57
4/24/80
240 NT

UCID-1860

DEVELOPMENT AND UTILIZATION OF A TWO-DIMENSIONAL
MODEL OF TRANIENT FLUID FLOW IN A
GENERIC REPOSITORY (OGRE)

MAST

John A. Korver

October 10, 1979

Lawrence
Livermore
Laboratory

This is an internal report intended primarily for internal or limited external distribution. The opinions and conclusions stated are those of the author and may or may not be those of the Laboratory.

This work was supported by the United States Nuclear Regulatory Commission under a Memorandum of Understanding with the United States Department of Energy.

TABLE OF CONTENTS

	Page
Abstract.....	1
1.0 Introduction.....	4
1.1 Background	4
1.2 A Steady-State Analysis of Repository Resaturation	5
2.0 Time Dependent Simulation Models	7
2.1 The BIFEPS Model	7
2.2 The OGRE Model	9
3.0 OGRE Model Verification Studies	12
3.1 One-Dimensional, Nonlinear Steady-state Verification	12
3.2 One-Dimensional, Linear Transient Verification	13
3.3 Comparison of Linear and Nonlinear Solutions	15
3.4 Other Model Modifications	15
4.0 Repository Repressurization Simulations	17
4.1 A Comparison of an OGRE Model Simulation With a GAI Steady-State Analysis of Repository Recharge	19
4.2 Relationships Between System Compressibility and Time Frames For Resaturation and Repressurization	35

DISCLAIMER

This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or approval by the United States Government or any agency thereof. The views and opinions of authors included herein do not necessarily state or reflect those of the United States Government or any agency thereof.

fy

TABLE OF CONTENTS (con't)

	Page
5.0 Summary and Conclusions	37
References	41
Appendices	42
A. Development of the Current OGRE Model	42
B. Field Parameters and Initial Pressure Distribution	48
C. Steady-State Analysis by Golder Associates	51

LIST OF FIGURES

	page
1. Unflawed Repository Saturation Times vs. Flow Velocities	6
2. Description of Computational Domain and Boundary and Initial Conditions	11
3. Comparison of 1-D Model Calculations with Analytical Solutions for Heat Flow	14
4. Comparison of 1-D Calculations with Linear and Nonlinear Versions of the Model	16
5. Repository in Relation to 5-Layer Computational Grid	18
6. Water Pressure Distribution at End of Operational Phase	20
7. Water Velocity Field at End of Operational Phase	21
8. Water Pressure Distribution at 8.3 Years	22
9. Repository Plot of Pressure Recovery at 8.3 Years	23
10. Water Pressure Distribution at 27.5 Years	24
11. Repository Plot of Complete Pressure Recovery at 27.5 Years	25
12. Initial Pressure Distribution - GAI Analysis	27
13. Initial Pressure Distribution - OGRE Model	30
14. Pressure Distribution at End of Operational Phase	31

LIST OF FIGURES (con't)

	page
15. Pressure Distribution When Repository is Flooded	33
16. Pressure Distribution When Formation is Repressurized	34
17. Time When Radioactivity Could Begin to Migrate From Repository vs. Hydraulic Conductivity	38
18. Linear and Nonlinear Governing Equations and Boundary Conditions for the OGRE Model	43
19. Schematic Drawing of the Initial Pressure Distribution.....	50

DEVELOPMENT AND UTILIZATION OF A TWO-DIMENSIONAL
MODEL OF TRANSIENT FLUID FLOW IN A GENERIC REPOSITORY (OGRE)*

John A. Korver

Lawrence Livermore Laboratory, University of California,
Livermore, CA 94550

ABSTRACT

An existing time-dependent numerical model (OGRE) has been modified to examine the time frames associated with repressurizing the formation rocks surrounding a "generic" nuclear waste repository following the operational period when wastes are being stored. The model is two-dimensional in the vertical plane, and assumes that the entire regime is saturated, but the repository is at one atmosphere during the operational period.

For the physical and geometric parameters assumed, the results of a simulation of the time necessary to repressurize the formation after the operational period was 421.5 years. These results were in close agreement with a steady-state calculation performed by Golder Associates, Inc., in 1977. The fact that the time-dependent model results were close to the steady-state calculation resulted from the use (in the model) of a very small compressibility value, which caused the simulation to reach a "steady-state" condition in a relatively short time.

Based on these studies we find that the magnitude of the system (water plus matrix) compressibility is of great importance in determining whether the time for repressurization can be determined from analytical methods or requires the use of a time-dependent numerical model.

PREFACE

The original version of the OGRE model was based on the mathematical methods developed in the petroleum industry for numerically simulating the time-dependent flow of oil and gas in petroleum reservoirs. Following the development of the OGRE model, it was reviewed by some of the leading experts in the industry and found to be at least as correct and rigorous as the models they were currently using.

Because of the relatively high compressibilities of the two liquid phases (oil and gas), both advective and diffusive processes are found to be important in the flow regime of oil and gas. On the other hand, if the flow process involves only water, which has a relatively low compressibility, the advective process probably contributes little to the flow regime.

Therefore, during the process of modifying the OGRE model to examine the time frames associated with reflooding and repressurizing a nuclear waste repository, the effect of the advective process in the advection-diffusion equation in the model was tested. The result showed that, indeed, the advective process was unimportant, and ensuing analyses were performed without the advective term in the governing equation. This effect has been well-known to those working in the field of ground water hydrology, and has been further verified by this exercise.

Nevertheless, the inclusion of the advection process in the model is mathematically correct and will be necessary if the time-dependent simulation of radionuclide transport within or from the repository and/or the two-phase behavior of air and water within the repository is desired.

Another important finding in exercising the current model is that extreme perturbations on both internal and external boundaries will return to the initial conditions with no measurable residual errors after many computational time cycles. Section 4.0 in the body of this report describes an example of this capability.

Since the model is thus based on a sound mathematical structure, its extension to three dimensions or the inclusion of other physical processes, such as thermal gradients or the presence of a second fluid phase can be undertaken without undue concern for the model's viability. In this regard, a three-dimensional version of the model is already being tested.

1.0 INTRODUCTION

In this study, we developed a model to evaluate the relative importance of the geohydrologic and geologic properties of a generic repository to the time required to reestablish initial conditions through the repository, and, thus, the time when radionuclides, if present, could be expected to leave the repository. In this report, generic means hypothetical or nonspecific.

1.1 BACKGROUND

The concept of storing nuclear wastes permanently in repositories in deep geologic formations is considered to be the most practical method for isolating these wastes from the biosphere. Such geologic formations, if properly chosen, could provide an effective long-time barrier against the escape of radioactivity from the repository.

There is, however, a mitigating property of most geologic formations which must be considered, and that is the presence of mobile groundwater. Canisters containing radioactive wastes in contact with moving groundwater can be eroded, and the wastes dissolved and transported by the groundwater. Erosion and dissolution will probably be quite slow, but because of the long half-lives of the radionuclides, the danger of radioactivity entering the biosphere may exist for many thousands of years.

In past studies^(1,2,3) it was assumed that radioactivity might be expected to begin migrating from the repository about 100 years after the final sealing. The 100 year period was considered the time needed to resaturate (fill) the repository with groundwater and begin leaching the wastes. Until the repository is again filled with water it acts as a sink, and radioactivity (if present in the water) cannot leave the repository. (Of course, it is possible that, as the repository fills, volatile elements in the dissolved radionuclides could be present in the air above the water level, and could be forced out of the top of the repository, but this is another issue).

The actual rate of resaturation and repressurization of the repository is, then, an extremely important parameter in determining the time for the onset of nuclide migration from the repository. Because of radioactive decay, this time period, to a great extent, determines the nature and concentration of the species being transported.

1.2 A STEADY-STATE ANALYSIS OF REPOSITORY RESATURATION

We can find a first approximation (steady-state) of the time required to resaturate the repository by three parameters: the effective void volume of the repository, the groundwater velocity into the repository, and the cross-sectional area corresponding to this velocity. The relationship can be expressed as shown below:

$$T = \frac{Vol}{AV}$$

where

T is time

A is the effective cross-sectional flow area

V is the flow velocity

Vol is the effective void volume of the repository

Figure 1 illustrates the relationship of time to a (constant) flow velocity for several assumed ratios of repository volume to cross-sectional flow area. In this figure the repository volume (Vol) is that from a proposed generic repository ($2.75 \times 10^6 \text{ m}^3$) (4). This volume is derived from the geometry and material properties chosen for this generic repository listed below:

Length:	2500 meters
Width:	2000 meters
Height:	5.5 meters
Porosity of backfill:	10%

Using these values in this relationship, we find that the time needed to completely resaturate the repository at the low groundwater velocities anticipated could be greater than 100 years. Figure 1 illustrates the relationship of time to a constant flow velocity for several assumed ratios of repository volume to cross-sectional area. The curve corresponding to $Vol/A = 2.75m$ represents a repository with a 10% porosity backfill. If the backfill porosity is, for example 1%, the fill times would correspond to the curve represented by $Vol/A = 0.275m$. The other curves with higher values of Vol/A might represent repositories with larger volumes or higher backfill porosities.

This steady-state approach may be a conservative estimate of the times necessary to refill the repository, since it assumes a constant flow rate across the repository boundaries. A more realistic determination would take into account the time-dependent flow rates, which would decline as the repository fills. The author therefore suggested carrying out a time-dependent analysis, using one of two available time-dependent calculational models of flow through porous media.

2.0 TIME DEPENDENT SIMULATION MODELS

The first of these time-dependent simulation models is a two- or three-dimensional, finite element simulation model of porous media flow and the second is a two-dimensional, finite-difference simulation model with similar capabilities. The following section describes the mathematical basis and computational methods for the first model, and the next section describes briefly the modifications required for the second model.

2.1 THE BIFEPS MODEL

The BIFEPS model⁽⁵⁾ was developed by C. Voss, G. Pinder, and others at Princeton University in 1976-77. It is a highly-optimized IBM code which, unfortunately, is far from optimized for the CDC computer we used. Nevertheless, we obtained a copy of the code, and spent several months

converting it to run on the CDC 7600 computer (no optimization has been done). We checked out the code by successfully solving several steady-state and one time-dependent test problem. Because this code was inefficient to use on our system, we decided to make the necessary modifications to the second model (UGRE), rather than spend whatever time might be required to optimize the BIFEPS model. This model, however, is still available if needed.

The BIFEPS code solves a very general pair of coupled, time-dependent, nonlinear partial differential equations of the form

$$A_1 \frac{\partial u}{\partial t} + B_1 \frac{\partial v}{\partial t} + \frac{A}{2} \cdot \nabla u + \frac{B}{2} \cdot \nabla v + \nabla \cdot \left(\frac{A}{3} \cdot \nabla u \right) + \nabla \cdot \left(\frac{B}{3} \cdot \nabla v \right) \\ + A_1 u + B_1 v + \nabla \cdot \frac{A}{5} + A_6 = 0$$

$$C_1 \frac{\partial u}{\partial t} + D_1 \frac{\partial v}{\partial t} + \frac{C}{2} \cdot \nabla u + \frac{D}{2} \cdot \nabla v + \nabla \cdot \left(\frac{C}{3} \cdot \nabla u \right) + \nabla \cdot \left(\frac{D}{3} \cdot \nabla v \right) \\ + C_4 u + D_4 v + \nabla \cdot \frac{C}{5} + C_5 = 0$$

Where A_i , B_i , C_i , D_i are all arbitrarily specified functions of x , y , z , t , u , and v . This generality is obtained at the cost of requiring the user to do some work prior to using the code, as explained below. In particular, since any of the coefficients can be constants, or zero, it is a simple matter to solve any subset of the above coupled system: e.g., the transient heat equation,

$$\frac{\partial u}{\partial t} = K \nabla^2 u \quad \text{in 2-D or 3-D.}$$

Another obvious combination is to let $u = P$ (pressure), $v = C$ (concentration), and solve the groundwater flow equation and the solute (radionuclide) transport equation simultaneously.

The basic method of solution is the Galerkin finite element method (GFEM) for spatial discretization (using isoparametric 'quadrilateral' elements and linear, or quadratic, or a mixture of both for the approximations) and any

combination of explicit Euler, implicit Euler, or trapezoid rule (Crank-Nicolson) for the time integration. The resulting algebraic systems (which makes explicit Euler implicit, owing to the mass matrix of GFEM; hence, implicit integrators are to be preferred) are solved uniquely by nonlinear block (or line) successive over relaxation (SOR), using Carre's method of dynamically estimating an "optimum" relaxation factor. This describes the code in general.

In order to use the code, the user must already know the principles of GFEM and how to use it. Then, given an equation or set of equations, initial boundary conditions, and a finite element discrete mesh (easily obtainable with any of several mesh generator codes at LLL), the steps to a solution are:

1. Apply Galerkin's method to the equation(s) and boundary conditions. This converts the equation to the weak (integral) form and generates the GFEM matrices.
2. Define the appropriate Galerkin integrals (input data to code; define only those integrals (or functions, coefficients, etc.) required by the problem.
3. Select a time integration method (a single parameter 'mixes' Euler and trapezoid rule), time step, and certain iteration and convergence parameters.
4. Run the pre-processor part of the code. This is done once per problem and generates and stores the global Galerkin integrals, (coefficients for matrices, etc.).
5. Run the main code which integrates the GFEM-generated ordinary differential equations in time.

2.2 THE OGRE MODEL

The author originally developed the OGRE model at LLL in 1968 to simulate the transient radial flow of one or two compressible fluids in petroleum reservoirs.⁽⁶⁾ Modifying the boundary conditions in the model from the original form to the form required to simulate flow in a repository region was necessary for the following reasons:

1. Flow into or out of a repository in two dimensions is linear, rather than radial.

2. Radial flow into or out of a cylindrical structure, such as a well, can be zoned logarithmically in the horizontal direction, so that a no-flow condition on the outer vertical boundary of the computational domain can be assumed. This condition is valid if the outer boundary is sufficiently removed from the inner boundary so that pressure changes are not felt during the simulation period.

The current model was reformulated in Cartesian coordinates and the boundary conditions along the inner (left-hand, or upstream) boundary, the outer (right-hand or downstream) boundary, and the lower boundary, were changed to simulate constant horizontal and vertical pressure gradients.

These modifications, plus reformulation of the governing equations to remove the effect of the hydrostatic pressure gradient, are illustrated in Figure 2. The rationale for these code modifications and the derivation of the governing equation are described in Appendix A.

By examining the governing equation shown in Figure 2, we can see that only one fluid phase, liquid, is present in the current version of the OGRE model. We justify omitting the second fluid phase, air, on three factors:

1. Retaining the governing equations which describe the flow of the second phase would require considerably more effort in modifying the original code.
2. Assuming a fully saturated flow regime in the Figure 2 repository leads to conservative time frames for the reestablishment of the pre-repository pressure field.
3. Analyzing the single phase transient pressure field in and around the repository, and its resultant fluid velocities, would be sufficient to determine, at least approximately, the time frames associated with the resaturation of the repository.

As a result, since only fully saturated flow is assumed, it must be recognized that the results of any analysis with the current version of the OGRE model can only be applied to evaluating the recovery of the pressure field in the repository and surrounding medium following the operational period (when the repository pressure is one atmosphere).

3.0 OGRE MODEL VERIFICATION STUDIES

Following the modifications of the boundary conditions and the governing equation in the OGRE model, diagnostic tests were made with the new model to verify the code's ability to reproduce the results from several one-dimensional linear and nonlinear analytical solutions. The code was operated in a one-dimensional mode by setting either the horizontal or vertical space derivative terms equal to 0.

3.1 ONE-DIMENSIONAL, NONLINEAR, STEADY-STATE VERIFICATION

The equation describing the one-dimensional, nonlinear, steady-state case is:

$$\frac{d^2 p}{dx^2} + C \left(\frac{dp}{dx} \right)^2 = 0$$

A one-dimensional (horizontal only) calculation with constant density was made with the model to compare the result with an exact steady-state solution of the following equation:

$$P = P_0 + \frac{1}{C} \ln \left[1 - \frac{\gamma C x}{1 + \gamma C L} \right]$$

where P_0 is the fixed pressure of $x = 0$,
 C is the fluid compressibility, and
 $\gamma = -\partial p / \partial x$ is the fixed gradient at $x = L$.

The model results agreed perfectly, to 5 significant figures, with the analytical solution, and thus, the horizontal terms in the model were verified.

3.2 ONE-DIMENSIONAL LINEAR TRANSIENT VERIFICATION

The equation describing the one-dimensional, linear, transient case is:

$$\frac{\partial P}{\partial t} = K \frac{\partial^2 P}{\partial z^2}$$

where $P = 0$ at $t = 0$

$P = 1$ at $z = 1$,

$\partial P / \partial z = 0$ at $z = 0$.

Figure 3 shows some comparisons between the results from a one-dimensional (i.e., nonlinear, vertical direction only) model calculation with an analytical solution for heat flow between two parallel plates (Carslaw and Jaeger). For this comparison, the equation used to generate the curves in Figure 3, in dimensionless form is:

$$\frac{v}{V} = 1 - \frac{4}{\pi} \sum_{n=0}^{\infty} \frac{(-1)^n}{2n+1} \exp \left[- (2n+1)^2 \frac{T}{4} \cos \left(\frac{(2n+1)\pi \epsilon}{2} \right) \right]$$

where $T = Kt/\ell^2$,

$\epsilon = x/\ell^2$,

t = time,

K = thermal diffusivity

V = initial constant surface temperature

v = temperature.

Again, as can be seen in Figure 3, the agreement is excellent between the results of the model and the analytical solution, and the time integration scheme in the model has been shown to be correct.

These tests have shown that, although the model is two-dimensional and transient, it faithfully reproduces both steady-state, nonlinear, and transient, linear one-dimensional analytical results.

FIG. 3 COMPARISON OF ONE-D CALCULATIONS WITH ANALYTICAL SOLUTIONS FOR HEAT FLOW

561894

3.3 COMPARISON OF LINEAR AND NONLINEAR SOLUTIONS TO THE EQUATION

The current formulation of the OGRE model exists in two forms: a linear form that considers diffusion only (in which the nonlinear terms multiplied by τ on the RHS of the equation in Figure 2 are omitted) and the full nonlinear form that considers both advection and diffusion. The original form⁽⁶⁾ was also nonlinear.

Early in the testing of the model we decided to determine the relative contributions of each of the processes, advection and diffusion to the final transient solution. Two one-dimensional calculations were made, both with the same parameters and the same five-layer grid configuration, with the linear and nonlinear versions of the model. The results from these calculations are shown in Figure 4. It is apparent from this figure that the divergence of the two calculations is essentially zero during the early transient period, and is still very small (4.5%) at later times. Obviously, even for the extreme conditions in this analysis (i.e., a three-fold step change in the pressure at the bottom of the grid and up to a thousand-fold change in permeability across the individual layers) the flow is largely diffusion-dominated. Therefore, we believe that most future analyses can be carried out with the linear version of the model. This, of course, means that model calculations can be carried out more efficiently and economically, with essentially no loss of accuracy. Therefore, the remainder of the analyses in this study were carried out with the linear version of the model.

3.4 OTHER MODEL MODIFICATIONS

We made other adjustments and tests with the calculational model to make the results from the simulations more useful and understandable. These included:

1. Detailed pressure and velocity field plots in and near the repository region. The usefulness of these detailed plots is obvious from the size of the repository relative to the size of the computational domain (see Figure 5).
2. Initial and incremental time step studies were carried out to determine maximum time steps allowable for computational accuracy and stability. (An automatic time integrator is not presently employed.)
3. A dynamic dimensioning capability was incorporated so that any grid dimension can be used with the same executable program.
4. The flow rates across the repository boundaries are integrated in space and time to give a measure of the amount of water entering, or leaving, the repository.
5. The initial space variable field parameters and pressure distribution are generated in a separate program for input to the model.

4.0 REPOSITORY REPRESSURIZATION SIMULATIONS

The computational domain, with a repository of size 10 meters x 2400 meters, is shown in Figure 5. This domain contains five horizontal regions representing five geologic layers, each with different geohydrologic properties.⁽⁴⁾ The uppermost and lowermost layers represent "aquifers" with high values of porosity and horizontal and vertical permeability. The two layers above and below the middle layer represent "aquitards" with much lower values of porosity and permeability. The middle layer also represents an "aquitard," but with even lower values of porosity and permeability. This layer contains the generic repository.

The numerical values for the hydrologic properties of each layer (shown in Figure 5) were obtained from Golder Associates⁽⁷⁾ as were the properties for the back-filled repository. It is assumed that a regional hydrologic gradient exists in both the horizontal and vertical directions such that the groundwater flows upward and from left to right. The numerical values for the porosity, permeability, and hydraulic gradients are given in Appendix B.

FIG. 5 REPOSITORY IN RELATION TO 5-LAYER COMPUTATIONAL GRIDS

A time-dependent simulation was run with this 5-layer model to test the model's ability to handle the repressurization of the formation following reflooding of the repository at one atmosphere of pressure. Figures 6 and 7 show, respectively, the pressure and velocity fields from the simulation at the end of an operational phase of 6.2 years. Figure 8 shows the pressure field at a later time (8.3 years), when it appears that the pressure field has fully recovered. Figure 9, on the other hand, shows the pressure field at the same time in the vicinity of the repository. As can be seen in this figure, the pressure has not yet fully recovered, and also illustrates the usefulness of the detailed plots. Figures 10 and 11 again show, respectively, the pressure field over the entire field and in the vicinity of the repository at 27.5 years. In Figure 11 it is apparent that the pressure field is fully recovered.

4.1 A COMPARISON OF AN OGRE MODEL SIMULATION WITH A STEADY-STATE ANALYSIS OF REPOSITORY RECHARGE

We compared another OGRE model simulation of repository recharge with a steady-state analysis done by Golder Associates, Inc., (GAI).⁽³⁾ The GAI analysis was carried out in one dimension (vertical) and the formation surrounding the repository was homogeneous and isotropic. The only hydrologic gradient present was between the upper and lower aquifers and the repository, which was at one atmosphere. It should be pointed out here that the term "recharge" includes both reflooding (resaturation) of the repository and repressurization of the surrounding rock medium following reflooding. Both processes must be completed before radioactivity is able to migrate from the repository and enter the aquifers.

The OGRE simulation employed the same geometry and hydrologic parameters as those used in the GAI analysis. Although both methodologies analyzed the sequential phases of resaturation and repressurization, the GAI analysis only

DCRE

FIG. 6 WATER PRESSURE DISTRIBUTION AT 6.2 YEARS

58195

OCRE

FIG.7 WATER VELOCITY FIELD AT 6.2 YEARS

OGRE

FIG. 8 WATER PRESSURE DISTRIBUTION AT 8.3 YEARS

FIG. 9 REPOSITORY PLOT OF RECOVERY AT 8.3 YEARS

OGRE

FIG.10 WATER PRESSURE DISTRIBUTION AT 27.5 YEARS

FIG. 11. REPOSITORY PLOT OF COMPLETE PRESSURE RECOVERY AT 27.5 YEARS

assumed a 30-year operational phase, while the OGRE analysis actually simulated this phase. These three phases are described below:

1. Operational Phase - Time when the repository is open to the atmosphere and receiving wastes.
2. Resaturation Phase - Time following the operational phase and final sealing while the repository is being reflooded.
3. Repressurization Phase - Time after resaturation while the formation is repressurizing to pre-repository conditions.

The OGRE Model Configuration and Model Parameters

The geometry and initial pressure (head) distribution were obtained from Reference 7, while the field parameters and analytic results were obtained from two later GAI reports^(8,9) (see Figure 12). Since the GAI analysis was one-dimensional, we made the OGRE simulation operate in one-dimension by zeroing out the horizontal space derivative terms. As is shown in Figure 12, the system is homogeneous and the pressure gradients between the aquifers and the repository are symmetric about the repository. This symmetry is consistent with the assumption in the GAI analysis.

The additional GAI assumptions and parameter values are shown below, along with the equivalent OGRE values.

1. Repository is at atmospheric pressure (head = 10 meters) during the operational and resaturation phases (OGRE: same, $P = 1.01 \times 10^{10}$ dynes/m²).
2. Head drop from either aquifer to repository is 600 meters (OGRE: same, $P = 5.88 \times 10^{11}$ dynes/m²).
3. Hydraulic conductivity (vertical) is constant at 1×10^{-11} m/sec. (OGRE: same, permeability = 1×10^{-20} m³/cm).
4. Horizontal dimensions of the repository are 2500 meters by 2000 meters (OGRE: 2500 meters).

FIG. 12 INITIAL PRESSURE DISTRIBUTION

- 5.^A Vertical dimension of repository is 5.5 meters (OGRE: 6 meters).
- 6.^B Repository backfill porosity is 6% (OGRE: 5.5%).
- 7.^C Repository void volume is 1.65×10^6 meters³ (OGRE: 1.196×10^3 meters²).
8. Resaturation time is determined from flow velocities into repository (OGRE: same, but integrated in time).
- 9.^D Repressurization time is determined by time to replace water in formation drained into repository (OGRE: same).

Footnote A

In the OGRE model the vertical repository dimension is 6 meters because the vertical resolution (grid increment) is 1 meter.

Footnote B

Since the vertical height of the repository is 6 meters, reducing the porosity from 6% to 5.5% compensates for the void volume.

Footnote C

The OGRE void volume (area) might be expected to be $2500 \times 6 \times 5.5 \times 10^{-2} = 8.25 \times 10^2 \text{ m}^2$, rather than $1.196 \times 10^3 \text{ m}^2$. The increased volume results from the density difference between the water in the repository at one atmosphere and that of the water in the formation where the pressure varies from one atmosphere up to six atmospheres. This density difference has the effect of an increased void volume in the repository.

Footnote D

In the GAI analysis, a volumetric replacement of the water drained into the repository was sufficient for the calculation. In the OGRE model, the compressibility, and concurrent density change, must be taken into account by mass conservation of the water in both the repository and the formation. A porosity increase (to 7.97%) in the repository compensates for the density differences between the repository and the formation.

Grid Configuration and Other Parameter Values

Since the model is two-dimensional, but operated in this case in a one-dimensional mode, a 2-D grid was set up with five zones (5 nodes) in the horizontal direction and 600 zones (601 nodes) in the vertical direction. The horizontal zones were 500 meters in length and the vertical zones were one meter in length. This results in a computational grid 2500 meters wide and 600 meters high, with a repository 6 meters high and 2500 meters long centrally located between the upper and lower aquifer boundaries (see Figure 12).

Other Parameter Values

Permeability in the repository was the same as that in the formation
- $1 \times 10^{-20} \text{ m}^3/\text{cm}$.

Porosity in the formation was set at 10%.

Compressibility of the system was $5.37 \times 10^{-13} \text{ m}^2/\text{dyne}$ to correspond to a specific storage value of $3.3 \times 10^{-5}/\text{m}$, as used in the GAI analysis.

OGRE Simulation Results

As described earlier, the simulation was carried out in three sequential time-dependent phases.

Phase I is the operational phase, in which the repository is operated at atmospheric pressure, and any water seeping into the repository is pumped out. During this time the surrounding formation is depressurizing, and the pressure transient moves away from the repository at a rate depending on the pressure gradient, formation permeability, porosity, and compressibility. In our simulation, this phase continued for a computed time of 30 years. GAI assumed, without analysis, that this phase would last this long. The OGRE model, however, simulated the phase. Figure 13 shows the computer-generated pressure field at the initial time and Figure 14 shows the pressure field at the end of 30 years.

OGRE

FIG. 13 INITIAL PRESSURE DISTRIBUTION-OGRE MODEL

OGRE

FIG. 14 PRESSURE DISTRIBUTION AT END OF OPERATIONAL PHASE

Phase 2 is the resaturation phase, which begins when the repository is abandoned and backfilled. The 7.97% porosity of the backfill assigned in the model is an effective porosity which includes not only the backfill in the corridors but also the pillars in between. In the OGRE model this porosity is distributed throughout the repository. Phase 2 was simulated, with the repository still at atmospheric pressure, as was assumed by GAI, until the time-integrated flow velocities indicated that the repository was completely resaturated. This time was computed to be 250.7 years after the repository was sealed. See Figure 15 for the pressure conditions following resaturation.

Phase 3 is the repressurization phase, which begins when the repository is completely resaturated. Repressurization of the surrounding formation can take place once the repository is completely filled. During Phase 3, the repository is no longer maintained at atmospheric pressure, but can respond to the repressurization of the surrounding region. This repressurization phase is allowed to continue until the mass (or volume, in the case of the GAI analysis) of water removed from the formation to resaturate the repository is replaced in the surrounding formation. In the case of the OGRE simulation this time was computed to be 421.5 years after the repository was refilled. Figure 16 shows the pressure distribution at the end of repressurization.

Comparison of the OGRE Simulation Results with Those from GAI

Using the GAI steady-state formula and reported parameters for resaturation time, we performed a hand calculation which showed that resaturation would take 261.5 years. This time agrees well with GAI's reported value of 260 years, but it is somewhat longer (~4%) than the OGRE simulation results of 250.7 years.

Using GAI's formula and parameters for the repressurization time, we performed a hand calculation which showed that repressurization would take 942 years, or ~2.2 times longer than the OGRE results of 421.5 years. Their reported result,⁽²⁾ however, is 420 years, which is essentially the same result that the OGRE model computed. The discrepancy here in the hand-

OGRE

FIG. 15 PRESSURE DISTRIBUTION WHEN REPOSITORY IS FLOODED.

OGRE

MG 16 PRESSURE DISTRIBUTION WHEN FORMATION IS REPRESSURIZED

calculated result and the GAI reported result is not yet resolved, but it is curious that a value of 418.6 years can be obtained using another formula reported by GAI,^(8,9) which is based on an analytic transient formula.

Discussion

The OGRE model simulation of repository operational, resaturation, and repressurization times were in very close agreement with those times computed or reported from the GAI steady-state analytical technique. These results are not too surprising, since the same field and geometric parameters were used in both analyses. From this result one can conclude that the OGRE model has again been validated with several one-dimensional, steady-state analytical solutions. One could also conclude that, for these specific conditions, the analytical technique, which is both faster and easier to use, is valid.

Unfortunately, the specific physical conditions assumed for this analysis, although easy to evaluate with a closed form steady-state procedure, are physically impossible and much too simplified. An instantaneous, linear pressure gradient between the repository and an aquifer three hundred meters away, even in a homogeneous medium, could not exist. Moreover, the likelihood of a homogeneous, isotropic, porous medium in nature is quite small. Therefore, the steady-state analysis is only marginally useful.

Relative to the concept of steady-state, steady-state conditions were never achieved at the end of any of the three phases. The simulation was, however, continued until steady-state was achieved (at 148,000 years), when the pressure was uniform over the entire grid at a value of 5.88×10^{11} dynes/meter.² This was the original value of the pressure in the two aquifers.

4.2. RELATIONSHIPS BETWEEN SYSTEM COMPRESSIBILITY AND THE TIME FRAMES FOR RESATURATION AND REPRESSURIZATION

The compressibility of the system, both the water and the formation, is important to the time required to reach a "steady-state condition," or any other desired condition. Compressibility is analogous to the specific storage

parameter, S_s , which is used in the GAI analyses. Specific storage is defined as

$$S_s = \rho g \left[\frac{1-\phi}{G} + \phi C \right]$$

where G is the bulk modulus of the formation

ϕ is the formation porosity

C is the compressibility of water

ρ is the water density, and

g is the gravitational constant.

Specific storage, therefore, is the summation of both formation and fluid compressibility. The time to reach a "steady-state condition" is proportional to the value of the specific storage, i.e., as specific storage goes to 0, the time to reach "steady-state" goes to 0.

Since we are attempting to determine the time necessary to repressurize the formation surrounding the repository after the operational period, and, indirectly, the time necessary to resaturate the repository, the compressibility of the system is critical.

A high compressibility has two important influences on the time required for repressurization of the surrounding medium and the resaturation of the repository. First, the repressurization to the initial steady-state conditions is slower and, second, since high compressibility implies a "spongy" rock, the pressure transient does not move out as far during the operational period, and resaturation of the repository takes place more quickly after repository closure because of steeper pressure gradients.

Since the time frames for repressurization are longer for a higher total system compressibility, a third effect is evident: the transient period of pressure recovery can be significant. GAI has examined the influence of specific storage (compressibility) on the time to resaturate the repository, and, as might be expected, this time is inversely proportional to the specific storage value. They have presented a plot of time to resaturate as a function

of hydraulic conductivity for several values of specific storage.⁽⁸⁾ These curves were generated from trial and error solutions of their nonsteady-state analysis and the figure also includes the curve for their steady-state analysis.⁽³⁾

Because migration of radioactivity from the repository cannot take place before the repository is resaturated and the surrounding pressure field is restored to its pre-mining condition, we have drawn new curves on this plot by adding the time for repressurization. The results are shown in Figure 17. As may be seen in this figure, the addition of the repressurization to the resaturation times extend the time for the onset of radioactivity migration, despite the reduction in resaturation time caused by the higher compressibilities.

Finally, a more significant result from this exercise is the fact that the time period for transient processes is increased by larger values of compressibility (and low values of permeability). Therefore, a steady-state analysis of the hydrologic behavior in a repository setting is in serious question.

5.0 SUMMARY AND CONCLUSIONS

A new version of the OGRE model has been constructed and successfully verified with analytical results. This new version primarily entailed reformulating the pressure equation to simulate a linear, rather than a radial, flow regime, redefining the boundary conditions, and substituting a concentration equation for the saturation equation.

Test simulations were performed with two forms of the new model, one which included in the pressure equation both the linear.(diffusion) terms and the nonlinear (advection) terms, and one which included only the linear terms. We made these tests to determine the relative contributions of the linear and nonlinear terms to the final solutions and found that, for the physical conditions expected in the generic repository environment, the linear terms

FIG.17 TIME WHEN RADIOACTIVITY COULD BEGIN TO MIGRATE FROM REPOSITORY VERSUS HYDRAULIC CONDUCTIVITY

were dominant (see Figure 4). Since the linear version is more efficient and economic to exercise, all simulations in this report have been made with this version. We have retained the nonlinear version to use whenever it is desirable.

Other revisions to the OGRE model have included:

1. Dynamic dimensioning of the computational grid.
2. Integrating flow rates in time and space across the repository boundaries to give a measure of the amount of water entering (or leaving) the repository.
3. Providing Detailed plots of the pressure and velocity fields in and around the repository.

We have carried out a time-dependent simulation of the pressure response in and around a generic repository during the operational period and following final sealing with the new OGRE model. This simulation used parameter values which were very close to those used by GAI in a series of steady-state and nonsteady-state analytical evaluations of depressurization, resaturation, and repressurization of the region surrounding the generic repository, and resaturation.

The times for depressurization, resaturation and repressurization of the formation surrounding the repository have been computed by the OGRE model simulation and compared with a steady-state analysis by GAI of the same processes. This time of 251 years compares favorably with the analytic results of 260 years. These results agree because the OGRE model used a very low compressibility factor, which leads to a result which is similar to the analytical solutions obtained by GAI. However, since the simulation was made with the linear version of the model, where the compressibility appears only as a multiplier of the time derivative, a change in the value of the compressibility is reflected in a corresponding change in the time for repressurization.

One of the important findings in this study was the great dependence of the the time to resaturate the repository and to repressurize the formation on the compressibility of the system. Since the compressibility of the formation

can vary by orders of magnitude, depending on the rock type, depth of burial, age and history of the formation, large variations can occur in the actual resaturation and repressurization times. These times, of course, are critical in determining the nature of the radioactive species which can migrate from the repository. More important, the degree of compressibility will determine how effective a steady-state analysis of these phenomena can be.

Finally, we recognize that the OGRE model in its present form is not strictly suitable for accurately determining the behavior of the hydrologic regime associated with a generic, or any other repository. The model would produce more realistic results if:

1. it were three-dimensional
2. the behavior of both air and water were considered (2-phase flow).
3. the effects of heat sources in the repository on the flow regime were taken into account.

All these improvements could be incorporated into the OGRE model, but it would have to be recognized that the resultant new model would be more complex and more difficult to exercise. Nevertheless, at least some of these improvements can be implemented, and would result in more realistic, and defensible, results.*

We believe, however, that despite these shortcomings, the present study has resulted in some useful information and insights.

*Note: A three-dimensional version of the OGRE model has already been constructed, and is in the process of being tested.

ACKNOWLEDGMENTS

The author wishes to express his appreciation for the constructive criticisms and technical assistance provided by P. M. Gresho and J. B. Knox. Thanks are also due to W. G. Sutcliffe, who suggested the writing of this report.

REFERENCES

1. "Analysis of Nuclear Waste Management," TASC (UCRL-13766), October 31, 1976.
2. "Documentation Information for Peer Review Report - Site Suitability Criteria Study," GAI, September 1977.
3. "Second Report - Development of Site Suitability Criteria for the High Level Waste Repository," GAI, November 1977.
4. "Waste Isolation Facility Description, Bedded Salt," Parsons, Brinkerhoff Quade and Douglas, Inc., Y/OWI/SUB-76/16506, September 1976.
5. "Block Iterative Finite Element Preprocessed Scheme (BIFEPS), a Package for Simulation of Nonlinear Transient Problems With One or Two Governing Equations in Two or Three Dimensions," G. F. Pinder et al., Princeton University, 1977.
6. "The OGRE Code - A Two Dimensional Numerical Model of the Transient Flow of One or Two Compressible Fluids Through Confined Porous Media," John A. Korver, UCRL-50820, February 1970.
7. "Hydrology Parameters, TASC Basic Model - Shale and Salt Repository," GAI Memorandum to TASC, February 8, 1977.
8. "Recharge Behavior," Memorandum from R. L. Plum (GAI) to A. M. Kaufman (LLL), April 24, 1978.
9. "Interim Report - Results of Work, Period of April 26, 1978 to June 7, 1978," GAI, June 15, 1978.

APPENDIX A

Development of the Current OGRE Model

Since we originally designed the OGRE model to simulate the simultaneous flow of two compressible fluid phases in a radial geometry, we needed to make a number of modifications to convert it to single phase flow with mass transport in a cartesian geometry. Four major areas of modification were involved in this conversion:

- 1) Deleting those processes relating to the second fluid phase.
- 2) Reformulating the pressure equation to simulate linear flow, rather than radial flow.
- 3) Redefining the boundary and initial conditions for flow through heterogeneous porous media with finite dimensions.
- 4) Adding the process equations describing the time-dependent transport of radionuclides by groundwater.

Modification 1) was relatively straightforward because the time-dependent saturation equation is solved explicitly (no matrix solution is necessary), and few saturation terms occur in the matrix solutions to the pressure equation.

Modification 2) required only the removal of the radial dependence term ($1/r$) from the time-dependent pressure equation, and the conversion of the horizontal space dependent terms from a logarithmic distribution to a linear distribution i.e., $\ln(r/r_w)$ to x .

Modification 3) was, by far, the most difficult and time-consuming operation, because we had to formulate new boundary conditions describing continuous linear horizontal flow through the computational domain. We have the following derivations of the boundary equations and the corresponding matrix coefficient equations which are due to the not inconsiderable efforts of Philip Gresho. An illustration of the computational domain, similar to Figure 2, is shown in Figure 18.

$\frac{\partial p'}{\partial z} = g$

NON-LINEAR

$$T \mu \frac{\partial p'}{\partial t} = -\frac{\partial}{\partial x} \left(k_x \frac{\partial p'}{\partial x} \right) - \frac{\partial}{\partial z} \left(k_z \frac{\partial p'}{\partial z} \right) + T \left[k_x \left(\frac{\partial p'}{\partial x} \right)^2 + k_z \frac{\partial p'}{\partial x} \left(\frac{\partial p'}{\partial z} - g \right) \right]$$

$\frac{\partial p'}{\partial x} + \beta p' = \gamma$

$\gamma = \frac{\partial p_0}{\partial x} + \beta p_0'$

LINEAR

$$T \mu \frac{\partial p'}{\partial t} = \frac{\partial}{\partial x} \left(k_x \frac{\partial p'}{\partial x} \right) - \frac{\partial}{\partial z} \left(k_z \frac{\partial p'}{\partial z} \right)$$

$p' = p_0(x)$

$T = -C \rho_r / \rho \quad C = \frac{1}{\rho_r} \frac{d\rho}{dp} \Big|_{p_r} \quad p_r = \text{REFERENCE PRESSURE}$

$v_x = \frac{k_x}{\mu} \frac{\partial p'}{\partial x} \quad v_z = -\frac{k_z}{\mu} \frac{\partial p'}{\partial z} \quad \frac{\partial p'}{\partial z} = \frac{\partial p}{\partial z} + \rho g$

$\rho = \rho_r [1 + C(p - p_r)] \Rightarrow \frac{\partial p}{\partial z} = \rho_r C \frac{\partial p}{\partial z}$

FIG. 18 LINEAR AND NON-LINEAR GOVERNING EQUATIONS AND BOUNDARY CONDITIONS FOR THE OGRE MODEL

We use the deviation from the hydrostatic pressure, P' rather than P to back out the hydrostatic pressure. This new definition was deemed appropriate to reduce truncation and roundoff error. P' is defined as:

$$\frac{\partial P'}{\partial z} = \frac{\partial P}{\partial z} + G$$

Upper Boundary $\frac{\partial P'}{\partial z} = 0$

We assumed that the upper boundary is impermeable (i.e., no flow takes place across this boundary). This boundary condition could be modified to allow flow across it if necessary.

Left Boundary $P' = P'_0(z)$

The pressure along this boundary is initially a specified function of the vertical coordinate, and held constant with time. The pressure change along this boundary reflects a constant upward or downward flow.

Right Boundary $\frac{\partial P'(z)}{\partial x} = \frac{\partial P'_0(z)}{\partial x} + \beta P'_0(z)$

The pressure gradient along this boundary is initially a specified function of the vertical coordinate, and held constant with time. The factor, β , is an empirical factor, generally set equal to 0.

Lower Boundary $P' = P'_0(x)$

The pressure along this boundary, like the pressure along the left boundary, is initially a specified function of the horizontal coordinate, and held constant with time. Pressure changes along this boundary reflect a constant horizontal flow.

The method of solution of the finite difference equations employs a modified alternating direction implicit (ADI) tri-diagonal matrix solver designed by Richard Von Holdt (LLL), and optimized by P. M. Gresho.

The difference equations, as used in the model, are given below both for the interior nodes and the boundaries.

Difference Equations

The interior points of the difference equation are:

Nonlinear Form

$$\begin{aligned} \tau_{j,k} \phi_{k,k}^{\mu} = & \frac{(p_{j,k}^{n+1} - p_{j,k}^n)}{\Delta t} = \frac{K_{x,j,k} (p_{j-1,k}^i - p_{j,k}^i) + K_{x,j+1,k} (p_{j+1,k}^i - p_{j,k}^i)}{\Delta x^2} \\ & + \frac{K_{z,j,k} (p_{j,k-1}^i - p_{j,k}^i) + K_{z,j,k+1} (p_{j,k+1}^i - p_{j,k}^i)}{\Delta z^2} \\ & * \left[+ \tau_{j,k} \left\{ \frac{1}{2} \left(K_{x,j,k} \cdot \frac{p_{j,k}^i - p_{j-1,k}^i}{\Delta x} + K_{x,j+1,k} \cdot \frac{p_{j+1,k}^i - p_{j,k}^i}{\Delta x} \right) \left(\frac{p_{j+1,k}^i - p_{j-1,k}^i}{2\Delta x} \right) \right\}^2 \right. \\ & \left. + \left\{ \frac{1}{2} \left(K_{z,j,k} \cdot \frac{p_{j,k}^i - p_{j,k-1}^i}{\Delta z} + K_{z,j,k+1} \cdot \frac{p_{j,k+1}^i - p_{j,k}^i}{\Delta z} \right) \left(\frac{p_{j,k+1}^i - p_{j,k-1}^i}{2\Delta z} + \rho_{j,k} \right) \right\} \right] * \end{aligned}$$

Linear Form

The linear form is the same as the nonlinear form without the terms inside * [].

Downstream Boundary (x = JJ)

The downstream boundary for constant horizontal flow is described by:

$$\text{Let } H \equiv \frac{\partial}{\partial x} \left(K_x \frac{\partial P'}{\partial x} \right) + \tau K_x \left(\frac{\partial P'}{\partial x} \right)^2$$

In difference form, this equation becomes:

$$H_{JJ,k}^{n+1} = \frac{2 K_x K_{JJ,k}}{\Delta x^2} \left[P_{JJ-1,k}^{n+1} - (1 + \beta \Delta x) P_{JJ,k}^{n+1} + \gamma \Delta x \right] + \left[\tau_{JJ,k} K_{JJ,k} \left(\gamma - \beta P_{JJ,k}^{n+1} \right) \left(\gamma - P_{JJ,k}^{n+1} \right) \right]$$

where

$$\gamma = \frac{\partial P'_0}{\partial x} + \beta P'_0 = \frac{P'_{0,JJ,k} - P'_{0,JJ-1,k}}{\Delta x} + \beta P'_{JJ,k}$$

and P'_0 is the initial value of P' .

Again, the * terms are omitted to obtain the linear form.

Top Boundary (z = JK)

$$\text{Let } V \equiv \frac{\partial}{\partial z} \left(K_z \frac{\partial P'}{\partial z} \right) + \tau K_z \frac{\partial P'}{\partial z} \left(\frac{\partial P'}{\partial z} - \rho g \right)$$

$$\text{but } \frac{\partial P'}{\partial z} = \rho g \text{ so } V \equiv \frac{\partial}{\partial z} \left(K_z \frac{\partial P'}{\partial z} \right)$$

or in difference form.

$$V_{J,JK} = \frac{2 K_z}{\Delta z^2} \left(P'_{J,JK-1} - P'_{J,JK} \right)$$

Top Downstream Corner Node

Let $H + V = \rho \mu \frac{\partial P}{\partial t}$ where H is $H_{JJ,JK}$ from downstream B.C. and V is $V_{JJ,JK}$ from top B.C.

Modification 1) consisted of inserting a mass transport equation for the migration of radioactive material from the repository. This insertion takes the place of the saturation equation in the original version of the model. Solution of this equation therefore is carried out explicitly, just as the saturation equation is, since it is primarily dependent on the velocities computed from the pressure equation. The form of this equation is shown below.

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x} \left(D_x \frac{\partial C}{\partial x} \right) + \frac{\partial}{\partial z} \left(D_z \frac{\partial C}{\partial z} \right) - \frac{\partial}{\partial x} (C V_x) - \frac{\partial}{\partial z} (C V_z) - \lambda C$$

where C is the nuclide concentration
 D_x is the horizontal dispersivity
 D_z is the vertical dispersivity
 V_x is the horizontal velocity
 V_z is the vertical velocity
 λ is the nuclide decay rate

In the present form of the model the radioactive source is distributed along a row of nodes in the repository. After the repository is resaturated, and the regional flow regime is reestablished, the radionuclide source can be turned on at any predetermined time, and its migration can be followed.

APPENDIX B

Field Parameters and Initial Pressure Distribution⁽⁷⁾
 (Permeability units have been converted from cm/sec to m³/cm and
 heads have been converted from feet to dynes/m²)

Permeability and Porosity

Layer	Horizontal Permeability(m ³ /cm)	Porosity	Formation Type
1	1x10 ⁻¹⁵	0.10	Aquifer
2	1x10 ⁻¹⁷	0.02	Aquitard
3	1x10 ⁻¹⁹	0.01	Aquitard
4	1x10 ⁻¹⁷	0.02	Aquitard
5	1x10 ⁻¹⁵	0.10	Aquifer

(vertical permeability = 0.1 x horizontal permeability)

Natural horizontal gradient = 0.005 meter/meter.

Artesian pressure between layers 1 and 5 = 200 feet (61 meters).

Excess pressure distribution (artesian).

Let: P_T = total artesian head (dynes/m²) = 1.138×10^{12} dynes/m².

t_2, t_3, t_4 = thickness of layers 2,3,4. (200 meters)

k_2, k_3, k_4 = permeability of layers 2,3,4. (see above table)

Then

Pressure at contact between Layers 4 and 5

$$P_{4,5} = P_T = 1.138 \times 10^{12} \text{ dynes/m}^2.$$

Pressure at contact between Layers 3 and 4.

$$P_{3,4} = \frac{t_3 \frac{k_4}{k_3} + t_2 \frac{k_4}{k_2}}{t_4 + t_3 \frac{k_4}{k_3} + t_2 \frac{k_4}{k_2}} \cdot P_T = 1.126 \times 10^{12} \text{ dynes/m}^2$$

Pressure at contact between Layers 2 and 3

$$P_{2,3} = \frac{t_2 \frac{k_4}{k_2}}{t_4 + t_3 \frac{k_4}{k_3} + t_2 \frac{k_4}{k_2}} \cdot P_T = 1.115 \times 10^{11} \text{ dynes/m}^2$$

Pressure at contact between Layers 1 and 2

$$P_{1,2} = 9.8 \times 10^{10} \text{ dynes/m}^2$$

A schematic drawing of the pressure distribution is shown in Figure 19.

Layer 1 } (200 m)	$\phi = 0.10$	$\uparrow P = 9.8 \times 10^{10} \text{ dynes/m}^2$ $k = 1 \times 10^{-15} \text{ m}^3/\text{cm}$	} P (artesian)
Layer 2 } (200 m)	$\phi = 0.02$	$\uparrow P = 9.8 \times 10^{10} \text{ dynes/m}^2$ $k = 1 \times 10^{-17} \text{ m}^3/\text{cm}$	
Layer 3 } (200 m)	$\phi = 0.01$	$\uparrow P = 1.115 \times 10^{11} \text{ dynes/m}^2$ $k = 1 \times 10^{-19} \text{ m}^3/\text{cm}$	
Layer 4 } (200 m)	$\phi = 0.02$	$\uparrow P = 1.126 \times 10^{12} \text{ dynes/m}^2$ $k = 1 \times 10^{-17} \text{ m}^3/\text{cm}$	
Layer 5 } (200 m)	$\phi = 0.10$	$\uparrow P = 1.138 \times 10^{12} \text{ dynes/m}^2$ $k = 1 \times 10^{-15} \text{ m}^3/\text{cm}$ $\downarrow P = 1.138 \times 10^{12} \text{ dynes/m}^2$	

FIG. 19 PRESSURE DISTRIBUTION .

APPENDIX C

Steady-State Analyses by Golder Associates, Inc

Golder Associates, Inc., performed steady-state calculations of the times required to resaturate the repository and to repressurize the surrounding formation and reported them in November of 1977.⁽⁷⁾ The parameter values obtained from personal communication were used to recalculate the steady-state analyses in Reference 7 and in the OGRE model simulation. The following text reproduces the pertinent parts of the GAI report, showing the methodology used by GAI.

Repository Recharge Behavior

1. General: During the construction and operation of the repository, the repository openings will be maintained essentially dry. Certain portions of the repository, such as the shaft, may extend through pervious, saturated zones (aquifers). Within these areas, the openings will probably be hydraulically isolated from the aquifer by grouting, shaft lining, and/or other appropriate measures. However, in general, the dry openings will be in direct hydrologic communication with the host rock. This would probably not pose an operational problem since the inflow rates would be negligible from the types of low permeability host rocks anticipated (shale, salt, etc.). In fact, any infiltration would probably be carried off by the ventilation system. However, the result of maintaining "dry" openings for about 20 to 50 years will be to depressurize the formation. After repository abandonment, time will be required to saturate the repository area and reestablish the original groundwater regime. This section of the report presents a preliminary discussion of anticipated repository recharge behavior.

Since the hydrology of a resaturating repository is very complex, requiring site specific information for any realistic and rigorous evaluation, several simplifying assumptions were made for the purposes of this discussion. These assumptions included:

- a. The geometry of the repository was assumed to be similar to that presented in the Parsons, et al. report as shown on Figure C-2 in Reference 4.
- b. The effects of lateral flow and end effects into the sides of the repository were ignored. This is tantamount to assuming the repository is infinite in areal extent.
- c. The effects of temperature were ignored.
- d. The repository formation was assumed to be below the water table and to be overlain and underlain by a stratum of significantly greater permeability. The repository host formation was also assumed to have a finite permeability which would result in an eventual resaturation of the repository backfill.
- e. The repository was assumed to be backfilled.
- f. The repository openings were assumed to be maintained "dry" long enough to reach a steady state flow system prior to decommissioning.

2. Resaturation With Air Free to Escape: The most rapid method of resaturation of the repository would occur if the air in the backfill were vented at atmospheric pressure during the fillup stage. After all the air had been displaced from the repository, the water pressure in the surrounding rock would be gradually raised to approximately its original (pre-mining) value by continued flow towards the low pressure zone. Only when the water pressure regime approaches the original condition will vertical flow be reestablished. For the purposes of the radionuclide escape problem, it is at this instant that the repository can be considered to be "resaturated."

- a. Refilling of Repository: The refilling of the repository depends upon the rate of inflow, the percent of material extracted in the repository, and the percentage of voids in the material used for backfilling. Consider the repository to be situated in a layer of rock of thickness $2D$, vertical hydraulic conductivity K_v , and with a pre-mining water pressure of H , expressed as a head of water. If the pressure in the repository is lowered to atmospheric, the inflow is given by Darcy's law as

$$Q_o = 2K_v \cdot H/D \cdot A \quad (1)$$

where Q_o = flow to the repository

A = area of repository

H = head drop between "aquifers" and repository

D = distance from "aquifers" to repository

K_v = vertical hydraulic conductivity of repository layer

The void volume in the repository is given by

$$V_m = LenA \quad (2)$$

where V_m = void volume in repository after backfilling

L = height of rooms

e = extraction ratio

n = porosity of backfill material

A = area of repository

The time to refill the repository is thus given by

$$t_m = \frac{V_m}{Q} = \frac{LenD}{2K_v H} \quad (3)$$

- b. Pressure Reequilibration: Once the repository is refilled at atmospheric pressure, the inflow proceeds to reestablish the pressure regime which previously existed in the repository layer. The time taken to achieve a degree of reequilibration of the pressure regime adequate to allow vertical flow of radionuclides from the repository is

dependent on the volume of water required for repressurization, and upon the time/pressure behavior of the medium.

If the pressure at the repository was atmospheric before repressurization began, then the volume of water required for reequilibrium of the pressure regime is:

$$V_R = DAHS_S \quad (4)$$

where V_R = volume of water required to repressurize rock
 D = distance from repository to aquifers above and below

A = mine area

H = head change in mine

S_S = specific storage of rock mass (or the volume of required to raise the pressure of water in a unit volume of rock by one unit of head).

The initial inflow rate is Q_0 as given in Equation (1), and dwindles to zero as the pressure in the repository and nearby rock increases towards the pre-mining value. It is necessary to determine the time taken for the pressure to reach a value high enough to allow vertical flow. We will assume that the time taken to approach pressure equilibrium is twice the time that would have been taken to reach equilibrium if the inflow continued at Q_0 . This is a reasonable approximation since the volume of voids in the backfill will probably be much greater than the volume computed in Equation (4). Thus:

$$t_R = \frac{2V_R}{Q_0} = \frac{D^2 S_S}{K_V} \quad (5)$$

where

t_R = time for pressure in rock to approach equilibrium;
 other variables are as above.

- c. Unflawed Resaturation Time: The total time for resaturation can be simply obtained by adding Equations (3) and (5).

$$t_o = \frac{LD}{2K_vH} \left[\frac{2DS_sH}{L} + en \right] \quad (6)$$

where t_o = unflawed resaturation time; other variables as defined above.

0926z/D113/NB

LLL:1980/4