these limitations.

```
OPTIONS  1 0   2 0   3 0   4 0   5 0   6 0   7 0   8 0   9 0  10 0  11 0  12 0  13 0  14 0  15 0  16 0  17 0  18 0  19 0  20 0
 NUMBER OF ISOTOPES    2


         ISOTOPE NAME           HALF LIFE (YEARS)     INITIAL AMOUNT (CI)

            PU240                    6.760E+03               1.000E+03
             U236                    2.390E+07               1.000E+03

         LEACH TIME =    1.000E+05 YEARS     DISPERSIVITY =   5.000E+02 FEET

NO OF VECTORS =    0 TIME UPPER BOUND =        1.00E+06
```

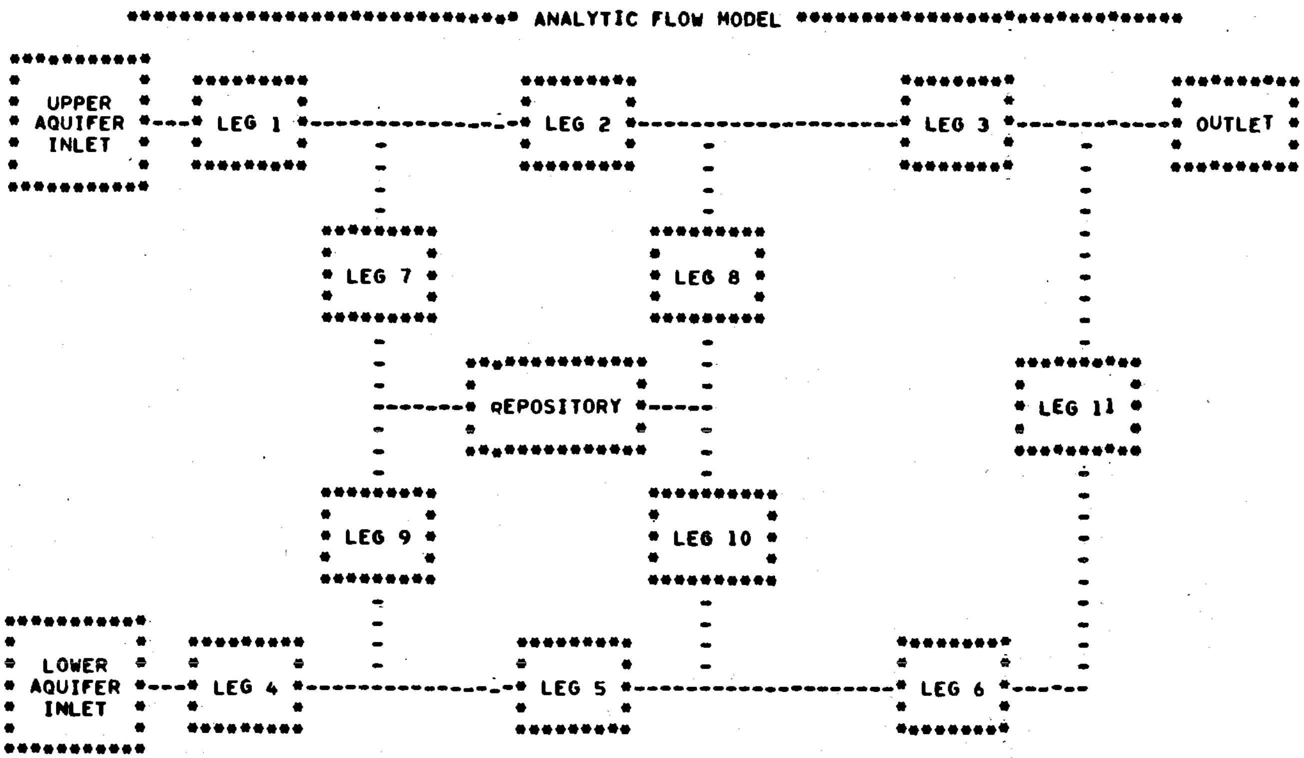



Table 5.5. NWFT Output for Sample Problem 1

```
            UPPER AQUIFER INLET
              INLET HEAD =  1000.00 FT
               ELEVATION =  3498.90 FT

            LOWER AQUIFER INLET
              INLET HEAD =  1505.00 FT
               ELEVATION =  2398.90 FT

                  OUTLET
            OUTLET HEAD =  1000.00 FT
               ELEVATION =  1487.06 FT

                   ELEVATIONS OF OTHER POINTS
          JUNCTION LEGS 1-7-2 =  3363.05 FT
          JUNCTION LEGS 2-8-3 =  3259.55 FT
          JUNCTION LEGS 4-9-5 =  2263.05 FT
         JUNCTION LEGS 5-10-6 =  2159.55 FT
 JUNCTION LEGS 7-9-REPOSITORY =  2738.05 FT
JUNCTION LEGS 8-10-REPOSITORY =  2738.05 FT
         JUNCTION LEGS 6-11 =   387.06 FT

                  LEG PROPERTIES

LEG  1                  LENGTH =  1.05E+04 FT
********                  AREA =  1.00E+06 FT**2
                  CONDUCTIVITY =  1.83E+04 FT/YR
                      POROSITY =   .3000
                       DENSITY =  1.19E+02 LB/FT**3
            RETARDATION FACTOR =  6.36E+02
      DISTRIBUTION COEFFICIENT =  1.60E+00 FT**3/LB

                  LEG PROPERTIES

LEG  2                  LENGTH =  8.00E+03 FT
********                  AREA =  1.00E+06 FT**2
                  CONDUCTIVITY =  1.83E+04 FT/YR
                      POROSITY =   .3000
                       DENSITY =  1.19E+02 LB/FT**3
            RETARDATION FACTOR =  6.36E+02
      DISTRIBUTION COEFFICIENT =  1.60E+00 FT**3/LB
```

```
                         LEG PROPERTIES

 LEG   3                  LENGTH =  1.37E+05 FT
********                    AREA =  1.00E+06 FT**2
                    CONDUCTIVITY =  1.83E+04 FT/YR
                        POROSITY =   .3000
                         DENSITY =  1.19E+02 LB/FT**3
               RETARDATION FACTOR =  6.36E+02
   DISTRIBUTION COEFFICIENT =  1.60E+00 FT**3/LB

                         LEG PROPERTIES

 LEG   4                  LENGTH =  1.05E+04 FT
********                    AREA =  3.00E+05 FT**2
                    CONDUCTIVITY =  1.46E+04 FT/YR
                        POROSITY =   .3000
                         DENSITY =  1.19E+02 LB/FT**3
               RETARDATION FACTOR =  6.36E+02
   DISTRIBUTION COEFFICIENT =  1.60E+00 FT**3/LB

                         LEG PROPERTIES

 LEG   5                  LENGTH =  8.00E+03 FT
********                    AREA =  3.00E+05 FT**2
                    CONDUCTIVITY =  1.46E+04 FT/YR
                        POROSITY =   .3000
                         DENSITY =  1.19E+02 LB/FT**3
               RETARDATION FACTOR =  6.36E+02
   DISTRIBUTION COEFFICIENT =  1.60E+00 FT**3/LB

                         LEG PROPERTIES

 LEG   6                  LENGTH =  1.37E+05 FT
********                    AREA =  3.00E+05 FT**2
                    CONDUCTIVITY =  1.46E+04 FT/YR
                        POROSITY =   .3000
                         DENSITY =  1.19E+02 LB/FT**3
               RETARDATION FACTOR =  6.36E+02
   DISTRIBUTION COEFFICIENT =  1.60E+00 FT**3/LB

                         LEG PROPERTIES

 LEG   7                  LENGTH =  6.25E+02 FT
********                    AREA =  6.25E+02 FT**2
                    CONDUCTIVITY =  3.65E+03 FT/YR
                        POROSITY =   .1500
                         DENSITY =  1.45E+02 LB/FT**3
               RETARDATION FACTOR =  1.00E+00
   DISTRIBUTION COEFFICIENT =  0.       FT**3/LB
```

```
                              LEG PROPERTIES

 LEG  8                  LENGTH =  5.22E+02 FT
********                   AREA =  6.25E+02 FT**2
                   CONDUCTIVITY =  3.65E+03 FT/YR
                       POROSITY =   .1500
                        DENSITY =  1.45E+02 LB/FT**3
              RETARDATION FACTOR =  1.00E+00
        DISTRIBUTION COEFFICIENT =  0.       FT**3/LB

                              LEG PROPERTIES

 LEG  9                  LENGTH =  4.75E+02 FT
********                   AREA =  1.00E+00 FT**2
                   CONDUCTIVITY =  3.65E-04 FT/YR
                       POROSITY =   .1500
                        DENSITY =  1.45E+02 LB/FT**3
              RETARDATION FACTOR =  1.00E+00
        DISTRIBUTION COEFFICIENT =  0.       FT**3/LB

                              LEG PROPERTIES

 LEG 10                  LENGTH =  5.79E+02 FT
********                   AREA =  1.00E+00 FT**2
                   CONDUCTIVITY =  3.65E-04 FT/YR
                       POROSITY =   .1500
                        DENSITY =  1.45E+02 LB/FT**3
              RETARDATION FACTOR =  1.00E+00
        DISTRIBUTION COEFFICIENT =  0.       FT**3/LB

                              LEG PROPERTIES

 LEG 11                  LENGTH =  1.10E+03 FT
********                   AREA =  2.10E+07 FT**2
                   CONDUCTIVITY =  5.11E+02 FT/YR
                       POROSITY =   .3000
                        DENSITY =  1.19E+02 LB/FT**3
              RETARDATION FACTOR =  6.36E+02
        DISTRIBUTION COEFFICIENT =  1.60E+00 FT**3/LB
```

PRESSURE HEADS AT LEG JUNCTIONS

| | | |
|---|---|---|
| UPPER AQUIFER INLET | = | 1.0000E+03 FT |
| LOWER AQUIFER INLET | = | 1.5050E+03 FT |
| AQUIFER OUTLET | = | 1.0000E+03 FT |
| JUNCTION LEGS 1-7-2 | = | 1.0000E+03 FT |
| JUNCTION LEGS 2-8-3 | = | 1.0001E+03 FT |
| JUNCTION LEGS 4-9-5 | = | 1.5455E+03 FT |
| JUNCTION LEGS 5-10-6 | = | 1.5763E+03 FT |
| JUNCTION LEGS 7-9-DEPOSITORY | = | 1.5686E+03 FT |
| JUNCTION LEGS 8-10-DEPOSITORY | = | 1.5686E+03 FT |
| JUNCTION LEGS 6-11 | = | 2.1041E+03 FT |

| LEG NO. | FLOW VOL. (CU FT)/DAY | DARCY VEL. FT/DAY | PORE VEL. FT/DAY |
|---|---|---|---|
| 1 | 6.47E+05 | 6.47E-01 | 2.16E+00 |
| 2 | 6.46E+05 | 6.46E-01 | 2.15E+00 |
| 3 | 6.47E+05 | 6.47E-01 | 2.16E+00 |
| 4 | 1.09E+05 | 3.63E-01 | 1.21E+00 |
| 5 | 1.09E+05 | 3.63E-01 | 1.21E+00 |
| 6 | 1.09E+05 | 3.63E-01 | 1.21E+00 |
| 7 | -5.64E+02 | -9.02E-01 | -6.01E+00 |
| 8 | 5.64E+02 | 9.02E-01 | 6.01E+00 |
| 9 | -1.05E-06 | -1.05E-06 | -6.99E-06 |
| 10 | -9.87E-07 | -9.87E-07 | -6.58E-06 |
| 11 | 1.09E+05 | 5.19E-03 | 1.73E-02 |

RADIONUCLIDE MIGRATION PATH-----LEGS 8 3

PATH LENGTH (FT) = 1.3752E+05
ISOTOPE VEL. (FT/DAY) = 3.4053E-03
MIGRATION TIME (YEARS) = 1.1064E+05

RADIONUCLIDE DISCHARGE RATE (CI/DAY)

| TIME (YEARS) | PU240 | U236 |
|---|---|---|
| 1.1064E+04 | 0. | 0. |
| 1.2560E+04 | 0. | 0. |
| 1.4056E+04 | 0. | 0. |
| 1.5552E+04 | 0. | 0. |
| 1.7047E+04 | 0. | 0. |
| 1.8543E+04 | 0. | 0. |
| 2.0039E+04 | 0. | 0. |
| 2.1535E+04 | 0. | 0. |
| 2.3031E+04 | 0. | 0. |
| 2.4526E+04 | 0. | 0. |
| 2.6022E+04 | 0. | 0. |
| 2.7518E+04 | 0. | 0. |
| 2.9014E+04 | 0. | 0. |
| 3.0510E+04 | 0. | 0. |
| 3.2005E+04 | 0. | 0. |
| 3.3501E+04 | 0. | 0. |
| 3.4997E+04 | 0. | 0. |
| 3.6493E+04 | 0. | 0. |
| 3.7988E+04 | 0. | 0. |
| 3.9484E+04 | 0. | 0. |
| 4.0980E+04 | 0. | 0. |
| 4.2476E+04 | 0. | 0. |
| 4.3972E+04 | 0. | 0. |
| 4.5467E+04 | 0. | 0. |
| 4.6963E+04 | 0. | 0. |
| 4.8459E+04 | 0. | 4.5893E-28 |
| 4.9955E+04 | 0. | 2.0489E-26 |
| 5.1451E+04 | 0. | 6.9614E-25 |
| 5.2946E+04 | 0. | 1.8424E-23 |
| 5.4442E+04 | 1.4612E-24 | 3.8773E-22 |
| 5.5938E+04 | 2.1368E-23 | 6.6094E-21 |
| 5.7434E+04 | 2.5733E-22 | 9.2783E-20 |
| 5.8929E+04 | 2.5902E-21 | 1.0887E-18 |
| 6.0425E+04 | 2.2086E-20 | 1.0822E-17 |
| 6.1921E+04 | 1.6148E-19 | 9.2232E-17 |
| 6.3417E+04 | 1.0236E-18 | 6.8148E-16 |
| 6.4913E+04 | 5.6807E-18 | 4.4089E-15 |
| 6.6408E+04 | 2.7857E-17 | 2.5204E-14 |
| 6.7904E+04 | 1.2171E-16 | 1.2836E-13 |
| 6.9400E+04 | 4.7737E-16 | 5.8690E-13 |
| 7.0896E+04 | 1.6926E-15 | 2.4257E-12 |
| 7.2392E+04 | 5.4597E-15 | 9.1213E-12 |
| 7.3887E+04 | 1.6117E-14 | 3.1387E-11 |
| 7.5383E+04 | 4.3775E-14 | 9.9377E-11 |
| 7.6879E+04 | 1.0995E-13 | 2.9096E-10 |
| 7.8375E+04 | 2.5655E-13 | 7.9144E-10 |
| 7.9871E+04 | 5.5855E-13 | 2.0086E-09 |
| 8.1366E+04 | 1.1392E-12 | 4.7756E-09 |

| | | |
|---|---|---|
| 8.2862E+04 | 2.1847E-12 | 1.0676E-08 |
| 8.4358E+04 | 3.9534E-12 | 2.2520E-08 |
| 8.5854E+04 | 6.7723E-12 | 4.4971E-08 |
| 8.7349E+04 | 1.1016E-11 | 8.5273E-08 |
| 8.8845E+04 | 1.7064E-11 | 1.5398E-07 |
| 9.0341E+04 | 2.5241E-11 | 2.6551E-07 |
| 9.1837E+04 | 3.5743E-11 | 4.3828E-07 |
| 9.3333E+04 | 4.8574E-11 | 6.9431E-07 |
| 9.4828E+04 | 6.3496E-11 | 1.0580E-06 |
| 9.6324E+04 | 8.0015E-11 | 1.5542E-06 |
| 9.7820E+04 | 9.7411E-11 | 2.2056E-06 |
| 9.9316E+04 | 1.1480E-10 | 3.0300E-06 |
| 1.0081E+05 | 1.3122E-10 | 4.0372E-06 |
| 1.0231E+05 | 1.4575E-10 | 5.2274E-06 |
| 1.0380E+05 | 1.5760E-10 | 6.5893E-06 |
| 1.0530E+05 | 1.6620E-10 | 8.1005E-06 |
| 1.0679E+05 | 1.7124E-10 | 9.7288E-06 |
| 1.0829E+05 | 1.7265E-10 | 1.1435E-05 |
| 1.0979E+05 | 1.7064E-10 | 1.3174E-05 |
| 1.1128E+05 | 1.6558E-10 | 1.4902E-05 |
| 1.1278E+05 | 1.5800E-10 | 1.6576E-05 |
| 1.1427E+05 | 1.4850E-10 | 1.8160E-05 |
| 1.1577E+05 | 1.3766E-10 | 1.9625E-05 |
| 1.1727E+05 | 1.2607E-10 | 2.0950E-05 |
| 1.1876E+05 | 1.1420E-10 | 2.2123E-05 |
| 1.2026E+05 | 1.0247E-10 | 2.3141E-05 |
| 1.2175E+05 | 9.1194E-11 | 2.4006E-05 |
| 1.2325E+05 | 8.0584E-11 | 2.4729E-05 |
| 1.2474E+05 | 7.0783E-11 | 2.5320E-05 |
| 1.2624E+05 | 6.1863E-11 | 2.5796E-05 |
| 1.2774E+05 | 5.3844E-11 | 2.6173E-05 |
| 1.2923E+05 | 4.6707E-11 | 2.6466E-05 |
| 1.3073E+05 | 4.0407E-11 | 2.6691E-05 |
| 1.3222E+05 | 3.4883E-11 | 2.6860E-05 |
| 1.3372E+05 | 3.0064E-11 | 2.6985E-05 |
| 1.3521E+05 | 2.5878E-11 | 2.7077E-05 |
| 1.3671E+05 | 2.2253E-11 | 2.7143E-05 |
| 1.3821E+05 | 1.9123E-11 | 2.7190E-05 |
| 1.3970E+05 | 1.6424E-11 | 2.7222E-05 |
| 1.4120E+05 | 1.4101E-11 | 2.7245E-05 |
| 1.4269E+05 | 1.2103E-11 | 2.7260E-05 |
| 1.4419E+05 | 1.0386E-11 | 2.7269E-05 |
| 1.4569E+05 | 8.9120E-12 | 2.7276E-05 |
| 1.4718E+05 | 7.6461E-12 | 2.7279E-05 |
| 1.4868E+05 | 6.5597E-12 | 2.7281E-05 |
| 1.5017E+05 | 5.6274E-12 | 2.7282E-05 |
| 1.5167E+05 | 4.8275E-12 | 2.7282E-05 |
| 1.5316E+05 | 4.1412E-12 | 2.7282E-05 |
| 1.5466E+05 | 3.5524E-12 | 2.7281E-05 |
| 1.5616E+05 | 3.0473E-12 | 2.7281E-05 |
| 1.5765E+05 | 2.6141E-12 | 2.7280E-05 |

| | | |
|---|---|---|
| 1.5915E+05 | 2.2424E-12 | 2.7279E-05 |
| 1.6064E+05 | 1.9235E-12 | 2.7278E-05 |
| 1.6214E+05 | 1.6500E-12 | 2.7276E-05 |
| 1.6363E+05 | 1.4154E-12 | 2.7275E-05 |
| 1.6513E+05 | 1.2142E-12 | 2.7274E-05 |
| 1.6663E+05 | 1.0415E-12 | 2.7273E-05 |
| 1.6812E+05 | 8.9343E-13 | 2.7272E-05 |
| 1.6962E+05 | 7.6639E-13 | 2.7271E-05 |
| 1.7111E+05 | 6.5742E-13 | 2.7269E-05 |
| 1.7261E+05 | 5.6394E-13 | 2.7268E-05 |
| 1.7411E+05 | 4.8375E-13 | 2.7267E-05 |
| 1.7560E+05 | 4.1497E-13 | 2.7266E-05 |
| 1.7710E+05 | 3.5596E-13 | 2.7264E-05 |
| 1.7859E+05 | 3.0534E-13 | 2.7263E-05 |
| 1.8009E+05 | 2.6191E-13 | 2.7260E-05 |
| 1.8158E+05 | 2.2464E-13 | 2.7256E-05 |
| 1.8308E+05 | 1.9265E-13 | 2.7248E-05 |
| 1.8458E+05 | 1.6518E-13 | 2.7234E-05 |
| 1.8607E+05 | 1.4157E-13 | 2.7208E-05 |
| 1.8757E+05 | 1.2124E-13 | 2.7163E-05 |
| 1.8906E+05 | 1.0372E-13 | 2.7088E-05 |
| 1.9056E+05 | 8.8583E-14 | 2.6968E-05 |
| 1.9205E+05 | 7.5472E-14 | 2.6784E-05 |
| 1.9355E+05 | 6.4089E-14 | 2.6514E-05 |
| 1.9505E+05 | 5.4188E-14 | 2.6132E-05 |
| 1.9654E+05 | 4.5565E-14 | 2.5615E-05 |
| 1.9804E+05 | 3.8058E-14 | 2.4940E-05 |
| 1.9953E+05 | 3.1536E-14 | 2.4091E-05 |
| 2.0103E+05 | 2.5894E-14 | 2.3059E-05 |
| 2.0253E+05 | 2.1044E-14 | 2.1845E-05 |
| 2.0402E+05 | 1.6910E-14 | 2.0462E-05 |
| 2.0552E+05 | 1.3423E-14 | 1.8935E-05 |
| 2.0701E+05 | 1.0519E-14 | 1.7297E-05 |
| 2.0851E+05 | 8.1316E-15 | 1.5587E-05 |
| 2.1000E+05 | 6.1985E-15 | 1.3851E-05 |
| 2.1150E+05 | 4.6575E-15 | 1.2132E-05 |
| 2.1300E+05 | 3.4488E-15 | 1.0472E-05 |
| 2.1449E+05 | 2.5163E-15 | 8.9067E-06 |
| 2.1599E+05 | 1.8090E-15 | 7.4641E-06 |
| 2.1748E+05 | 1.2814E-15 | 6.1633E-06 |
| 2.1898E+05 | 8.9442E-16 | 5.0149E-06 |
| 2.2047E+05 | 6.1529E-16 | 4.0215E-06 |
| 2.2197E+05 | 4.1722E-16 | 3.1788E-06 |
| 2.2347E+05 | 2.7893E-16 | 2.4773E-06 |
| 2.2496E+05 | 1.8390E-16 | 1.9039E-06 |
| 2.2646E+05 | 1.1959E-16 | 1.4434E-06 |
| 2.2795E+05 | 7.6740E-17 | 1.0796E-06 |
| 2.2945E+05 | 4.8600E-17 | 7.9704E-07 |
| 2.3094E+05 | 3.0386E-17 | 5.8091E-07 |
| 2.3244E+05 | 1.8761E-17 | 4.1811E-07 |
| 2.3394E+05 | 1.1443E-17 | 2.9728E-07 |
| 2.3543E+05 | 6.8966E-18 | 2.0885E-07 |

| | | |
|---|---|---|
| 2.3693E+05 | 4.1083E-18 | 1.4503E-07 |
| 2.3842E+05 | 2.4197E-18 | 9.9575E-08 |
| 2.3992E+05 | 1.4095E-18 | 6.7614E-08 |
| 2.4142E+05 | 8.1220E-19 | 4.5419E-08 |
| 2.4291E+05 | 4.6314E-19 | 3.0191E-08 |
| 2.4441E+05 | 2.6140E-19 | 1.9864E-08 |
| 2.4590E+05 | 1.4608E-19 | 1.2940E-08 |
| 2.4740E+05 | 8.0845E-20 | 8.3480E-09 |
| 2.4889E+05 | 4.4321E-20 | 5.3350E-09 |
| 2.5039E+05 | 2.4075E-20 | 3.3782E-09 |
| 2.5189E+05 | 1.2961E-20 | 2.1200E-09 |
| 2.5338E+05 | 6.9170E-21 | 1.3189E-09 |
| 2.5488E+05 | 3.6602E-21 | 8.1355E-10 |
| 2.5637E+05 | 1.9208E-21 | 4.9770E-10 |
| 2.5787E+05 | 9.9996E-22 | 3.0203E-10 |
| 2.5936E+05 | 5.1648E-22 | 1.8185E-10 |
| 2.6086E+05 | 2.6473E-22 | 1.0865E-10 |
| 2.6236E+05 | 1.3468E-22 | 6.4439E-11 |
| 2.6385E+05 | 6.8025E-23 | 3.7939E-11 |
| 2.6535E+05 | 3.4115E-23 | 2.2180E-11 |
| 2.6684E+05 | 1.6991E-23 | 1.2877E-11 |
| 2.6834E+05 | 8.4055E-24 | 7.4260E-12 |
| 2.6984E+05 | 4.1310E-24 | 4.2545E-12 |
| 2.7133E+05 | 2.0173E-24 | 2.4219E-12 |
| 2.7283E+05 | 9.7898E-25 | 1.3701E-12 |
| 2.7432E+05 | 4.7220E-25 | 7.7034E-13 |
| 2.7582E+05 | 0. | 4.3057E-13 |
| 2.7731E+05 | 0. | 2.3927E-13 |
| 2.7881E+05 | 0. | 1.3221E-13 |
| 2.8031E+05 | 0. | 7.2652E-14 |
| 2.8180E+05 | 0. | 3.9708E-14 |
| 2.8330E+05 | 0. | 2.1589E-14 |
| 2.8479E+05 | 0. | 1.1677E-14 |
| 2.8629E+05 | 0. | 6.2845E-15 |
| 2.8778E+05 | 0. | 3.3656E-15 |
| 2.8928E+05 | 0. | 1.7939E-15 |
| 2.9078E+05 | 0. | 9.5174E-16 |
| 2.9227E+05 | 0. | 5.0259E-16 |
| 2.9377E+05 | 0. | 2.6412E-16 |
| 2.9526E+05 | 0. | 1.3843E-16 |
| 2.9676E+05 | 0. | 7.2203E-17 |
| 2.9826E+05 | 0. | 3.7451E-17 |
| 2.9975E+05 | 0. | 1.9497E-17 |
| 3.0125E+05 | 0. | 1.0038E-17 |
| 3.0274E+05 | 0. | 5.2116E-18 |
| 3.0424E+05 | 0. | 2.7022E-18 |
| 3.0573E+05 | 0. | 1.5440E-18 |
| 3.0723E+05 | 0. | 7.7199E-19 |
| 3.0873E+05 | 0. | 3.8598E-19 |
| 3.1022E+05 | 0. | 3.8596E-19 |

```
OPTIONS  1 0   2 0   3 0   4 0   5 0   6 0   7 0   8 0   9 0  10 0  11 0  12 0  13 0  14 0  15 0  16 0  17 0  18 0  19 0  20 0
 NUMBER OF ISOTOPES     2


        ISOTOPE NAME            HALF LIFE (YEARS)     INITIAL AMOUNT (CI)

           PU240                     6.760E+03              1.000E+03
            U236                     2.390E+07              1.000E+03

        LEACH TIME =    1.000E+05 YEARS      DISPERSIVITY =   5.000E+02 FEET

NO OF VECTORS =    0 TIME UPPER BOUND =         1.00E+06


                    ****************************** ANALYTIC FLOW MODEL ******************************
```

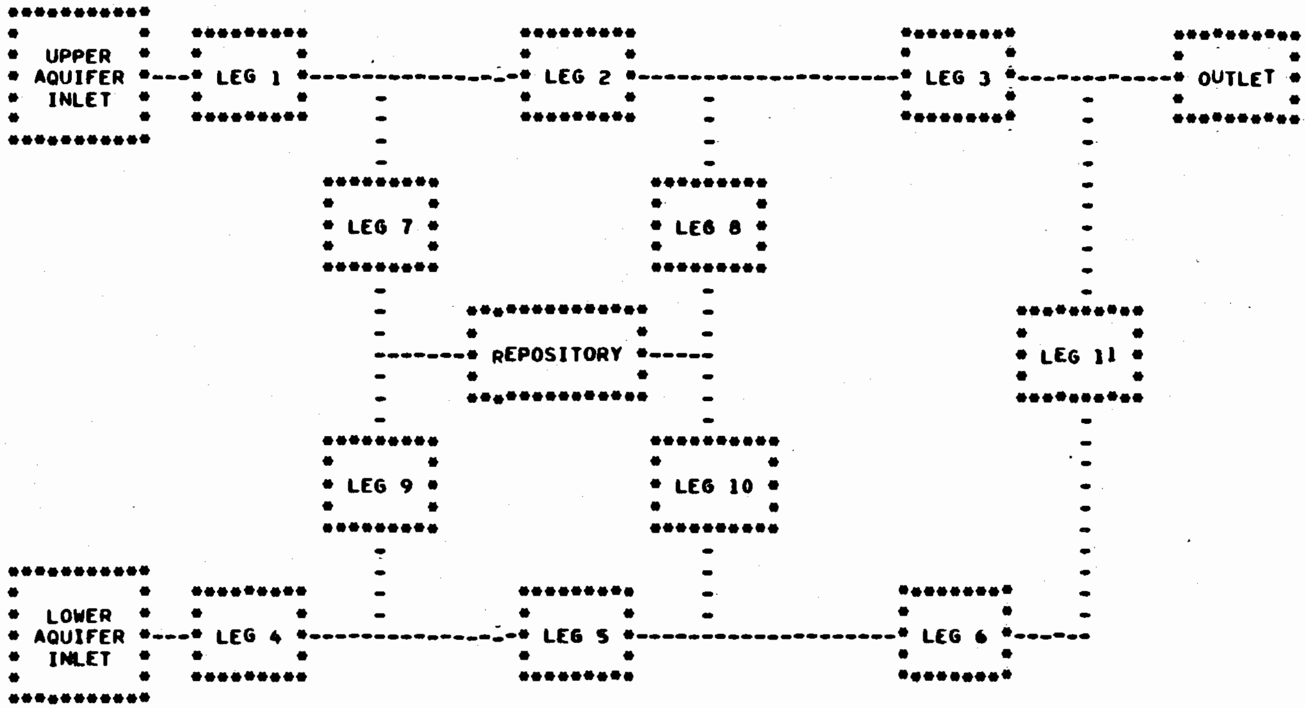



Table 5.6. NWFT Output for Sample Problem 2.

```
                 UPPER AQUIFER INLET
                  INLET HEAD =  1000.00 FT
                   ELEVATION =  3498.90 FT

                 LOWER AQUIFER INLET
                  INLET HEAD =  1505.00 FT
                   ELEVATION =  2398.90 FT

                       OUTLET
                 OUTLET HEAD =  1000.00 FT
                   ELEVATION =  1487.06 FT

                    ELEVATIONS OF OTHER POINTS
             JUNCTION LEGS 1-7-2 =   3363.05 FT
             JUNCTION LEGS 2-8-3 =   3259.55 FT
             JUNCTION LEGS 4-9-5 =   2263.05 FT
            JUNCTION LEGS 5-10-6 =   2159.55 FT
     JUNCTION LEGS 7-9-REPOSITORY =   2738.05 FT
    JUNCTION LEGS 8-10-REPOSITORY =   2738.05 FT
              JUNCTION LEGS 6-11 =    387.06 FT

                       LEG PROPERTIES

LEG   1                  LENGTH =  1.05E+04 FT
********                   AREA =  1.00E+06 FT**2
                   CONDUCTIVITY =  1.83E+04 FT/YR
                       POROSITY =   .3000
                        DENSITY =  1.19E+02 LB/FT**3
              RETARDATION FACTOR =  6.36E+02
        DISTRIBUTION COEFFICIENT =  1.60E+00 FT**3/LB

                       LEG PROPERTIES

LEG   2                  LENGTH =  8.00E+03 FT
********                   AREA =  1.00E+06 FT**2
                   CONDUCTIVITY =  1.83E+04 FT/YR
                       POROSITY =   .3000
                        DENSITY =  1.19E+02 LB/FT**3
              RETARDATION FACTOR =  6.36E+02
        DISTRIBUTION COEFFICIENT =  1.60E+00 FT**3/LB

                       LEG PROPERTIES

LEG   3                  LENGTH =  1.37E+05 FT
********                   AREA =  1.00E+06 FT**2
                   CONDUCTIVITY =  1.83E+04 FT/YR
                       POROSITY =   .3000
                        DENSITY =  1.19E+02 LB/FT**3
              RETARDATION FACTOR =  6.36E+02
        DISTRIBUTION COEFFICIENT =  1.60E+00 FT**3/LB
```

```
                      LEG PROPERTIES

LEG   4                LENGTH =  1.05E+04 FT
********                 AREA =  3.00E+05 FT**2
                 CONDUCTIVITY =  1.46E+04 FT/YR
                     POROSITY =   .3000
                      DENSITY =  1.19E+02 LB/FT**3
            RETARDATION FACTOR =  6.36E+02
   DISTRIBUTION COEFFICIENT =  1.60E+00 FT**3/LB

                      LEG PROPERTIES

LEG   5                LENGTH =  8.00E+03 FT
********                 AREA =  3.00E+05 FT**2
                 CONDUCTIVITY =  1.46E+04 FT/YR
                     POROSITY =   .3000
                      DENSITY =  1.19E+02 LB/FT**3
            RETARDATION FACTOR =  6.36E+02
   DISTRIBUTION COEFFICIENT =  1.60E+00 FT**3/LB

                      LEG PROPERTIES

LEG   6                LENGTH =  1.37E+05 FT
********                 AREA =  3.00E+05 FT**2
                 CONDUCTIVITY =  1.46E+04 FT/YR
                     POROSITY =   .3000
                      DENSITY =  1.19E+02 LB/FT**3
            RETARDATION FACTOR =  6.36E+02
   DISTRIBUTION COEFFICIENT =  1.60E+00 FT**3/LB

                      LEG PROPERTIES

LEG   7                LENGTH =  6.25E+02 FT
********                 AREA =  1.00E+00 FT**2
                 CONDUCTIVITY =  3.65E-04 FT/YR
                     POROSITY =   .1500
                      DENSITY =  1.45E+02 LB/FT**3
            RETARDATION FACTOR =  1.00E+00
   DISTRIBUTION COEFFICIENT =  0.         FT**3/LB
```

```
                          LEG PROPERTIES

 LEG  8                    LENGTH =  5.22E+02 FT
********                     AREA =  6.25E+02 FT**2
                     CONDUCTIVITY =  3.65E+03 FT/YR
                         POROSITY =   .1500
                          DENSITY =  1.45E+02 LB/FT**3
                RETARDATION FACTOR =  1.00E+00
          DISTRIBUTION COEFFICIENT =  0.        FT**3/LB

                          LEG PROPERTIES

 LEG  9                    LENGTH =  4.75E+02 FT
********                     AREA =  1.00E+00 FT**2
                     CONDUCTIVITY =  3.65E-04 FT/YR
                         POROSITY =   .1500
                          DENSITY =  1.45E+02 LB/FT**3
                RETARDATION FACTOR =  1.00E+00
          DISTRIBUTION COEFFICIENT =  0.        FT**3/LB

                          LEG PROPERTIES

 LEG 10                    LENGTH =  5.79E+02 FT
********                     AREA =  6.25E+02 FT**2
                     CONDUCTIVITY =  3.65E+03 FT/YR
                         POROSITY =   .1500
                          DENSITY =  1.45E+02 LB/FT**3
                RETARDATION FACTOR =  1.00E+00
          DISTRIBUTION COEFFICIENT =  0.        FT**3/LB

                          LEG PROPERTIES

 LEG 11                    LENGTH =  1.10E+03 FT
********                     AREA =  2.10E+07 FT**2
                     CONDUCTIVITY =  5.11E+02 FT/YR
                         POROSITY =   .3000
                          DENSITY =  1.19E+02 LB/FT**3
                RETARDATION FACTOR =  6.36E+02
          DISTRIBUTION COEFFICIENT =  1.60E+00 FT**3/LB
```

PRESSURE HEADS AT LEG JUNCTIONS

| | |
|---|---|
| UPPER AQUIFER INLET = | 1.0000E+03 FT |
| LOWER AQUIFER INLET = | 1.5050E+03 FT |
| AQUIFER OUTLET = | 1.0000E+03 FT |
| JUNCTION LEGS 1-7-2 = | 9.9946E+02 FT |
| JUNCTION LEGS 2-8-3 = | 9.9904E+02 FT |
| JUNCTION LEGS 4-9-5 = | 1.5477E+03 FT |
| JUNCTION LEGS 5-10-6 = | 1.5803E+03 FT |
| JUNCTION LEGS 7-9-DEPOSITORY = | 1.2746E+03 FT |
| JUNCTION LEGS 8-10-DEPOSITORY = | 1.2746E+03 FT |
| JUNCTION LEGS 6-11 = | 2.1041E+03 FT |

| LEG NO. | FLOW VOL. (CU FT)/DAY | DARCY VEL. FT/DAY | PORE VEL. FT/DAY |
|---|---|---|---|
| 1 | 6.49E+05 | 6.49E-01 | 2.16E+00 |
| 2 | 6.49E+05 | 6.49E-01 | 2.16E+00 |
| 3 | 6.47E+05 | 6.47E-01 | 2.16E+00 |
| 4 | 1.06E+05 | 3.55E-01 | 1.18E+00 |
| 5 | 1.06E+05 | 3.55E-01 | 1.18E+00 |
| 6 | 1.09E+05 | 3.65E-01 | 1.22E+00 |
| 7 | -5.60E-07 | -5.60E-07 | -3.73E-06 |
| 8 | -2.95E+03 | -4.72E+00 | -3.14E+01 |
| 9 | -4.25E-07 | -4.25E-07 | -2.83E-06 |
| 10 | -2.95E+03 | -4.72E+00 | -3.14E+01 |
| 11 | 1.09E+05 | 5.21E-03 | 1.74E-02 |

RADIONUCLIDE MIGRATION PATH-----LEGS 10 6 11

PATH LENGTH (FT) = 1.3868E+05
ISOTOPE VEL. (FT/DAY) = 1.2389E-03
MIGRATION TIME (YEARS) = 3.0668E+05

RADIONUCLIDE DISCHARGE RATE (CI/DAY)

| TIME (YEARS) | PU240 | U236 |
|---|---|---|
| 3.0668E+04 | 0. | 0. |
| 3.3928E+04 | 0. | 0. |
| 3.7188E+04 | 0. | 0. |
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| 6.7943E+05 | 0. | 9.5462E-20 |

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