TERRA THERMA, INC.

WATER CONSULTANTS AND ENGINEERS

U.S NUCLEAR REGULATORY COMMISSION
DIVISION OF WASTE MANAGEMENT

Technical Report #13

EFFECT OF REPOSITORY HEAT ON GROUNDWATER FLUX: ONE-DIMENSIONAL NUMERICAL ANALYSIS

Basalt Waste Isolation Project
Subtask 2.5
Numerical Evaluation of Conceptual Models

Prepared by

Terra Therma Inc.

for

Nuclear Waste Consultants

TECHNICAL ASSISTANCE IN HYDROGEOLOGY
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1.0 INTRODUCTION

High level nuclear waste, buried in a geologic repository, will liberate substantial quantities of heat by radioactive decay. The rate of heat generation, although initially high, will decrease substantially within the first 200 years after emplacement. Because regulatory criteria require that radionuclide transport be predicted for post-emplacement conditions, the effect of repository heat on groundwater flux needs to be evaluated. Some investigators have assumed that because the rate of heat generation is minimal after 200 years, the effects of repository heat can be neglected for all but early times after emplacement. However, this assumption does not consider that latent heat may persist within the geologic medium long after heat production has been reduced to minimal levels.

The purpose of this technical report is to assess the relative importance of repository heat on vertical groundwater flow within the emplacement horizon at BWIP. A one-dimensional numerical model is formulated which incorporates the effects of temperature on groundwater density and viscosity, but does not consider convection. Using this model, rates of vertical groundwater flux attributed to thermal effects are computed.

1.1 GENERAL STATEMENT OF THE PROBLEM

The purpose of this analysis is to address the following question:

> Does heat generated by a high level waste repository have a significant effect on groundwater flux rates within the emplacement horizon?

Temperature changes in the hydrogeologic system will have two effects which can potentially change groundwater flux rates. First, a reduction in groundwater fluid density, due to a rise in temperature, will lead to buoyancy forces. These forces will result in a tendency for groundwater to move vertically upward in vicinity of the repository. Secondly, increased temperatures will reduce fluid viscosity, which by Darcy's law, will increase the flux rate for a given hydraulic gradient.

1.2 RELEVANCE TO NRC

As described in Section 10 CFR 60.122 (a) (1), qualitative siting criteria have been developed by the NRC which require the license applicant to provide information that can be used to assess "reasonable assurance" that performance objectives will be met. These siting criteria are based on pre-emplacement/post-emplacement conditions and are categorized in terms of "favorable" and "potentially adverse" conditions. The conditions relevant to

BWIP which require a knowledge of post-emplacement groundwater flux rates are listed below:

Favorable Conditions

No favorable conditions have been identified which are related to thermal effects on post-emplacement groundwater flux.

Potentially Adverse Conditions

122(c)(2) "Potential for foreseeable human activity to adversely affect the groundwater flow system, such as groundwater withdrawals, extensive irrigation, subsurface injection of fluids, [repository heat] ..."

122(c)(5) "Potential for changes in hydrologic conditions that would affect the migration of radionuclides ..."

With regard to groundwater flux, "potentially adverse conditions" require an evaluation of changes in hydraulic gradients and rock/fluid properties resulting from man-made phenomena.

In addition to the above qualitative siting criteria, the NRC has formulated performance objectives in Section 10 CFR 60.111-60.113. With regard to groundwater flow, the EPA Cumulative Flux Standard specifies the maximum amount of radionuclides which can reach the accessible environment over a period of 10,000 years. Since temperature changes may be significant during this post-emplacement period, the effects of repository heat on radionuclide transport will have to be addressed. As a consequence, the effect of heat on hydraulic gradients and rock/fluid hydraulic properties will be an important concern in evaluating the EPA Criterion.

1.3 RELATIONSHIP TO OTHER SITE CHARACTERIZATION/REGULATORY TASKS

An important factor in assessing the suitability of the BWIP site is application of the EPA Cumulative Flux Standard. This regulatory criterion will require an understanding and quantification of the three-dimensional groundwater flow field under post-emplacement conditions. Since thermal effects may cause significant variations in hydraulic gradients, buoyancy forces, and hydraulic conductivity, the impact of repository heat on groundwater flow will be an important consideration in applying this regulatory standard.

DOE is currently formulating plans for future testing and analysis at the BWIP site. These activities will probably result in extension of the Baseline Monitoring Program, performance of Large-Scale Hydraulic Stress (LHS) testing, and application of relevant data to the EPA Standard. The impact of repository heat on post-emplacement groundwater flux may be an important consideration in developing future test programs and analyses. For example, if post-emplacement hydraulic gradients were shown to be dominated by temperature effects, data obtained from the current (pre-emplacement) Baseline Monitoring Program may be of relatively little importance in evaluating the EPA Standard.

2.0 OBJECTIVE

The objective of this study is to determine through the use of a simple numerical model, the relative importance of repository heat on post-emplacement groundwater flux rates within the emplacement horizon (currently the Cohassett Flow Interior).

3.0 EVALUATION

3.1 OPERATIONAL APPROACH

The calculations performed herein analyze vertical groundwater flow in a heated system with simple geometry. Parameter values chosen for the analysis are consistent with known characteristics of the BWIP site. The purpose of this analysis is not to simulate groundwater flow at BWIP in detail, but to assess (in a sensitivity manner) the relative importance of repository heat on post-emplacement groundwater flux. The general approach is to calibrate the model to simulate zero flux for pre-emplacement conditions and then determine the change in flux that results from temperature distributions associated with post-emplacement repository heat.

3.2 CONCEPTUAL MODEL

3.2.1 Framework

The candidate repository horizon is situated within Columbia River Basalt at a depth of about 960 meters below ground surface. In this simulation, only vertical flow is considered. Thus, the physical system shown in Figure 1 consists of a column of dense basalt (Cohassett Flow Interior) situated between two interflows of relatively high permeability (Cohassett and Birkett Interflows). The repository constitutes a heat source of variable strength located at the midpoint of the emplacement horizon.

3.2.2 Groundwater Flow System

The assumed physical system discussed above leads to the groundwater flow analytical model shown in Figure 2. Flow within the geologic medium is treated as steady state and one-dimensional (vertical). The steady state approach is considered valid because transient hydraulic responses are expected to be rapid compared to the changes in the thermal regime. Flow is driven by the vertical pressure distribution and buoyancy forces (resulting variations in fluid density). The density of groundwater is dependent on temperature and salinity.

Prescribed (constant) pressure boundaries are placed at the top and bottom of the flow system. Use of these boundary conditions implies that vertical flow within the flow interior (induced by repository heat) is insufficient to result in significant hydraulic perturbations within the adjacent interflows. This assumption would seem reasonable considering the permeability contrast which typically exists between flow interiors and interflows at BWIP.

3.2.3 Heat Flow System

The heat flow analytical model is illustrated in Figure 3. This model assumes that a homogeneous, one-dimensional, and semi-infinite thermal medium exists above and below the repository horizon. Thus, no distinction is made between the thermal properties of the candidate horizon and other flow interiors and interflows existing at BWIP. The repository is treated as a heat source of variable strength located at the common boundary between the two semi-infinite systems. This model for analysis of heat flow is the same as the formulation developed in Technical Report #3.

For pre-emplacement conditions, the temperature is assumed to increase linearly with depth (geothermal gradient). The assumption of a linear temperature distribution (uniform geothermal gradient) is reasonable based on temperature logs of test holes at BWIP. After emplacement, vertical temperature distributions are determined independently using the one-dimensional heat conduction analysis developed in Technical Report #3.

3.3 TECHNICAL APPROACH

3.3.1 Formal Statement of the Problem

Given a one-dimensional vertical flow system with fluid density and viscosity controlled by temperature, to what extent do groundwater flux rates within the emplacement horizon change when temperature distributions resulting from repository heat are superimposed on the system?

3.3.2 Solution Techniques

Darcy's law for a variable density fluid provides the basis for this analysis. The vertical component of flow can be expressed as follows (Runchal et al, 1985):

$$qz = - \frac{k\,D\,g}{u} \left(\frac{dH}{dz} + R \right) \qquad (1)$$

where:

$$H = \frac{p}{Do\,g} + E \qquad (2)$$

$$R = \frac{D}{Do} - 1 \qquad (3)$$

qz = vertical specific discharge (Darcy velocity) [L t^{-1}]
k = intrinsic permeability [L^2]
D = fluid density [M L^{-3}]
g = acceleration of gravity [L t^{-2}]
u = fluid viscosity [M L^{-1} t^{-1}]
z = vertical coordinate [L]
p = fluid pressure [M L^{-1} t^{-2}]
E = elevation above arbitrary datum [L]
R = buoyancy factor [ ]
Do = arbitrary reference density [M L^{-3}]

Because the reference density is commonly taken as 1 g cm^{-3}, the parameter H is sometimes referred to as a fresh water head. By definition, this parameter is directly related to fluid pressure and is not a true head (see Technical Report #10).

For a variable density system, it is required that mass be conserved rather than flow volume. This is because the mass of water associated with a given fluid volume will change as a function of density. Mass flux rate is expressed as:

$$Mz = qz\ D \qquad (4)$$

where:

Mz = vertical mass flux rate per unit area [$M\ t^{-1}\ L^{-2}$]

and other parameters are previously defined (a complete list of nomenclature is presented in Table 1).

Substituting (4) into (1) gives Darcy's law expressed in terms of mass flux:

$$Mz = -\frac{k\ D^2\ g}{u}\left(\frac{dH}{dz} + R\right) \qquad (5)$$

3.3.3 Assumptions

Principal assumptions associated with the analysis in this study are as follows:

1. Groundwater flow is one-dimensional (vertical) and steady state. Horizontal flow components are not considered. This assumption is reasonable due to the large permeability contrast between flow interiors and interflows at BWIP. For such a permeability contrast, the "law of refraction of streamlines" predicts that vertical flow would likely occur within the flow interiors.

2. With regard to groundwater flow, dense fractured basalt within the emplacement horizon is treated mathematically as an equivalent porous medium (continuum).

3. With regard to heat flow, heterogeneous basalt above and below the emplacement horizon is treated mathematically as an equivalent homogeneous medium.

4. Temperature increases linearly with depth for pre-emplacement conditions (geothermal gradient). After emplacement, transient temperature distributions are related to one-dimensional heat conduction away from the repository The temperature distributions are not affected by groundwater flow (i.e., convection is not considered).

5. Within the emplacement horizon, pre-emplacement temperature is assumed to be uniform and equal to the geothermal temperature existing at the midpoint of the flow interior.

6. Salinity is assumed to be constant within the emplacement horizon.

7. The flow system does not contain internal hydraulic sources or sinks. The repository represents an internal heat source.

8. Boundaries between the emplacement horizon and adjacent interflows are assumed to be maintained at constant pressure. If this assumption were invalid, the analysis would have a tendency to overestimate groundwater flux rate within the emplacement horizon.

9. The thermal medium is assumed to be semi-infinite above and below the repository. This assumption is not strictly valid above the repository because the physical medium is bounded by ground surface. If a significant thermal response occurs at ground surface, the assumption of a semi-infinite medium would result in a tendency to overestimate the temperature within the emplacement horizon. This would lead to an overestimation in groundwater flux rate.

4.0 ANALYSIS

4.1 BASIC RELATIONSHIPS

4.1.1 Temperature

The pre-emplacement temperature distribution is assumed to be linear with depth (geothermal gradient). If the mean temperature at ground surface (Elevation 190 m MSL) is 15 degrees C and the temperature at a depth of 990 meters (Elevation -800 m MSL) is 48 degrees C, the pre-emplacement temperature distribution is given by:

$$To = -.0333\,E + 21.333 \qquad (6)$$

where:

To = pre-emplacement temperature (C)
E = elevation MSL (m)

Using Equation 6, the pre-emplacement temperature at the repository horizon (Elevation -770 m MSL) is predicted to be 47 degrees C.

The change in temperature resulting from repository heat is given by the following equation:

$$Tr = f(t,x) \quad \text{for } t > 0 \tag{7}$$

where:

Tr = change in temperature due to repository heat [T]
t = time since waste emplacement [t]
x = vertical distance above or below the repository [L]

and f represents a function which accounts for thermal properties and time varying rates of heat generation. Equation (7) is applied using the methodology presented in Technical Report #3. This approach assumes one-dimensional (vertical) conduction and a heat source that varies in strength according to an arbitrary step function. For pre-emplacement conditions ($t <= 0$), the change in temperature is zero.

The net temperature at any time before or after emplacement is given by:

$$Tn = To \quad \text{for } t <= 0 \tag{8}$$

$$Tn = To + Tr \quad \text{for } t > 0 \tag{9}$$

where:

Tn = net temperature [T]

4.1.2 Functional Relationship Between Density and Temperature/Salinity

For this technical report it is desirable to develop a mathematical relationship between density, temperature, and pressure which covers the range of pre- and post-emplacement conditions expected at BWIP. Although not as important as temperature and salinity, the effects of pressure should also be considered. As developed in Technical Report #7, an empirical relationship for water density is as follows:

$$D = A(T) + B^* + S \qquad (10)$$

where:

$$A(T) = (+999.83952 + 16.945176\ T - 7.9870401 \times 10^{-3}\ T^2 - 46.170461 \times 10^{-6}\ T^3 + 105.56302 \times 10^{-9}\ T^4 - 280.54253 \times 10^{-12}\ T^5\ ) / (1 + 16.879850 \times 10^{-3}\ T) / 1000 \qquad (11)$$

D = density of pure water (g cm^{-3})
T = temperature (C)
B^* = pressure correction (0.00233 g cm^{-3})
S = salinity (g cm^{-3})

The parameter B^* represents an average pressure correction factor for all depths down to the repository horizon (see Technical Report #7). Since water density is relatively insensitive to fluid pressure, a specific correction factor for pressure conditions at the repository is not considered necessary. In this study, Equation (10) provides a convenient means for estimating water density for a given temperature and salinity.

4.1.3 Functional Relationship Between Viscosity and Temperature

Water viscosity is strongly dependent on temperature, but not particularly sensitive to pressure. Viscosity-temperature data result in the following empirical relationship (see Technical Report #7):

$$u = C(T) \tag{12}$$

where:

$$C(T) = \frac{u_{20}}{2.30259} \exp\left[\frac{1.3272\,(20-T) - 0.001053\,(T-20)^2}{T + 105} \right] \tag{13}$$

u = water viscosity (poise = g cm^{-1} s^{-1})
u_{20} = water viscosity at 20 degrees C (0.01002 poise)
T = temperature (C)

In this study, Equation (12) is used to estimate water viscosity for a given temperature.

4.2 NUMERICAL ANALYSIS

For steady-state flow, the following equation must be solved, subject to appropriate boundary conditions:

$$\nabla M = 0 \tag{14}$$

where:

M = mass flux rate per unit area [M t^{-1} L^{-2}]

This equation is a statement of conservation of mass for fluid within the flow region. For one-dimensional vertical flow, Equation 14 reduces to:

$$Mz = \text{constant} \tag{15}$$

where Mz is given by Darcy's law expressed in Equations (2), (3), and (5). Due to the nonlinear nature of Equation (5), resulting from variations in density and viscosity, simulation of groundwater flow requires numerical techniques. A detailed description of the finite difference numerical model used in this study is provided in Technical Report #7. The algorithm uses an iterative (trial and error) procedure until the same mass flux rate is calculated within each element. At each node, the program calculates true head, fresh water head, environmental head, and piezometer water level. When calculating water levels, the program assumes that salinity of the fluid column within the borehole is equal to formation salinity at the zone of completion (see Technical Report #7).

4.2.1 Finite Difference Discretization

Numerical simulation is accomplished by discretizing the system into N finite difference elements as shown in Figure 4. Boundary conditions at the top and bottom of the mesh are those of prescribed fresh water head (defined in Equation 2). Material and fluid properties are assumed to be uniform within each element and a constant value of intrinsic permeability is assigned throughout the flow system.

4.3 ANALYTICAL APPROXIMATION

An analytical approximation for Equation 5 is as follows:

$$Mz = \frac{-k\ D^{*2}\ g}{u^*} \left[\frac{(H2 - H1)}{b} + R^* \right] \qquad (16)$$

where:

$$R^* = \frac{D^*}{Do} - 1 \qquad (17)$$

H2 = prescribed fresh water head at top of flow system [L]
H1 = prescribed fresh water head at bottom of flow system [L]
D* = fluid density for average temperature and salinity of flow system [M L^{-3}]
u* = fluid viscosity for average temperature of flow system [M L^{-1} T^{-1}]
b = flow system thickness [L]
R* = buoyancy factor for average temperature conditions [ ]

For this approximation, D*, u*, and R* are average values which apply to the entire flow system. Equation 16 is used to compute approximate rates of groundwater flux within the modeled flow system. By comparing these values with the numerical results, the accuracy of the analytical approximation can be evaluated.

4.4 SIMULATION

The finite difference formulation described above was programed on LOTUS 123 and operated on an IBM compatible personal computer. The flow region was discretized into twenty elements as illustrated in Figure 5. Parameters were chosen to be consistent with known hydrogeologic and thermal conditions existing at BWIP. In addition to the numerical solution, the LOTUS spreadsheet directly computed mass flux rate using the approximating equations given in Section 4.3. This was performed in order to compare the numerical solution (assumed to be most accurate) and the analytical approximation.

Input data used for thermal analysis are summarized in Table 2. The heat generation step function is consistent with characteristics of radioactive decay for high level waste (see Technical Report #3). Throughout the Cohassett Flow Interior, the pre-emplacement temperature was assumed to be uniform (47 degrees C). Post-emplacement temperature profiles used in the simulations are shown in Figure 6. Average temperature within the emplacement horizon as a function of time is given in Figure 7.

The top and bottom of the flow system were placed at the contacts of the Cohassett Flow Interior with the Cohassett Interflow and Birkett Interflow, respectively. These units have relatively high transmissivity at the RRL and thus, are not likely to experience large changes in pressure as a result of thermally induced flow. Pressure in these units were assumed to remain constant, consistent with the prescribed fresh water head boundary conditions required by the numerical model at the top and bottom of the mesh.

Information pertaining to simulations performed in this study are summarized in Table 3. A total of nine computer runs were performed. In the first run, pre-emplacement temperature conditions (uniform temperature of 47 degrees C) were input into the model and prescribed head at the bottom of the flow region (H1) was adjusted until the model predicted zero flux. Subsequent runs retained this calibrated head value, but incorporated temperature distributions derived from the thermal analysis for different times after repository closure (Figure 6). In these subsequent runs, the program computed mass flux rate through the emplacement horizon. In addition, the program calculated mass flux, based on average temperature conditions, using the analytical approximation described in Section 4.3.

4.5 RESULTS

The finite difference model predicted that groundwater flow would be vertically upward for all modeling runs considered, with exception of Run 1 (zero flux calibration). This is to be expected, since increased temperatures (and hence buoyancy effects) occur for post-emplacement repository conditions. An example printout of the model results in shown in Table 3 and graphic output from the same run is given in Figure 7.

A significant finding of the numerical analysis is that the analytical approximation presented in Section 4.3 (Equations 16 and 17) produces virtually identical flux rates as the numerical results. For all cases considered, the mass flux given by the analytical approximation was within one percent of the numerical value. Thus, for the hydraulic/thermal conditions considered in this evaluation, the analytical approximation provides a convenient and accurate means of computing vertical mass flux rate through the emplacement horizon. A second finding, determined through supplementary computer runs, is that mass flux rate is directly proportional to intrinsic permeability. Therefore, to determine flux rates for any value of intrinsic permeability, one simply needs to multiply the numerical results by a factor equal to the permeability of interest divided by the permeability used in the simulations (10^{-14} cm^2).

Results from the numerical evaluation are summarized in Table 5. Mass flux rates associated with the input value of intrinsic permeability (10^{-14} cm^2) have been converted to specific discharge (Darcy velocity) values using the following equation:

$$q_z = \frac{M_z}{D^*} \quad (18)$$

and volumetric flow rate through the repository is given by:

$$Q = q_z a \quad (19)$$

where:

Q = volumetric flow rate [L^3 t^{-1}]
a = planimetric area of repository [L^2]

For intrinsic permeability values of 10^{-13} and 10^{-12} cm^2, the modeling results have been multiplied by a factor of 10 and 100, respectively. Table 5 also indicates the equivalent hydraulic conductivity (at standard temperature and pressure) associated with each intrinsic permeability value. Modeling results are shown graphically in Figure 9 as plots of repository flow rate vs time for different values of flow interior hydraulic conductivity. For each hydraulic conductivity case, the initially high repository flow rate (e.g., at 100 years after closure) decreases in a more or less exponential manner. Initial flow rates through the repository are about 13, 1.3, and 0.13 gpm for flow interior hydraulic conductivities of 10^{-7}, 10^{-8}, and 10^{-9} cm/s, respectively. Between 2,000 and 10,000 years after closure, groundwater flow rates are on the order of 3, 0.3, and 0.003 gpm for hydraulic conductivities of 10^{-7}, 10^{-8} and 10^{-9} cm/s, respectively.

5.0 CONCLUSIONS

The maximum flow rate resulting from thermal effects is on the order of ten gallons per minute, which corresponds to early times for an emplacement horizon with a hydraulic conductivity of 10^{-7} cm/s. Since this hydraulic conductivity is at the upper end of predicted values for flow interiors, 10 gpm is considered the reasonable maximum flow rate which could occur through the repository attributed to thermal effects. For Terra Therma's best guess hydraulic conductivity value of 10^{-8} cm/s, the thermally induced flow rate ranges from 1.3 gpm (100 years after closure) to 0.24 gpm (10,000 years). The ultimate flow rate which occurs within the emplacement horizon after closure will be related to superposition of thermally induced groundwater flow onto the pre-existing (pre-emplacement) flow field.

For the hydraulic/thermal conditions considered in this study, the analytical approximation in Section 4.3 provides a convenient and accurate means for computing thermally induced flux rates. To apply this approximation, one must determine the average temperature conditions within the emplacement horizon. For the Cohassett Flow Interior (current candidate horizon), average temperature as a function of time is shown in Figure 7. This information allows for rapid computations of the thermally induced flux rate within the Cohassett using the analytical approximation.

6.0 DISCUSSION

Results of this technical report will be used in conjunction with hydraulic, radiological, and chemical analyses to evaluate the significance of repository heat on application of regulatory criteria such as the EPA Standard. These evaluations will be presented in future technical reports. If required, the methodology developed herein will also be used to perform additional simulations of thermally induced flux to address specific concerns. For example, one dimensional modeling of flux through flow interiors may be used to qualify the results of more complex groundwater - heat flow numerical models such as SWIFT and PORFLO.

In Technical Report #10, the vertical groundwater flux associated with pre-emplacement conditions is predicted using the same analytical technique. Considering a one-dimensional flow region extending from the Birkett Interflow to the Priest Rapids Interflow, that study predicts a pre-emplacement vertical mass flux rate of 4×10^{-12} g s^{-1} cm^{-2} for an assumed intrinsic permeability of 10^{-14} cm^2 (see Technical Report #10, Table 3). These values correspond approximately to a specific discharge (darcy velocity) of 4×10^{-12} cm/s and a vertical hydraulic conductivity of 10^{-9} cm/s. In this study, post-emplacement specific discharge for the same hydraulic conductivity ranges from 3×10^{-11} to 2×10^{-10} cm/s, which represents a one to two order of magnitude increase over the pre-emplacement value. Since specific discharge is directly proportional to hydraulic conductivity, this relative increase due to thermal loading would be the same for other conductivities as well. Although the two studies consider different flow regions, the clear indication is that groundwater flow rates within the emplacement horizon will increase substantially after closure. Thus, post-emplacement performance modeling will need to consider the effects of thermally driven groundwater flow. A future technical report will evaluate the significance of post-emplacement repository flow rates on application of regulatory criteria such as the EPA Standard.

7.0 REFERENCES

Runchal, A.K., B. Sagar, R.G. Baca and N.W. Kline. 1985. PORFLO - A Continuum Model for Fluid Flow, Heat Transfer, and Mass Transport in Porous Media: Model Theory, Numerical Methods, and Computational Tests; Rockwell Hanford Operations, RHO-BW-CR-150P.

TABLE 1. NOMENCLATURE

Dimensions of parameter given in brackets. When used in empirical relationships, actual value and/or units of parameter shown in parentheses.

a = area of repository [L^2]
b = flow system thickness [L]
B* = pressure correction [M L^{-3}] (0.00233 g cm^{-3})
D = density of pure water [M L^{-3}] (g cm^{-3})
Do = arbitrary reference density [M L^{-3}]
D* = fluid density for average temperature and salinity of flow system [M L^{-3}]
E = elevation MSL [L] (m)
g = acceleration of gravity [L t^{-2}]
H1 = prescribed fresh water head at bottom of flow system [L]
H2 = prescribed fresh water head at top of flow system [L]
k = intrinsic permeability [L^2]
M = mass flux rate per unit area [M t^{-1} L^{-2}]
Mz = vertical mass flux rate per unit area [M t^{-1} L^{-2}]
p = fluid pressure [M L^{-1} t^{-2}]
qz = vertical specific discharge (Darcy velocity) [L t^{-1}]
Q = volumetric flow rate [L^3 t^{-1}]
R = buoyancy factor [ ]
R* = buoyancy factor for average temperature conditions [ ]
S = salinity [M L^{-3}] (g cm^{-3})
T = temperature [C]
t = time since waste emplacement [t]
To = pre-emplacement temperature [T] (C)
Tn = net temperature [T]
Tr = change in temperature due to repository heat [T]
u = water viscosity [M L^{-1} t^{-1}] (poise = g cm^{-1} s^{-1})
u_{20} = water viscosity at 20 degrees C [M L^{-1} t^{-1}] (0.01002 poise)
u* = fluid viscosity for average temperature of flow system [M L^{-1} t^{-1}]
x = vertical distance above or below the repository [L]
z = vertical coordinate [L]

TABLE 2. THERMAL INPUT DATA

Repository Heat Source Step Function

Step No.	Begin Time t_n (yr)	Rate (a) Q^* ($\times 10^6$ J/yr/m^2)
1	0	468
2	8	293
3	40	133
4	100	52
5	200	23
6	500	8.8
7	1000	5.2
8	3000	4.5
9	10000	2.0

Notes:

Description of step function provided in Technical Report #3

(a) Average rate of repository heat generation per unit planimetric area.

Thermal Parameters

Thermal Conductivity: 4.415×10^7 J m^{-1} yr^{-1} C^{-1}

Volumetric Heat Capacity: 2.513×10^6 J m^{-3} C^{-1}

Pre-Emplacement Temperature: 47 degrees C (uniform within the emplacement horizon)

Heat Source (Repository) Location: middle of emplacement horizon

TABLE 3. SIMULATIONS PERFORMED IN THIS STUDY

General Information

Number of elements: 20
Number of nodes: 21

Elevation at upper boundary: -730 m MSL (Cohassett IF)
Elevation at lower boundary: -810 m MSL (Birkett IF)

Prescribed fresh water head at upper boundary: 122 m MSL (approximately equal to water levels in Wanapum and Grande Ronde piezometers)

Prescribed fresh water head at lower boundary: adjusted until zero flux achieved for pre-emplacement conditions (Run 1). This calibrated prescribed head boundary condition (121.4313 m MSL) retained in subsequent runs.

Salinity within modeled flow region: 1200 mg/l

Reference density: 1 g cm^{-3}

Intrinsic permeability: 1.0 X 10^{-14} cm^2

Acceleration of gravity: 980 cm s^{-1}

Computer Runs

1 - For pre-emplacement conditions, prescribed fresh water head at lower boundary adjusted until zero flux achieved (zero flux calibration).

2 - Temperature distribution at 100 years after emplacement.

3 - Temperature distribution at 200 years after emplacement.

4 - Temperature distribution at 500 years after emplacement.

5 - Temperature distribution at 1,000 years after emplacement.

6 - Temperature distribution at 2,000 years after emplacement.

7 - Temperature distribution at 5,000 years after emplacement.

8 - Temperature distribution at 7,500 years after emplacement.

9 - Temperature distribution at 10,000 years after emplacement.

TABLE 4. EXAMPLE OF PROGRAM PRINTOUT

Analytical Approximation

COHASSETT GROUND WATER FLUX: 500 YEARS

TOP TEMP (C)	91.5593	REF. DENS. (g/cm3)	1		VERT INTRINSIC PERM (cm2)	1.0E-14
BOT. TEMP (C)	91.5593	NUMBER ELEMENTS	20		GRAVITY (cm/s2)	980
TOP EL (m MSL)	-730	PREDICTOR FACTOR	0.8			
BOT. EL (m MSL)	-810				AVG DENSITY (g/cm3) =	0.964063
TOP SAL. (mg/l)	1200	TOP REF. HEAD	122	(H2)	AVG VISCOSITY (poise) =	0.002915
BOT. SAL. (mg/l)	1200	BOT. REF. HEAD	121.4313	(H1)	CALC FLUX (g/s/cm2) =	9.01E-11

ELEMENT	MID POINT ELEV (m MSL)	TEMP. (deg C)	VISCOS. (poise)	PURE WATER DENSITY (g/cm3)	SALINITY (mg/l)	NET DENSITY (g/cm3)	R ( )	CURR. H (m MSL)	DH/DZ ( )	M (gm/s/cm2)	PRED. M	PRED. H (m MSL)
								122.000				122
1	-732	92.09	0.003073	0.96618	1200	0.96738	-0.03261	121.990	2.435E-03	8.98337E-11	8.98337E-11	121.990
2	-736	93.16	0.003036	0.96545	1200	0.96665	-0.03334	121.976	3.481E-03	8.98337E-11	8.98337E-11	121.976
3	-740	94.22	0.003001	0.96472	1200	0.96592	-0.03408	121.958	4.525E-03	8.98337E-11	8.98337E-11	121.958
4	-744	95.28	0.002966	0.96397	1200	0.96517	-0.03482	121.936	5.566E-03	8.98337E-11	8.98337E-11	121.936
5	-748	96.35	0.002931	0.96323	1200	0.96443	-0.03557	121.910	6.604E-03	8.98337E-11	8.98337E-11	121.910
6	-752	97.40	0.002898	0.96248	1200	0.96368	-0.03631	121.879	7.639E-03	8.98337E-11	8.98337E-11	121.879
7	-756	98.46	0.002865	0.96173	1200	0.96293	-0.03707	121.844	8.671E-03	8.98337E-11	8.98337E-11	121.844
8	-760	99.51	0.002833	0.96098	1200	0.96218	-0.03782	121.806	9.699E-03	8.98337E-11	8.98337E-11	121.806
9	-764	100.56	0.002802	0.96022	1200	0.96142	-0.03858	121.763	1.072E-02	8.98337E-11	8.98337E-11	121.763
10	-768	101.61	0.002771	0.95946	1200	0.96066	-0.03934	121.716	1.175E-02	8.98337E-11	8.98337E-11	121.716
11	-772	101.61	0.002771	0.95946	1200	0.96066	-0.03934	121.669	1.175E-02	8.98337E-11	8.98337E-11	121.669
12	-776	100.56	0.002802	0.96022	1200	0.96142	-0.03858	121.626	1.072E-02	8.98337E-11	8.98337E-11	121.626
13	-780	99.51	0.002833	0.96098	1200	0.96218	-0.03782	121.587	9.699E-03	8.98337E-11	8.98337E-11	121.587
14	-784	98.46	0.002865	0.96173	1200	0.96293	-0.03707	121.552	8.671E-03	8.98337E-11	8.98337E-11	121.552
15	-788	97.40	0.002898	0.96248	1200	0.96368	-0.03631	121.522	7.639E-03	8.98337E-11	8.98337E-11	121.522
16	-792	96.35	0.002931	0.96323	1200	0.96443	-0.03557	121.495	6.604E-03	8.98337E-11	8.98337E-11	121.495
17	-796	95.28	0.002966	0.96397	1200	0.96517	-0.03482	121.473	5.566E-03	8.98337E-11	8.98337E-11	121.473
18	-800	94.22	0.003001	0.96472	1200	0.96592	-0.03408	121.455	4.525E-03	8.98337E-11	8.98337E-11	121.455
19	-804	93.16	0.003036	0.96545	1200	0.96665	-0.03334	121.441	3.481E-03	8.98337E-11	8.98337E-11	121.441
20	-808	92.09	0.003073	0.96618	1200	0.96738	-0.03261	121.4313	2.435E-03	8.98337E-11	8.98337E-11	121.431
		AVERAGE 96.86								AVERAGE 8.98337E-11		

Numerical Results

TABLE 4. (cont.)

NODE	NODE ELEV (m MSL)	TEMP. (C)	PURE WATER DENSITY (g/cm)	SALINITY (mg/l)	NET DENSITY (g/cm)	PRESSURE (dyne/cm2)	FRESH WTR HEAD (m MSL)	ENVIR HEAD (m MSL)	TRUE HEAD (m MSL)	PIEZO LEVEL (m MSL)
0	-730	91.56	0.96655	1200	0.96775	8.3496E+07	122.000	150.394	150.394	150.726
1	-734	92.63	0.96582	1200	0.96702	8.3887E+07	121.990	151.185	150.519	150.851
2	-738	93.69	0.96508	1200	0.96628	8.4278E+07	121.976	151.983	150.643	150.974
3	-742	94.75	0.96435	1200	0.96555	8.4668E+07	121.958	152.788	150.765	151.096
4	-746	95.82	0.96360	1200	0.96480	8.5058E+07	121.936	153.599	150.886	151.217
5	-750	96.87	0.96286	1200	0.96406	8.5447E+07	121.910	154.418	151.007	151.337
6	-754	97.93	0.96211	1200	0.96331	8.5836E+07	121.879	155.243	151.126	151.456
7	-758	98.98	0.96135	1200	0.96255	8.6225E+07	121.844	156.074	151.244	151.573
8	-762	100.04	0.96060	1200	0.96180	8.6613E+07	121.806	156.911	151.360	151.689
9	-766	101.08	0.95984	1200	0.96104	8.7001E+07	121.763	157.754	151.476	151.805
10	-770	101.61	0.95946	1200	0.96066	8.7388E+07	121.716	158.235	151.591	151.919
11	-774	101.08	0.95984	1200	0.96104	8.7776E+07	121.669	157.980	151.706	152.033
12	-778	100.04	0.96060	1200	0.96180	8.8163E+07	121.626	157.359	151.822	152.148
13	-782	98.98	0.96135	1200	0.96255	8.8552E+07	121.587	156.740	151.939	152.264
14	-786	97.93	0.96211	1200	0.96331	8.8940E+07	121.552	156.122	152.057	152.382
15	-790	96.87	0.96286	1200	0.96406	8.9329E+07	121.522	155.507	152.176	152.500
16	-794	95.82	0.96360	1200	0.96480	8.9719E+07	121.495	154.894	152.296	152.620
17	-798	94.75	0.96435	1200	0.96555	9.0108E+07	121.473	154.283	152.417	152.741
18	-802	93.69	0.96508	1200	0.96628	9.0499E+07	121.455	153.676	152.540	152.863
19	-806	92.63	0.96582	1200	0.96702	9.0889E+07	121.441	153.072	152.663	152.987
20	-810	91.56	0.96655	1200	0.96775	9.1280E+07	121.431	152.473	152.788	153.112

TABLE 5. MODELING RESULTS

COHASSETT GROUND WATER FLUX: SUMMARY

INTRINSIC PERMEABILITY (cm2)				-->	1E-14	1E-13	1E-12
HYDRAULIC CONDUCTIVITY AT STP (cm/s)				-->	1E-09	1E-08	1E-07

	(a)					(b)	(c)
TIME (yrs)	MASS FLUX (g/s/cm2)	AVG DENSITY (g/cm3)	SPECIFIC DISCHARGE (cm/s)	REPOS AREA (mi2)	REPOS VOL FLUX (gpm)	REPOS VOL FLUX (gpm)	REPOS VOL FLUX (gpm)
100	1.521E-10	0.95085	1.600E-10	2.00	1.31E-01	1.31E+00	1.31E+01
200	1.272E-10	0.95590	1.331E-10	2.00	1.09E-01	1.09E+00	1.09E+01
500	8.983E-11	0.96406	9.318E-11	2.00	7.65E-02	7.65E-01	7.65E+00
1000	5.929E-11	0.97164	6.102E-11	2.00	5.01E-02	5.01E-01	5.01E+00
2000	4.292E-11	0.97624	4.396E-11	2.00	3.61E-02	3.61E-01	3.61E+00
5000	3.668E-11	0.97813	3.750E-11	2.00	3.08E-02	3.08E-01	3.08E+00
7500	3.102E-11	0.97995	3.165E-11	2.00	2.60E-02	2.60E-01	2.60E+00
10000	2.869E-11	0.98072	2.925E-11	2.00	2.40E-02	2.40E-01	2.40E+00

NOTES:
(a) Results from numerical model (intrinsic permeability = E-14 cm2)
(b) A factor of 10 times numerical model results
(c) A factor of 100 times numerical model results
STP Standard temperature and pressure

FIGURE 1. PHYSICAL SYSTEM

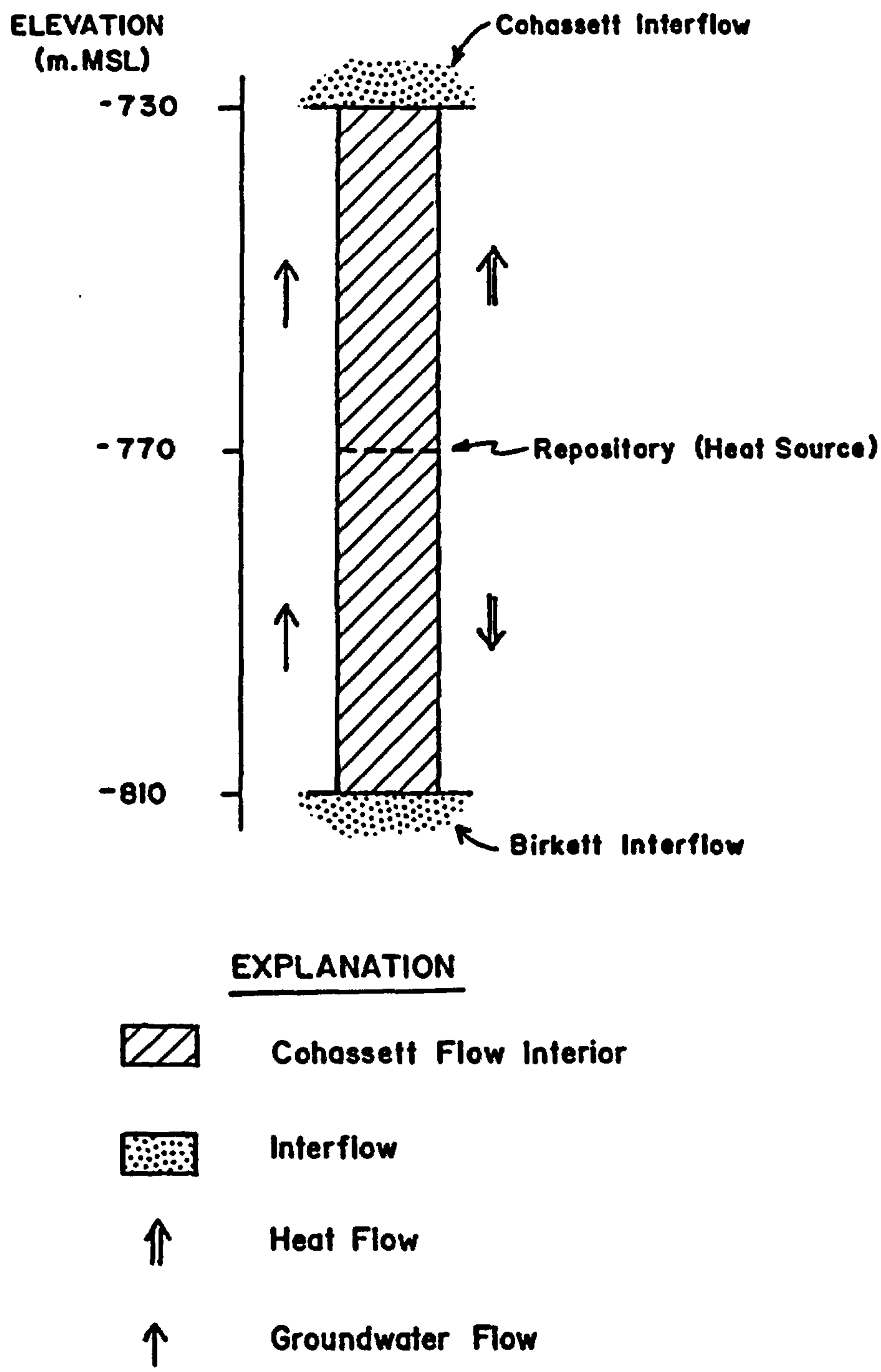


FIGURE 2. GROUNDWATER FLOW ANALYTICAL MODEL

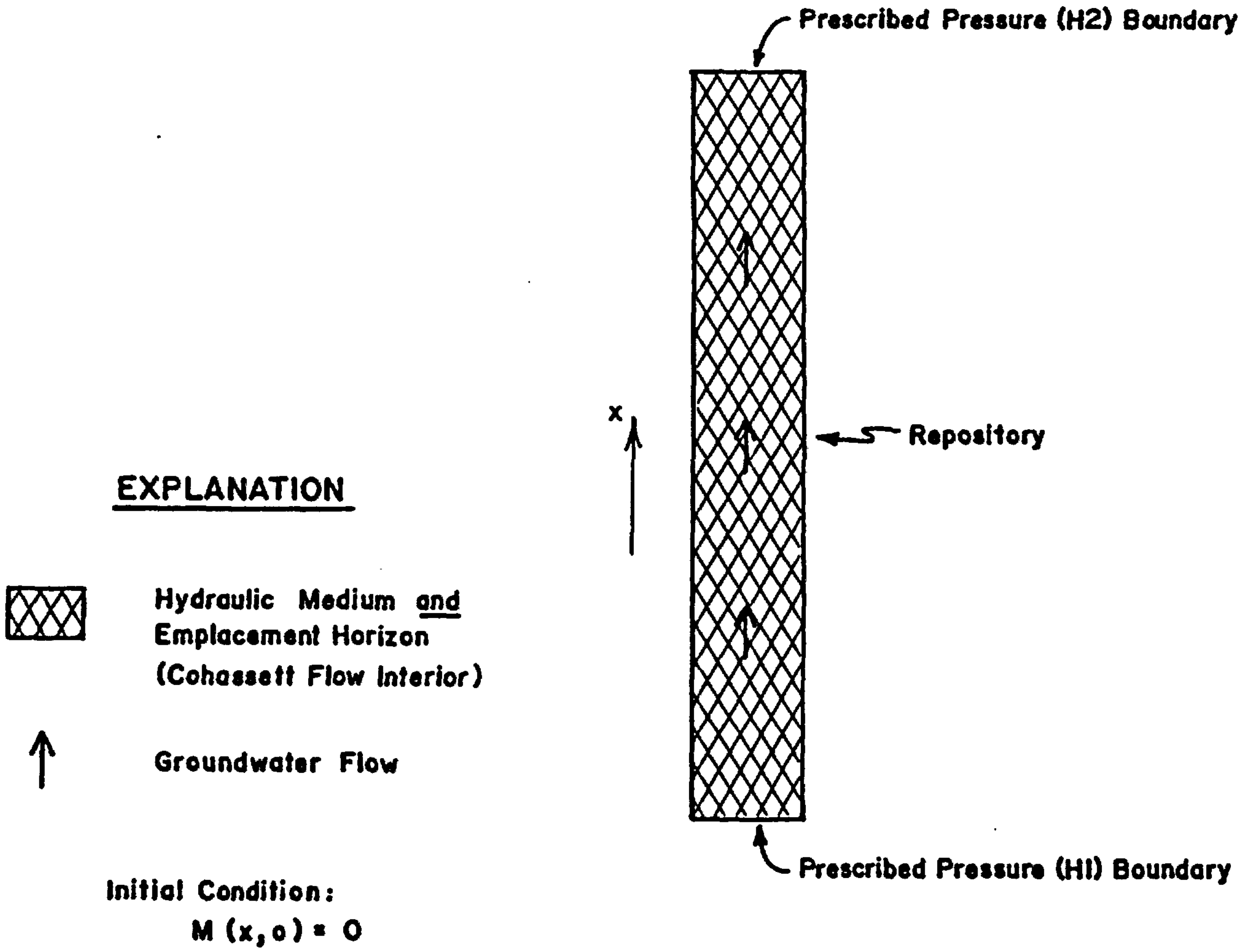


FIGURE 3. HEAT FLOW ANALYTICAL MODEL

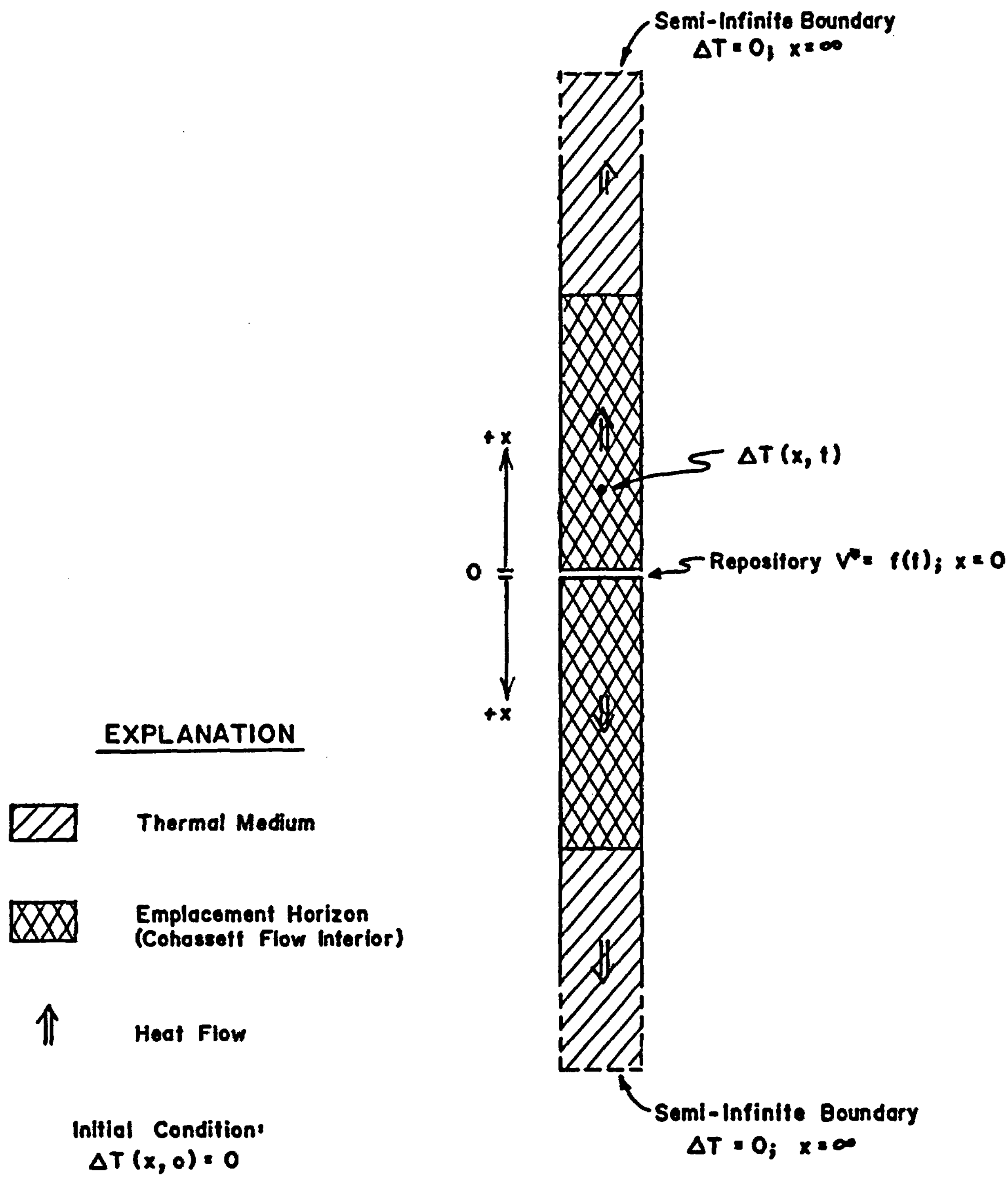


FIGURE 4. FINITE DIFFERENCE DISCRETIZATION

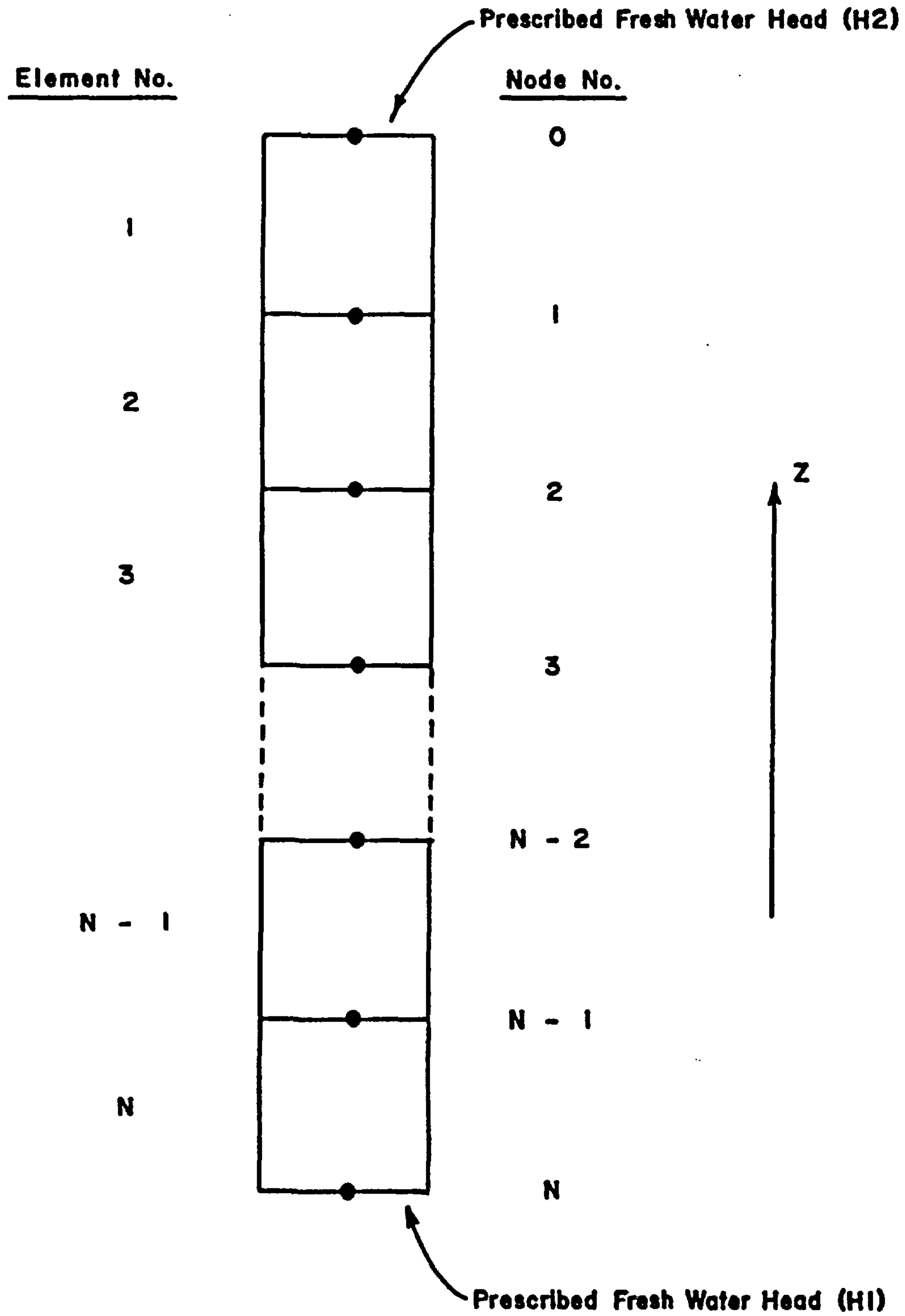


FIGURE 5. FINITE DIFFERENCE MODEL USED IN SIMULATIONS

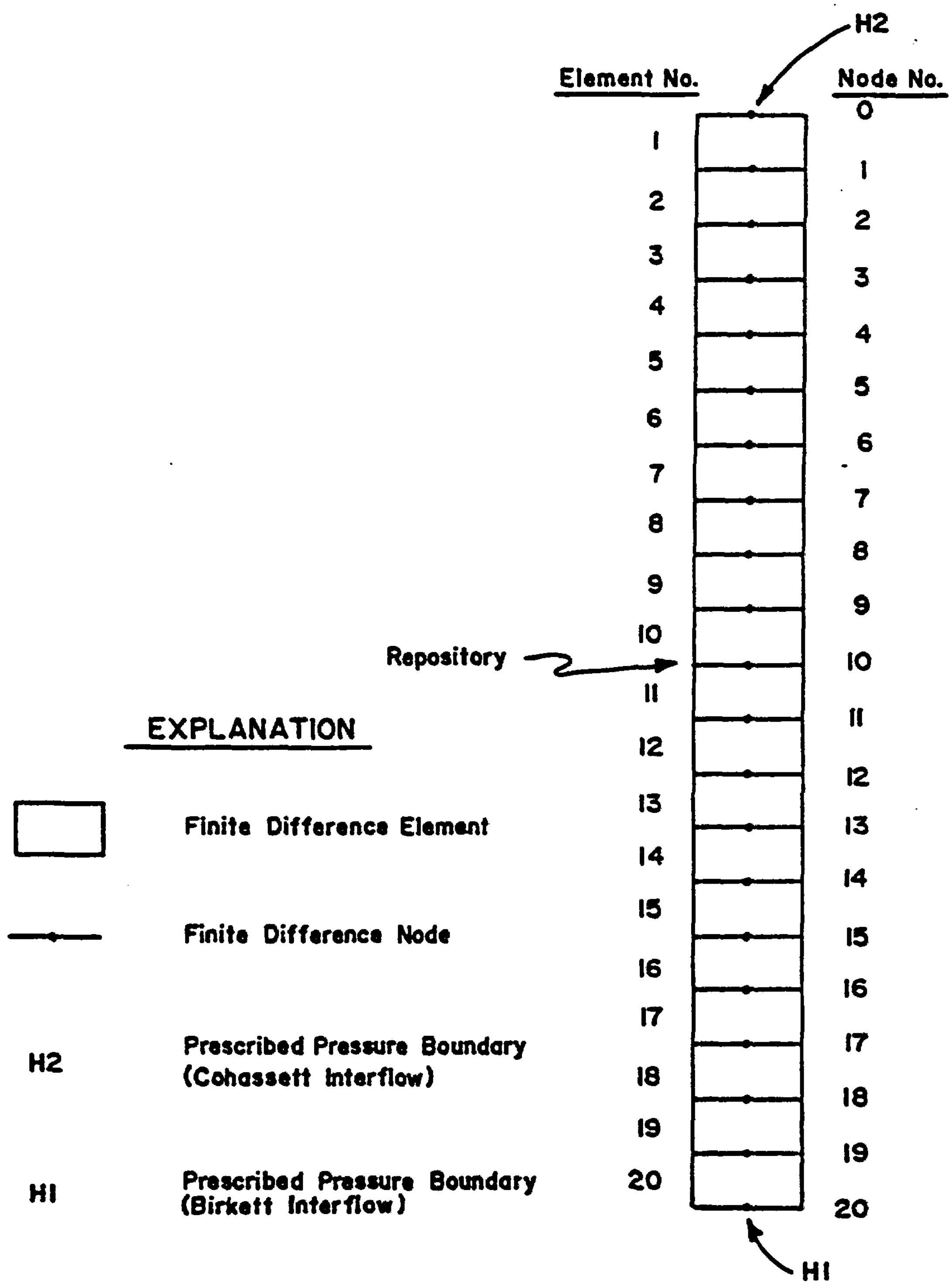
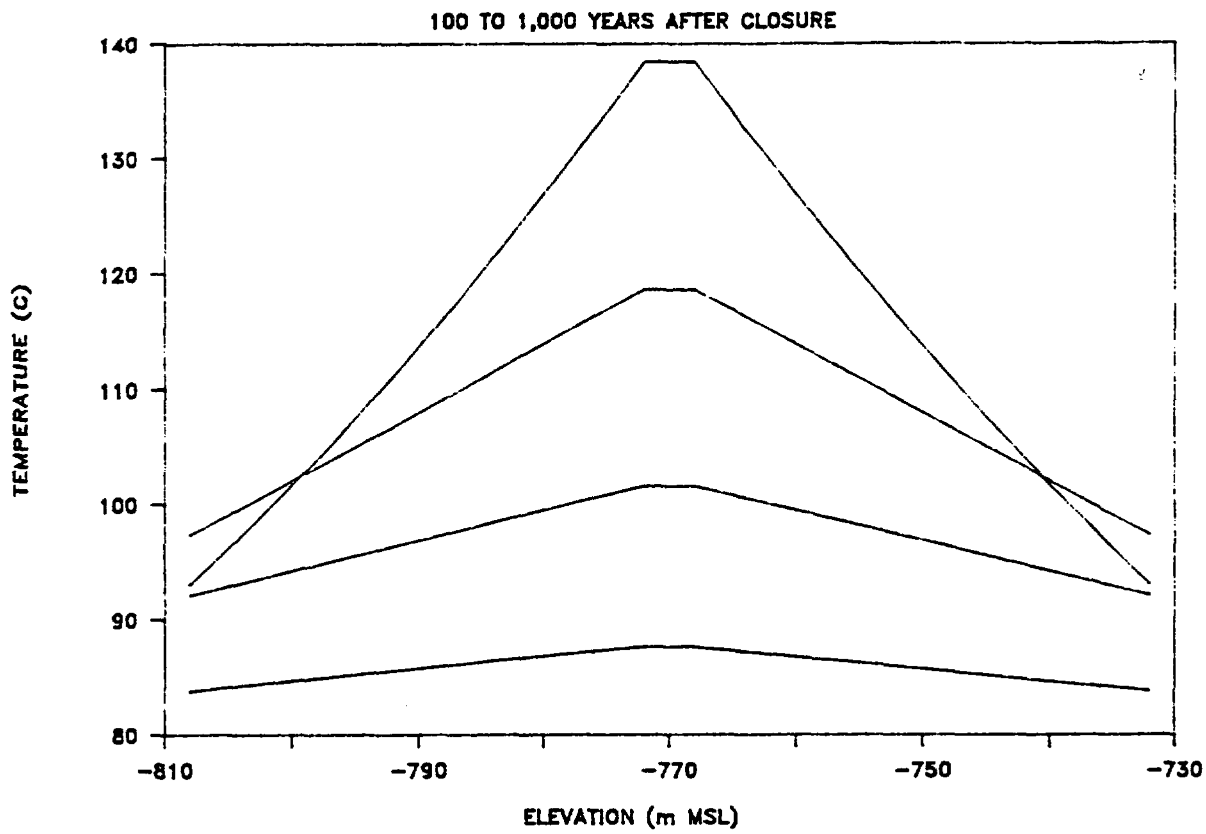


FIGURE 6. TEMPERATURE PROFILES USED IN SIMULATIONS



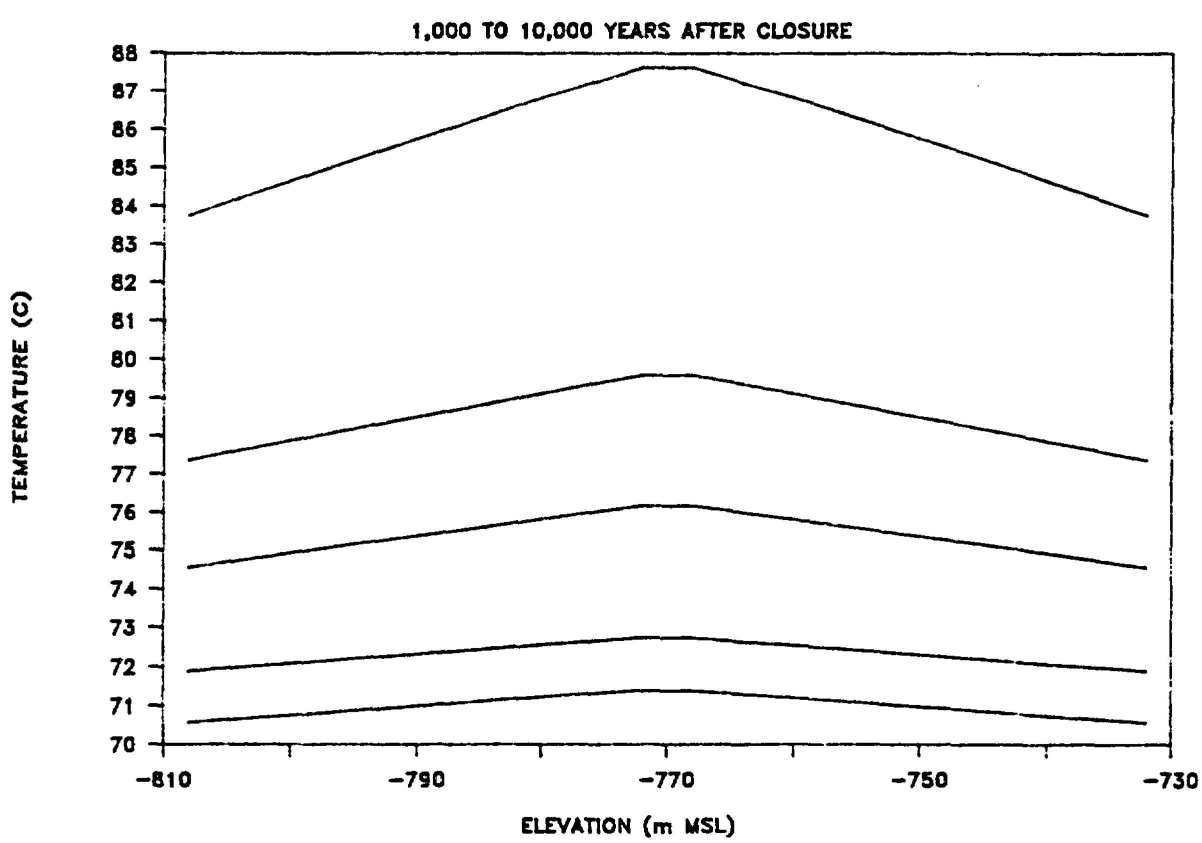


FIGURE 7. AVERAGE TEMPERATURE WITHIN THE EMPLACEMENT HORIZON

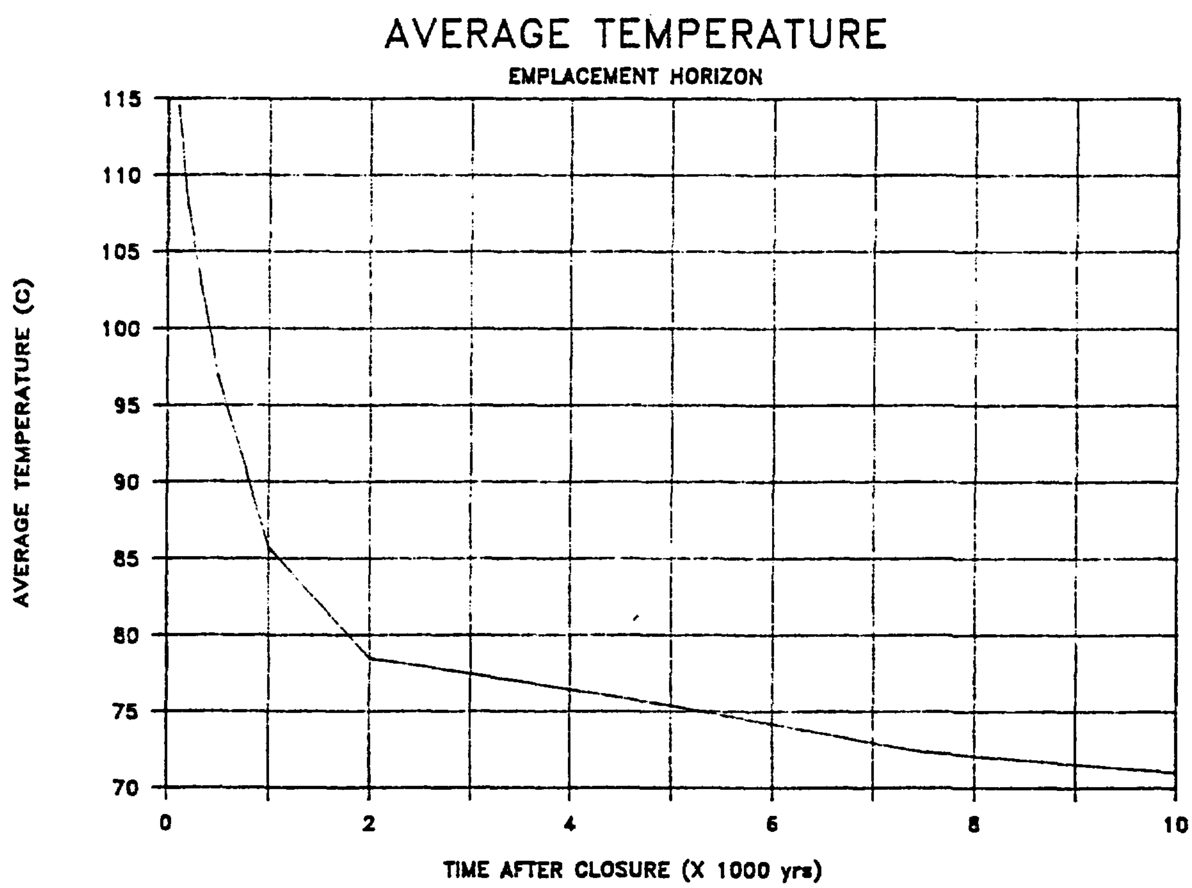


FIGURE 8. EXAMPLE OF PROGRAM GRAPHIC OUTPUT

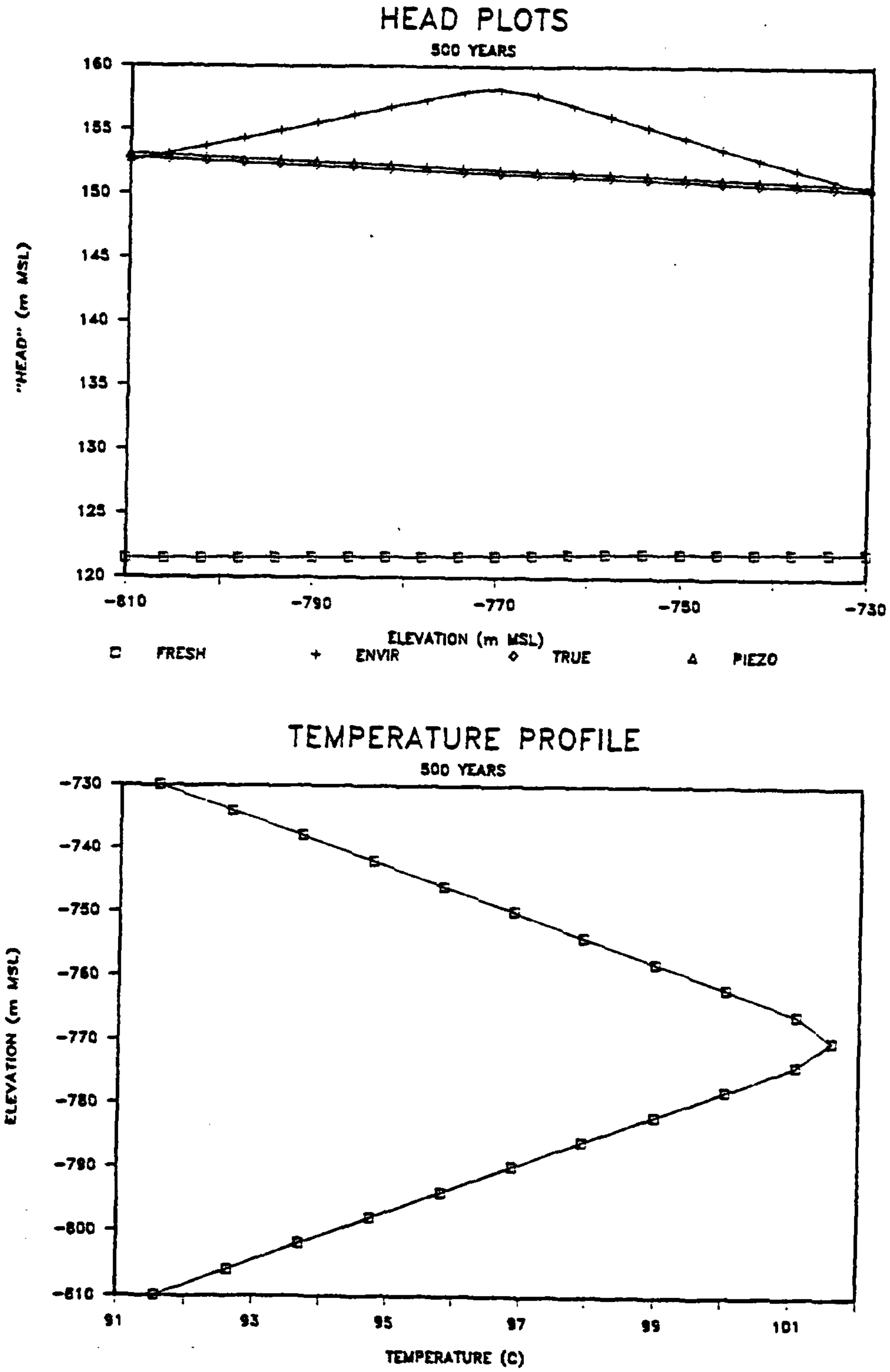


FIGURE 9. GROUNDWATER FLOW RATE THROUGH REPOSITORY AREA