PNL-3047

UC-94b

**Numerical Analysis of
Temperature and Flow Effects
in a Dry, Two-Dimensional,
Porous-Media Reservoir Used for
Compressed Air Energy Storage**

L. E. Wiles

October 1979

**Prepared for the U.S. Department of Energy
under Contract EY-76-C-06-1830**

**Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
by Battelle Memorial Institute**

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or 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.

The views, opinions and conclusions contained in this report are those of the contractor and do not necessarily represent those of the United States Government or the United States Department of Energy.

PACIFIC NORTHWEST LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
Under Contract EY-76-C-06-1830

Printed in the United States of America
Available from

National Technical Information Service
United States Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151

Price: Printed Copy \$ ____*; Microfiche \$3.00

*Pages	NTIS Selling Price
001-025	\$4.00
026-050	\$4.50
051-075	\$5.25
076-100	\$6.00
101-125	\$6.50
126-150	\$7.25
151-175	\$8.00
176-200	\$9.00
201-225	\$9.25
226-250	\$9.50
251-275	\$10.75

3 3679 00053 6542

NUMERICAL ANALYSIS OF
TEMPERATURE AND FLOW EFFECTS
IN A DRY, TWO-DIMENSIONAL,
POROUS-MEDIA RESERVOIR USED FOR
COMPRESSED AIR ENERGY STORAGE

L. E. Wiles

October 1979

Prepared for
the U.S. Department of Energy
under Contract EY-76-C-06-1830

Pacific Northwest Laboratory
Richland, Washington 99352

FOREWORD

The Compressed Air Energy Storage Technology Program at the Pacific Northwest Laboratory (PNL) is sponsored by the Department of Energy, Division of Energy Storage Systems. The program scope includes a group of studies directed at developing a new energy storage technology to improve the cost and efficiency of electrical power utilization and reducing the dependence on petroleum fuels such as oil and natural gas. The program has two major thrusts --- Reservoir Stability Criteria Studies and Advanced Concepts Studies. These have the following objectives:

- Reservoir Stability Criteria
Develop design and stability criteria for long-term operation of underground reservoirs used for compressed air energy storage (CAES) in order to accelerate the commercialization of the concept.
- Advanced Concepts Studies
Develop and assess advanced CAES concepts that require little or no supplementary firing by petroleum fuels in order to eliminate the dependence of CAES on petroleum fuels.

The ultimate objective of this program is to reduce the consumption of natural gas and oil used for peak-power generation plants by about 100,000,000 barrels per year. This could be accomplished by replacing conventional gas turbine peaking plants currently being used by utilities with CAES plants.

The following documents have been issued by PNL or by subcontractors to PNL, reporting the results of the work toward these objectives.

- Air Storage Peaking Power Plants Utilizing Modified Industrial Gas Turbines and Cavities with Nuclear Explosives, B.C. Fryer, BNWL-1748, May 1973.
- Technical and Economic Feasibility Analysis of the No-Fuel Compressed Air Energy Storage Concept, D.K. Kreid, BNWL-2065, May 1976.

- FY-1977 Progress Report - Stability and Design Criteria Studies for Compressed Air Energy Storage Reservoirs, G.C. Smith, J.A. Stottlemire, L.E. Wiles, W.V. Loscutoff and H.J. Pincus, PNL-2443 March 1978.
- FY-1977 Progress Report Compressed Air Energy Storage Advanced Systems Analysis, D.K. Kreid and M.A. McKinnon, PNL-2464, March 1978.
- Preliminary Stability Criteria for Compressed Air Energy Storage in Porous Media Reservoirs, J.A. Stottlemire, PNL-2685, June 1978.
- Preliminary Long-Term Stability Criteria for Compressed Air Energy Storage Caverns in Salt Domes, R.L. Thoms and J.D. Martinez, PNL-2871, August 1978.
- Numerical Analysis of Temperature and Flow Effects in a Dry, One-Dimensional Aquifer Used for Compressed Air Energy Storage, G. C. Smith, L.E. Wiles, and W.V. Loscutoff, PNL-2546, February 1979.
- The Effects of Water on Compressed Air Energy Storage in Porous Rock Reservoirs, L.E. Wiles, PNL-2869, March 1979.
- Pacific Northwest Laboratory Annual Report for 1978 to the DOE Division of Energy Storage Systems - Compressed Air Energy Storage Technology Program, W. V. Loscutoff, PNL-2935, June 1979.
- Incremental Cost Analysis of Advanced Concept CAES Systems, C.A. Knutsen, Knutsen Research Services, PNL-3118, September 1979.

SUMMARY

The analysis described in this report is a continuation of work initiated at PNL in FY-1977. The purpose of the work is to define the hydrodynamic and thermodynamic response of a CAES dry porous media reservoir subjected to simulated air mass cycling. The knowledge gained by this research will provide, or will assist in providing, design guidelines for the efficient and stable operation of the air storage reservoir. Previous investigations have dealt with one-dimensional modeling of both dry and water wet reservoirs.^(1,2) In this report the analysis and results obtained by two-dimensional modeling of dry reservoirs is presented. While the fluid/thermal response of the underground system is dependent on many parameters, the two-dimensional model was applied only to those parameters that entered the analysis by virtue of inclusion of the vertical dimension. In particular, the parameters or responses that were quantified or characterized include wellbore heat transfer, heat losses to the vertical boundaries of the porous zone, gravitationally induced flows, producing length of the wellbore, and the effects of non-uniform permeability. The analysis of the wellbore heat transfer included consideration of insulation, preheating (bubble development with heated air), and air mass flow rate. The significant results obtained from the analysis using the numerical computer model were:

- Wellbore heat losses can dramatically reduce thermal energy recovery.
- Wellbore heat losses reduce temperatures and extremes of thermal cycling in the porous zone.
- For some conditions wellbore insulation may result in increased thermal cycling of the air in the wellbore.
- Preheating improves the initial thermal energy recovery and reduces the thermal cycling.
- The effects of preheating are rapidly dissipated.
- A combination of factors involving air mass flow rate, air density, wellbore diameter, and reservoir depth influence the wellbore heat transfer.

- Heat transfer to the vertical boundaries of the porous zone has a negligible effect on the thermal energy recovery and temperature distributions in the porous zone.
- Gravitationally induced flows in the porous zone are small and contribute very little to the pressure losses in the reservoir or to the distribution of thermal energy in the reservoir.
- The producing length of the wellbore is the dominant factor determining pressure losses and thermal energy distribution in the reservoir. As such, the producing section of the wellbore should extend through the entire reservoir thickness, if possible, to avoid excessive pressure losses and sharp vertical thermal gradients.
- Reduced vertical permeability or permeability stratification do not greatly affect the pressure losses in the reservoir.
- The primary mode of energy transport is by forced convection. Therefore, non-uniform temperature distributions in the porous zone are primarily caused by the conditions that disrupt uniform flow. These include the producing length being less than reservoir thickness and permeability stratification.

CONTENTS

	<u>Page</u>
FOREWORD.	iii
SUMMARY	v
FIGURES	ix
TABLES.	xi
NOMENCLATURE.	xiii
1.0 INTRODUCTION	1
2.0 ANALYTICAL MODEL	5
2.1 GOVERNING EQUATIONS	5
2.2 BOUNDARY CONDITIONS	7
2.3 SUMMARY OF ASSUMPTIONS	9
2.4 LIMITATIONS OF THE MODEL.	9
3.0 NUMERICAL MODEL.	11
3.1 FLOW SOLUTION	11
3.2 THERMAL SOLUTION.	16
3.3 BOUNDARY CONDITIONS	20
3.4 CODE VERIFICATION	20
4.0 ANALYSIS AND RESULTS	23
4.1 REFERENCE CONDITIONS.	23
4.2 WEEKLY CAES CYCLE	25
4.3 WELLBORE HEAT TRANSFER.	26
4.3.1 Insulation	31
4.3.2 Preheating	35
4.3.3 Air Mass Flow Rate	40
4.3.3.1 Air Storage Volume.	41
4.3.3.2 Air Density	41
4.4 RESERVOIR ANALYSIS.	43
4.4.1 Pressure Response.	44
4.4.1.1 Producing Length of the Wellbore.	46
4.4.1.2 Permeability Ratio.	50
4.4.1.3 Permeability Stratification	50

	<u>Page</u>
4.4.2 Thermal Response	53
4.4.2.1 Non-Uniform Fluid Flow.	54
4.4.2.2 Natural Circulation (and Other Heat Transfers)	58
5.0 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS FOR FURTHER STUDY. .	65
REFERENCES.	69

FIGURES

	<u>Page</u>
1 Geometry for Two-Dimensional Analysis	7
2 Finite Difference Grid System	15
3 Reference Weekly Reservoir Pressure Cycle	26
4 Effect of Wellbore Heat Transfer on Thermal Energy Recovery.	29
5 Thermal Cycling of the Air in the Wellbore for the Reference Conditions, Week 1.	30
6 Thermal Cycling of the Air in the Wellbore for the Reference Conditions, Week 52	31
7 Thermal Cycling of the Air in an Insulated Wellbore, Week 1.	32
8 Thermal Cycling of the Air in an Insulated Wellbore, Week 52	33
9 Air Temperature at Depth in the Wellbore During Simulated Bubble Development, Air Mass Flow Rate = 5.45 kg/s (12.0 lbm/s)	36
10 Air Temperature at Depth in the Wellbore During Simulated Bubble Development, Air Mass Flow Rate = .545 kg/s (1.2 lbm/s)	37
11 Thermal Recovery Efficiency in the First Week of Reservoir Operation as a Function of the Delay Between Preheating by Bubble Development and the Start of Reservoir Operation. .	39
12 Thermal Cycling of the Air in the Wellbore for a Preheated Reservoir, Week 1	39
13 Thermal Cycling of the Air in an Insulated Wellbore for a Preheated Reservoir, Week 1	40
14 Thermal Cycling of the Air in the Wellbore for Doubled Air Mass Flow Rates, Week 1	42
15 Weekly Cycle of the Wellbore and Reservoir Average Pressure for the Reference Conditions	45
16 Reservoir Inlet Pressure Versus Time for Various Producing Lengths (m (ft)), Reservoir Thickness = 30.5 m (100 ft)	47

	<u>Page</u>
17 Quasi-Steady-State Pressure Difference Versus Producing Length, Reservoir Thickness = 30.5 m (100 ft).	48
18 Quasi-Steady-State Pressure Difference Versus the Permeability Ratio for Various Producing Lengths (m (ft)), Reservoir Thickness = 30.5 m (100 ft).	51
19 Vertical Temperature Distributions at Various Radii (m (ft)) for Producing Lengths of 30.5 m (100 ft) (Solid Lines) and 7.62 m (25 ft) (Dashed Lines).	55
20 Vertical Temperature Distributions at Various Radii (m (ft)) for the Reference Reservoir (Solid Lines) and a Stratified Reservoir (Dashed Lines)	56
21 Vertical Temperature Distributions at Various Radii (m (ft)) in the Reference Reservoir After 1 Week (Solid Lines) and After 5 Weeks (Dashed Lines).	57
22 Natural Circulation Paths in a Closed Reservoir with the Distribution of Mass Flows in and Along the Wellbore Indicated by the Length of the Arrows.	59
23 Thermal Cycling at Various Radii (m (ft)) in the Porous Zone of the Reference Reservoir.	62

TABLES

	<u>Page</u>
1 Reference Reservoir Conditions.	24
2 Parametric Cases for Wellbore Heat Transfer Analysis.	28
3 Effect of Stratified Permeability on the Quasi-Steady- State Pressure Difference	52
4 Contributions to Temperature Change, in °C (°F), During Reservoir Closure Between Hours 50 and 52 of the First Week of Reservoir Operation	61

NOMENCLATURE

A	=	transport area coefficient
AI, CI, AK, CK, B	=	numerical coefficients representing fluid or thermal conductance
C_s	=	heat capacity of solid rock
C_p, C_v	=	specific heat of air at constant pressure, constant volume
CR, CZ	=	numerical coefficients representing thermal conductance due to material thermal conductivity for the radial direction, vertical direction
DC	=	continuity error; i.e., the amount by which the flow solution does not satisfy continuity
DE	=	energy error; i.e., the amount by which the thermal solution does not satisfy conservation of energy
e	=	internal energy of air
$\vec{g}$	=	gravitational vector
g_z	=	gravitational component in the vertical direction
h	=	enthalpy of air
i	=	radial coordinate index
k	=	vertical coordinate index
k, k_r, k_z	=	permeability, in the radial direction, vertical direction
K, K_r, K_z	=	effective thermal conductivity, in the radial direction, vertical direction
κ_r, κ_a	=	thermal conductivity of the rock, air
ℓ	=	iteration index
M	=	integrated mass of air in the reservoir
n	=	time step index
P	=	pressure
r	=	radial coordinate
R	=	flow resistance coefficient defined for Equations 5 and 6
t	=	time

T	=	temperature
T^*	=	donor cell temperature
u	=	fluid velocity in radial direction
UP	=	upwind function
$\vec{v}$	=	fluid velocity vector
V	=	volume
w	=	fluid velocity in vertical direction
z	=	vertical coordinate
ρ	=	density of air
ρ_s	=	density of solid rock
ϕ	=	porosity
μ	=	viscosity of air
τ	=	coefficient for thermal energy accumulation term
λ	=	percent of maximum air mass that is cycled
δi	=	the operator δ indicates that the parameter i changes by a very small value relative to the magnitude of i
Δi	=	the operator Δ indicates that the parameter i changes by an arbitrary value
∇	=	standard "del" operator

NUMERICAL ANALYSIS OF TEMPERATURE AND FLOW EFFECTS IN A
DRY, TWO-DIMENSIONAL, POROUS-MEDIA RESERVOIR USED FOR
COMPRESSED AIR ENERGY STORAGE

1.0 INTRODUCTION

The analysis of the hydrodynamic and thermodynamic response of porous-media reservoirs to air cycling is one of several parallel research efforts being conducted by PNL that is intended to provide design guidelines for efficient and stable operation of the air storage reservoirs. Previous investigations performed at PNL^(1,2) have been based on one-dimensional (radial) modeling of the air storage reservoir. Several parameters were identified that could not be addressed with a one-dimensional model. These parameters were related to heat transfer from the wellbore to the caprock and overburden, heat transfer between the porous zone and its vertical boundaries, natural circulation in the porous zone, stratification of reservoir material properties and producing lengths being less than reservoir thickness. The objective of the two-dimensional (radial, vertical) modeling and analysis described in this report was to quantify these responses.

As indicated by the parameters or responses mentioned above, one key element in the two-dimensional analysis is the evaluation of conditions related to the fluid and thermal coupling of the wellbore and reservoir. The wellbore heat transfer will affect the magnitudes of the temperature and amplitude of thermal cycling that occurs at reservoir depth. Using the two-dimensional model, the heat transfer between the air in the wellbore and the surrounding material between the earth's surface and the porous zone was characterized according to wellbore insulation, preheating (bubble development using heated air), and air mass flow rate.

The fluid and thermal coupling of the wellbore and reservoir at reservoir depth is also important. Since the primary mode of energy transport in the porous zone is by convection, then anything that disturbs the uniformity of the flow field in the vicinity of the wellbore will also affect the uniformity of the temperature distribution. The producing length is the length of the wellbore through which air entering the porous zone must pass. The producing length and wellbore diameter define the minimum area for flow in the porous zone. This area, in turn, is associated with the highest flow velocities experienced in the porous zone. These velocities are significant in determining the overall pressure losses in the porous zone.

For producing lengths less than reservoir thickness, the air entering the porous zone must pass through the constricted flow area before expanding into the reservoir. While this will add to the flow losses, it also dramatically affects the temperature distribution. Thermal energy carried in by the injected air is deposited in the vicinity of where the air enters the porous zone, thus resulting in concentrations of thermal energy and sharp vertical temperature gradients.

An additional aspect of the wellbore/reservoir coupling is the effect of the wellbore on the distribution of mass flow into the reservoir. This effect results in mass flows into the reservoir that are greater at the top of the reservoir than at the bottom of the reservoir. This non-uniform flow from the wellbore results in vertical temperature gradients in the porous zone, even for wells where the producing length spans the reservoir thickness. This behavior was not reported for results obtained previously.⁽³⁾ This was due to the lack of a complete wellbore/reservoir coupling in the model used in that study.

Typically, the porous zone will be tightly closed to air mass transport by the vertical boundaries, those being the caprock and the basement rock. Therefore, heat loss to these boundaries will occur primarily by conduction. While conduction heat losses to the vertical boundaries were thought to be small and, as such, would have an insignificant effect on the thermal performance of the reservoir, the magnitude of the

losses had to be quantified. The thermal behavior in the caprock due to conduction from both the wellbore and the porous zone is important as it may impact the integrity of the caprock seal, especially in the vicinity of the well casing. Also, these thermal conditions will be used to study the structural stability of the caprock.

The magnitude of the redistribution of thermal energy by virtue of natural convection has been a question mark prior to this study. The thermal effects of natural circulation were thought to possibly impact thermal energy recovery, thermal cycling, and vertical temperature gradients.

Stratification of reservoir material properties can result in perturbation of the fluid and thermal behavior of the reservoir. Permeability was investigated as the parameter of principal interest. In actual reservoirs, the permeability as well as other properties, may vary dramatically over a relatively small vertical interval. Also, the permeability in the vertical direction within any given layer is likely to be less than that in the horizontal direction. In addition, a layer of very low permeability may virtually block vertical communication in the reservoir while the horizontal flow remains nearly undisturbed. This particular characteristic enhances the validity and applicability of the one-dimensional radial flow models.

The major drawback of the model used in this study is that it does not include the effects of residual water or moisture in the injected air stream. However, the results obtained with a one-dimensional model⁽²⁾ showed that for a wide band of conditions the presence of water was not significant to the fluid and thermal response of the reservoir.

In the body of this report, a description of the analytical and numerical models for the two-dimensional analysis are presented. Results are provided that quantify and characterize the fluid flow and thermal response of the wellbore and the porous zone to conditions of daily air mass cycling.

2.0 ANALYTICAL MODEL

The hydrodynamic and thermodynamic response of a CAES porous media reservoir that is subjected to daily cycling of dry air under nonisothermal conditions can be analytically described by an appropriate set of conservation equations and boundary conditions. A description of the analytical model is presented in this section.

2.1 GOVERNING EQUATIONS

A set of equations was presented in a preceding report⁽²⁾ that provided the general description of the transport of mass and energy in a porous media. These equations included the presence of liquid- and vapor-phase water in the porous material. In this analysis, the water component is excluded. The resultant set of equations for the reservoir are:

- Conservation of Mass^(a)

$$\frac{\partial}{\partial t} (\phi \rho) + \nabla \cdot (\phi \rho \vec{v}) = 0 \quad (1)$$

- Conservation of Momentum

$$\left(\frac{\mu \phi}{k \rho} \right) \phi \rho \vec{v} = - \phi \nabla P + \phi \rho \vec{g} \quad (2)$$

- Conservation of Energy

$$\frac{\partial}{\partial t} \left\{ (1-\phi) \rho_s C_s \right\} + \frac{\partial}{\partial t} (\rho e) + \nabla \cdot (\phi \rho \vec{v} h) - \nabla \cdot (K \nabla T) = 0 \quad (3)$$

To apply these equations it is particularly important to recognize that the velocity, $\vec{v}$, used in these equations is the local velocity. The product, $\phi \rho \vec{v}$, thus represents the bulk mass flux.

^(a) see the Nomenclature for definition of symbols

The emphasis of this analysis was to consider two-dimensional transport of mass and energy about a single well. Thus, Eqs. 1, 2, and 3 reduce to

- Conservation of Mass

$$\frac{\partial}{\partial t} (\phi \rho) + \frac{1}{r} \frac{\partial}{\partial r} (r \phi \rho u) + \frac{\partial}{\partial z} (\phi \rho w) = 0 \quad (4)$$

- Conservation of Momentum in the r-direction

$$R_r \phi \rho u = -\phi \frac{\partial P}{\partial r} \quad (5)$$

where $R_r = \frac{\mu \phi}{k_r \rho}$

- Conservation of Momentum in the z-direction

$$R_z (\phi \rho w) = -\phi \frac{\partial P}{\partial z} + \phi \rho g_z \quad (6)$$

where $R_z = \frac{\mu \phi}{k_z \rho}$

- Conservation of Energy

$$\begin{aligned} & \frac{\partial}{\partial t} \left\{ (1-\phi) \rho_s C_s \right\} + \frac{\partial}{\partial t} (\rho e) + \frac{1}{r} \frac{\partial}{\partial r} (hr \phi \rho u) + \frac{\partial}{\partial z} (h \phi \rho w) - \frac{1}{r} \frac{\partial}{\partial r} (r K_r \frac{\partial T}{\partial r}) \\ & - \frac{\partial}{\partial z} (K_z \frac{\partial T}{\partial z}) = 0 \end{aligned} \quad (7)$$

These equations can be applied to the flow in the well by treating the fluid friction in terms of the equivalent permeability required to achieve a similar pressure loss. This approach results in a permeability in the well that is about 7 or 8 orders of magnitude greater than those of the porous reservoir. The pressure gradients in the well are so small compared to those in the porous material, especially near the wellbore, that the exactness of this approach is not critical.

2.2 BOUNDARY CONDITIONS

The reservoir geometry adapted to this problem is shown in Figure 1. The region of influence of a single well is approximated as a radially symmetric cylinder. Four distinct zones are identified, these being the overburden, caprock, porous rock and basement rock. The wellbore extends from the surface to the porous zone where the producing length is specified. This is the length of wellbore through which air entering the porous zone must pass.

FIGURE 1. Geometry for Two-Dimensional Analysis

Anticipated CAES designs will be characterized by a large cushion air mass in the reservoir. The difference between the maximum and minimum stored mass will be approximately 10% of the average stored mass. Subject to these conditions, the total reservoir pressure swings will be small enough that a constant power input will result in a nearly constant air flow rate into the storage reservoir. A constant specified flow rate condition was, therefore, applied at the wellhead for the reservoir charging cycle. In addition to the flow rate, the temperature of the air stream was specified at the wellhead for the charging cycle.

During the power generation cycle, the power produced is approximately proportional to the air mass flow rate delivered from the reservoir. Therefore, during reservoir discharge (power production cycle) a constant specified flow rate condition at the wellhead was simulated in the analytical model to approximate constant power generation. The temperature of the extracted air was determined by the local thermal equilibrium condition in the well at the surface during the discharge cycle.

During the periods of CAES operation when the reservoir was closed, the boundary condition applied at the wellhead was zero flow of heat or mass into or out of the reservoir.

One of the assumptions of the analytical model was that the performance of the reservoir could be evaluated by consideration of the performance of a single well. This implies that adjacent wells will behave in a symmetric fashion. As a result, the outer diameter of a single well can be modelled as being insulated to the transport of mass and energy.

The transport of mass is assumed to occur only in the well and in the porous zone. The overburden, caprock, and basement rock are impermeable. However, conductive heat transport is permitted from the air in the well to the surrounding material. Vertical heat transfer by conduction is permitted between the porous zone, the caprock, and basement rock. The surface of the earth and the basement rock were modeled as thermally insulated boundaries.

2.3 SUMMARY OF ASSUMPTIONS

To arrive at the transport equations given above, a number of assumptions were applied. These are summarized as follows:

- The air behaves as an ideal gas.
- The rock porosity, density, and heat capacity are constant.
- The rock is immobile.
- Inertial effects are negligible.
- The air and rock are in local thermal equilibrium.
- Kinetic energy is negligible.
- Viscous dissipation of energy is negligible.
- The effective thermal conductivity is calculated by

$$K = (1 - \phi)\kappa_r + \phi\kappa_a \quad (8)$$

- The reservoir is free of vapor- and liquid-phase water.
- Darcy's law for low velocity flows is applied.
- The performance of the bulk of the reservoir can be evaluated by consideration of the performance of a single well.
- The reservoir geometry is modeled as a vertical cylinder.
- Transport of mass and energy occurs simultaneously in the horizontal, radial direction and the vertical direction.

2.4 LIMITATIONS OF THE MODEL

General limitations regarding the assumptions of the analytic model have been referred to in previous reports.^(1,2) The principal restriction in those analyses was that the transport equations were written only for one dimension, that being radial. The two-dimensional analysis permits evaluation of well/reservoir coupling, producing length,

buoyancy-induced flows, and heat losses to the vertical boundaries of the porous zone. These aspects of reservoir performance could not be evaluated with a one-dimensional model.

As was the case with one of the previous studies⁽¹⁾, the analysis reported here is restricted to dry reservoirs with fixed boundaries. While this limits the range of performance indicators that can be evaluated, it does not significantly affect the generality of the results. It was shown by the numerical results of a previous study⁽²⁾ that the effects of residual water on the pressure and temperature response of the reservoir are for reasonably typical conditions, insignificant. Thus, the validity of the evaluation of those aspects of reservoir performance mentioned in the paragraph above should not be significantly compromised by the assumption of a dry reservoir.

A particular limitation of the dry reservoir with fixed boundaries is that the phenomenon of water coning cannot be evaluated. Water coning will occur during the production cycle. Water beneath the air storage zone will rise due to depressurization in the vicinity of the wellbore. The extent of water coning will depend upon several factors including production rates, permeabilities, and well completion depth. The presence of a water cone is not likely to have a serious impact on reservoir performance unless the water enters the heated region near the well or the water actually enters the well. Thus, the present analysis assumes that this does not occur. The analysis of water coning will be the topic of future investigation.

3.0 NUMERICAL MODEL

The numerical model developed to solve Eqs. 4, 5, 6, and 7 is described in this section. The equations were linearized where appropriate to reduce computational costs. Code verification satisfies the question of accuracy concerning the linearization. The momentum equations and conservation of mass are used to solve for the flows. The flows are subsequently used in the solution of the energy equation. There is no iteration between the flow solution and thermal solution within a given time step. This approach reduces the coupling between the flow and thermal solutions and saves considerable computational expense. In spite of the reduced coupling, test case solutions compared very well with solutions from the one-dimensional model for which the coupling was available.⁽¹⁾ Also, mass and energy balances used as checks in the two-dimensional model were satisfactory.

3.1 FLOW SOLUTION

The continuity and momentum equations are solved simultaneously to provide the pressure and flow distributions within the porous zone and the wellbore. In general, it is computationally convenient to solve the continuity and momentum equations in terms of $\phi\rho$ and $\phi\rho\vec{V}$. In difference form these equations can be written as

- Continuity

$$\frac{(\phi\rho)_{i,k}^{n+1} - (\phi\rho)_{i,k}^n}{\Delta t} + \nabla \cdot (\phi\rho\vec{V})^{n+1} = 0 \quad (9)$$

- Momentum

$$\phi\nabla p^{n+1} = -R^n(\phi\rho\vec{V})^{n+1} + (\phi\rho)\vec{g} \quad (10)$$

The momentum equation has been linearized for numerical purposes by the indication that the coefficients R (defined for Eqs. 5 and 6) be evaluated at time n . Also, in the momentum equation $\phi\rho$ is evaluated at time n .

The solution of Eqs. 9 and 10 is based on iterative correction of the dependent variables, these being P , $\phi\rho$, and $\phi\rho\vec{v}$. At some point in the iterations the current solution values are different from the actual solution values by some correction. An improved solution at iteration $\ell+1$ would be

$$\left. \begin{aligned} p^{\ell+1} &= p^{\ell} + \delta P \\ (\phi\rho)^{\ell+1} &= (\phi\rho)^{\ell} + \delta(\phi\rho) \\ (\phi\rho\vec{v})^{\ell+1} &= (\phi\rho\vec{v})^{\ell} + \delta(\phi\rho\vec{v}) \end{aligned} \right\} \quad (11)$$

Equation 11 is substituted into Eqs. 9 and 10 to obtain

- Continuity

$$\frac{(\phi\rho)^{\ell} + \delta(\phi\rho) - (\phi\rho)^n}{\Delta t} + \nabla \cdot \left\{ (\phi\rho\vec{v})^{\ell} + \delta(\phi\rho\vec{v}) \right\} = 0 \quad (12)$$

- Momentum

$$\phi \nabla (p^{\ell} + \delta P) = - R^n \left\{ (\phi\rho\vec{v})^{\ell} + \delta(\phi\rho\vec{v}) \right\} + (\phi\rho)^n \vec{g} \quad (13)$$

Since the solution at iteration ℓ is known, then Eqs. 12 and 13 are solved for the corrections, which are effectively used to obtain the improved solution at $\ell+1$. Equation 12 is rearranged to solve for the correction terms as

$$\frac{\delta(\phi\rho)}{\Delta t} + \nabla \cdot \left\{ \delta(\phi\rho\vec{v}) \right\} = - \left\{ \frac{(\phi\rho)^{\ell} - (\phi\rho)^n}{\Delta t} + \nabla \cdot (\phi\rho\vec{v})^{\ell} \right\} \quad (14)$$

To get Eq. 14 in terms of one unknown, the correction terms are written in terms of the pressure correction as

$$\delta(\phi\rho) = \frac{\partial(\phi\rho)}{\partial P} \delta P \quad (15)$$

and

$$\delta(\phi\rho\vec{V}) = - \frac{\partial(\phi\rho\vec{V})}{\partial P} \delta P \quad (16)$$

To use Eq. 16 the flow derivative, i.e., the coefficient of δP , must be written in terms of known quantities. This begins by solving Eq. 10 for $\phi\rho\vec{V}$ after iteration ℓ . This yields

$$(\phi\rho\vec{V})^\ell = - \frac{1}{R^n} \left\{ \phi \nabla P^\ell - (\phi\rho)^n \vec{g} \right\} \quad (17)$$

Now Eq. 17 is substituted into Eq. 13. The result reduces to

$$\phi \nabla(\delta P) = - R^n \left\{ \delta(\phi\rho\vec{V}) \right\} \quad (18)$$

By Eqs. 16 and 18 the flow derivative is

$$\frac{\partial}{\partial P} (\phi\rho\vec{V}) = \frac{\phi}{R^n} \nabla \quad (19)$$

Note that the flow derivative is a vector operator.

By inclusion of Eqs. 15, 16, and 19, Eq. 14 becomes

$$\left\{ \frac{1}{\Delta t} \frac{\partial(\phi\rho)}{\partial P} \right\} \delta P - \nabla \cdot \left\{ \left(\frac{\phi}{R^n} \nabla \right) \delta P \right\} = - \left\{ \frac{(\phi\rho)^\ell - (\phi\rho)^n}{\Delta t} + \nabla \cdot (\phi\rho\vec{V})^\ell \right\} \quad (20)$$

If continuity were satisfied after iteration ℓ , then the right side of Eq. 20 would be zero and the solution would have been achieved. In general there is some continuity error at iteration ℓ . This is defined as

$$DC^\ell = \frac{(\phi\rho)^\ell - (\phi\rho)^n}{\Delta t} + \nabla \cdot (\phi\rho \vec{V})^\ell \quad (21)$$

The final form of the equation used to obtain the flow solution is

$$\left\{ \frac{1}{\Delta t} \frac{\partial(\phi\rho)}{\partial P} \right\} \delta P - \nabla \cdot \left[\left\{ \frac{\partial}{\partial P} (\phi\rho \vec{V}) \right\} \delta P \right] = -DC^\ell \quad (22)$$

This equation is used to solve for the pressure correction, δP . The continuity error, DC^ℓ , is based on a set of flows, determined at iteration ℓ , that do not satisfy continuity. The pressure correction is an adjustment of the pressures so that the resultant flows will decrease the continuity error. Equation 15 is subsequently solved for the density correction. Equations 16 and 19 are used to obtain the flow correction. The correction terms are applied in Eq. 11 to get the solution values at iteration $\ell+1$. The iterations are continued until the continuity error is satisfactorily small.

The numerical solution of Eq. 22 is based on the finite difference grid system shown in Figure 2. All material properties and state conditions are defined at the centers of the continuity cells at coordinate $(\bar{i}, \bar{k})$. Note the convention that the conditions defined at $(\bar{i}, \bar{k})$ are denoted by just i, k . The mass flux and the flow derivatives are defined for the momentum cells. In general, variable grid spacing is used whereby the momentum nodes are not necessarily located halfway between the continuity nodes. In the radial direction the mass flux is defined by $(\rho u)_{i,k}$ and the flow area is defined by $2\pi (r_i) \Delta z_k$. In the vertical direction the mass flux is defined by $(\rho w)_{i,k}$ and the flow area is defined by $2\pi (r_{\bar{i}}) \Delta r_i$.

FIGURE 2. Finite Difference Grid System

In finite difference form, Eq. 22 is

$$\begin{aligned}
 & \left\{ \frac{1}{\Delta t} \frac{\partial(\phi \rho)}{\partial P} \right\}_{i,k} \phi P_{i,k}^{\ell+1} - \frac{1}{(r_i) \Delta r_i} \left[\left\{ \frac{\partial}{\partial P} (\phi \rho u) \right\}_{i,k} r_i (\delta P_{i+1,k}^{\ell+1} - \delta P_{i,k}^{\ell+1}) \right. \\
 & \left. - \left\{ \frac{\partial}{\partial P} (\phi \rho u) \right\}_{i-1,k} r_{i-1} (\delta P_{i,k}^{\ell+1} - \delta P_{i-1,k}^{\ell+1}) \right] - \frac{1}{\Delta z_k} \left[\left\{ \frac{\partial}{\partial P} (\phi \rho w) \right\}_{i,k} (\delta P_{i,k+1}^{\ell+1} \right. \\
 & \left. - \delta P_{i,k}^{\ell+1}) - \left\{ \frac{\partial}{\partial P} (\phi \rho w) \right\}_{i,k-1} (\delta P_{i,k}^{\ell+1} - \delta P_{i,k-1}^{\ell+1}) \right] = -DC_{i,k}^{\ell}
 \end{aligned} \quad (23)$$

This reduces to the form of

$$\begin{aligned}
 & - AI_{i,k} \delta P_{i+1,k}^{\ell+1} - CI_{i,k} \delta P_{i-1,k}^{\ell+1} - AK_{i,k} \delta P_{i,k+1}^{\ell+1} - CK_{i,k} \delta P_{i,k-1}^{\ell+1} \\
 & + B_{i,k} \delta P_{i,k}^{\ell+1} = - DC_{i,k}^{\ell}
 \end{aligned} \quad (24)$$

where

$$B_{i,k} = \left[AI + CI + AK + CK + \left\{ \frac{1}{\Delta t} \frac{\partial(\phi \rho)}{\partial P} \right\} \right]_{i,k} \quad (25)$$

The basic solution method is successive line over-relaxation (SLOR). To solve by lines, either the flow connectors in the i-direction, AI and CI, or the flow connectors in the k-direction, AK and CK, and their respective pressure corrections (from iteration ℓ) are included in the right hand side of Eq. 24. In addition, an over-relaxation factor is introduced as a coefficient of the continuity error. The resultant set of equations is in standard tri-diagonal form. The solution is thereby achieved for the pressure correction.

3.2 THERMAL SOLUTION

The thermal solution is developed from Eqs. 4 and 7. The continuity equation, Eq. 4, is multiplied by $C_v T$ and the result is added to the energy equation, Eq. 7. For constant C_v the following equation can be derived.

$$\begin{aligned}
 & \left\{ (1-\phi) \rho_s C_s + \phi \rho C_v \right\} \frac{\partial T}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} (r \phi \rho u C_p T^*) + \frac{\partial}{\partial z} (\phi \rho w C_p T^*) \\
 & - C_v T \left\{ \frac{1}{r} \frac{\partial}{\partial r} (r \phi \rho u) + \frac{\partial}{\partial z} (\phi \rho w) \right\} - \left\{ \frac{1}{r} \frac{\partial}{\partial r} (K_r r \frac{\partial T}{\partial r}) + \frac{\partial}{\partial z} (K_z \frac{\partial T}{\partial z}) \right\} = 0
 \end{aligned} \quad (26)$$

The T^* designates that donor cell or upwind temperatures are to be used.

Several steps are taken to further refine Eq. 26 to enhance its adaptation to numerical form. The energy storage term for the air is small compared to the storage of thermal energy in the rock. Therefore, with little noticeable error, C_v could be replaced by C_p . This greatly simplifies the numerics of the flow terms. The heat conduction is written as the product of a heat conductance and temperature difference; e.g. in the r-direction,

$$K_r r \left. \frac{\partial T}{\partial r} \right|_{i,k} = CR_{i,k} (T_{i+1,k} - T_{i,k}) \quad (27)$$

where the subscripts refer to the grid system of Fig. 2. All the terms of Eq. 26 are multiplied by the volume of a numerical cell,

$$V_{i,k} = 2\pi(r_{\bar{i}})\Delta r_i \Delta z_k \quad (28)$$

With these modifications, the finite difference form of Eq. 26 is

$$\begin{aligned} V_{i,k} & \left\{ (1-\phi)\rho_s C_s + (\phi\rho)^n C_p \right\}_{i,k} \left(\frac{T^{n+1} - T^n}{\Delta t} \right)_{i,k} \\ & + 2\pi \Delta z_k \left\{ (r\phi\rho u)_{i,k} C_p T_{i,k}^* - (r\phi\rho u)_{i-1,k} C_p T_{i-1,k}^* \right\}^{n+1} \\ & + 2\pi(r_{\bar{i}})\Delta r_i \left\{ (\phi\rho w)_{i,k} C_p T_{i,k}^* - (\phi\rho w)_{i,k-1} C_p T_{i,k-1}^* \right\}^{n+1} \\ & - C_p T_{i,k}^{n+1} \left[2\pi \Delta z_k \left\{ (r\phi\rho u)_{i,k} - (r\phi\rho u)_{i-1,k} \right\} \right. \\ & \left. + 2\pi(r_{\bar{i}})\Delta r_i \left\{ (\phi\rho w)_{i,k} - (\phi\rho w)_{i,k-1} \right\} \right]^{n+1} \\ & - 2\pi \Delta z_k \left\{ CR_{i,k} (T_{i+1,k} - T_{i,k}) - CR_{i-1,k} (T_{i,k} - T_{i-1,k}) \right\}^{n+1} \\ & - 2\pi(r_{\bar{i}})\Delta r_i \left\{ CZ_{i,k} (T_{i,k+1} - T_{i,k}) - CZ_{i,k-1} (T_{i,k} - T_{i,k-1}) \right\}^{n+1} = 0 \end{aligned} \quad (29)$$

Flow areas are defined as

$$\left. \begin{aligned} A_i &= 2\pi\Delta z_k \\ A_k &= 2\pi(r_i)\Delta r_i \end{aligned} \right\} \quad (30)$$

An upwind or donor cell function is defined as follows:

$$\left. \begin{aligned} \text{If } (\phi\rho u)_i &> 0 & UP_i &= 1 \\ \text{If } (\phi\rho u)_i &< 0 & UP_i &= 0 \\ \text{If } (\phi\rho w)_k &> 0 & UP_k &= 1 \\ \text{If } (\phi\rho w)_k &< 0 & UP_k &= 0 \end{aligned} \right\} \quad (31)$$

With the substitution of Eqs. 30 and 31 and some rearrangement the energy equation becomes

$$\begin{aligned} & v_{i,k} \left\{ (1-\phi)\rho_s C_s + (\phi\rho)^n C_p \right\}_{i,k} \left(\frac{T^{n+1} - T^n}{\Delta t} \right)_{i,k} \\ & + A_i \left[- \left\{ CR_{i,k} - (r\phi\rho u)_{i,k} (1-UP_i) C_p \right\} T_{i+1,k}^{n+1} \right. \\ & + \left\{ CR_{i,k} + CR_{i-1,k} - (r\phi\rho u)_i (1-UP_i) C_p + (r\phi\rho u)_{i-1,k} UP_{i-1} C_p \right\} T_{i,k}^{n+1} \\ & - \left. \left\{ CR_{i-1} + (r\phi\rho u)_{i-1,k} UP_{i-1} C_p \right\} T_{i-1,k}^{n+1} \right] \\ & + A_k \left[- \left\{ CZ_{i,k} - (\phi\rho w)_{i,k} (1-UP_k) C_p \right\} T_{i,k+1}^{n+1} \right. \\ & + \left\{ CZ_{i,k} + CZ_{i,k-1} - (\phi\rho w)_{i,k} (1-UP_k) C_p + (\phi\rho w)_{i,k-1} UP_{i,k-1} C_p \right\} T_{i,k}^{n+1} \\ & - \left. \left\{ CZ_{i,k-1} + (\phi\rho w)_{i,k-1} UP_{i,k-1} C_p \right\} T_{i,k-1}^{n+1} \right] = 0 \end{aligned} \quad (32)$$

Equation 32 reduces to the following general form

$$\begin{aligned} & (-AI_{i,k} T_{i+1,k} - CI_{i,k} T_{i-1,k} \\ & - AK_{i,k} T_{i,k+1} - CK_{i,k} T_{i,k-1} + B_{i,k} T_{i,k})^{n+1} = \tau_{i,k} T_{i,k}^n \end{aligned} \quad (33)$$

where

$$B_{i,k} = (AI + CI + AK + CK + \tau)_{i,k}$$

and

$$\tau_{i,k} = \frac{V_{i,k}}{\Delta t} \left\{ (1-\phi) \rho_s C_s + (\phi \rho)^n C_p \right\}_{i,k} \quad (34)$$

After iteration ℓ the temperature deviates from the solution temperature at iteration $\ell+1$ by $\delta T^{\ell+1}$; i.e.,

$$T^{\ell+1} = T^{\ell} + \delta T^{\ell+1} \quad (35)$$

Substitution of $T^{\ell+1}$ into Eq. 33 for T^{n+1} gives, with some rearrangement,

$$\begin{aligned} & - AI_{i,k} \delta T_{i+1,k}^{\ell+1} - CI_{i,k} \delta T_{i-1,k}^{\ell+1} - AK_{i,k} \delta T_{i,k+1}^{\ell+1} - CK_{i,k} \delta T_{i,k-1}^{\ell+1} \\ & + B_{i,k} \delta T_{i,k}^{\ell+1} = DE_{i,k}^{\ell} \end{aligned} \quad (36)$$

The solution technique is essentially identical to that used for the pressure solution, SLOR. The solution is achieved by evaluating the energy error after iteration ℓ , DE^{ℓ} . The set of $\delta T^{\ell+1}$ that reduce the energy error is determined. Iterations continue until the energy error is satisfactorily small.

3.3 BOUNDARY CONDITIONS

Specific boundary conditions are required for both the flow and thermal solutions. The only type of boundary condition used in the flow analysis was that of specified mass flow. To achieve the desired boundary mass flow, the flow connectors based on Eq. 19 were set to zero. In the iteration cycle, if the flow was specified so that the flow connectors were zero, then the adjustment of the flow for a pressure correction by Eq. 16 would be zero. This also applied at impermeable boundaries where the flow is specified as zero. Internal boundaries can also have specified flows by setting the appropriate flow connectors to zero. In particular, the bottom of the wellbore was assumed to be closed to flow. This required the use of an internal boundary condition for cases when the producing length of the wellbore did not extend through the full thickness of the reservoir.

The two transport mechanisms for thermal energy are conduction and convection. To create a thermally insulated boundary the connectors representing these mechanisms are set to zero. These connectors are the coefficients of temperatures in Eq. 32 and are reduced to AI, CI, AK, and CK in Eq. 33. Constant-temperature boundaries, such as those required for the air entering the wellbore during the charging cycle, only require that the thermal connectors be calculated and applied according to the defining equations. Temperature corrections, DT of Eq. 36, are not calculated for the boundary nodes, since the temperature is specified.

3.4 CODE VERIFICATION

The validity of the one-dimensional numerical models has been discussed in previous reports^(1,2). The two-dimensional model employs a different solution scheme, not only due to the addition of the second dimension but also due to a new scheme for testing and iterating to achieve convergence of the flow and thermal solutions. However, despite

these changes, the two-dimensional model can replicate the solutions of the one-dimensional model for dry conditions. Although Ramey's⁽⁴⁾ method for evaluating wellbore heat transfer could not be applied to the cyclic conditions of this analysis, a prediction based on his method was compared against a solution developed for continuous injection using the numerical model. The agreement was satisfactory.

These internal checks and the consistent and explainable results obtained in the analysis suggest that the numerical computer model are valid, given the assumptions that were used.

4.0 ANALYSIS AND RESULTS

The development of the multi-dimensional numerical model has provided the capability to investigate several important aspects of reservoir behavior that were previously beyond the consideration of the available one-dimensional models. The additional phenomena that could be evaluated were generally related to either the wellbore heat transfer problem or to the fluid and thermal behavior of the porous zone.

The wellbore heat transfer analysis provided results which allowed the air temperature in the wellbore at the top of the porous zone to be approximated as a constant. This made it possible to uncouple the solutions for the wellbore and the porous zone. The wellbore heat transfer problem was investigated while ignoring the details of the fluid and thermal distributions in the porous zone. The approximation of the boundary condition inlet air temperature allowed the details of the porous zone to be evaluated without simultaneously solving for the thermal solution in the wellbore. This uncoupling led to significant savings of computational expense.

Many reservoir parameters were evaluated using the one-dimensional models developed previously^(1,2). It was possible to characterize the effect of a parametric difference in permeability, porosity, temperature of injected air, etc. on the pressure solution. The same analysis done with a multi-dimensional model would undoubtedly lead to the same conclusions, although computational costs would be greater. Therefore, the two-dimensional model was reserved for the analysis of parameters and the description of phenomena that were encountered only by the inclusion of the vertical dimension.

4.1 REFERENCE CONDITIONS

The two-dimensional reservoir analysis is based upon a set of reference conditions applied to the reservoir geometry, material properties and operating conditions. The values used for these parameters are given in Table 1. These values are consistent with those used in the

TABLE 1. Reference Reservoir Conditions

<u>Parameter</u>	<u>Reference Value</u>	
Geometry		
Reservoir Depth	518.2 m	(1700 ft)
Vertical Thickness	30.5 m	(100 ft)
Reservoir Diameter	121.2 m	(400 ft)
Well Diameter	0.17 m	(7 in.)
Producing Length	30.5 m	(100 ft)
Properties		
Porosity		20%
Permeability		500 md
Rock Thermal Conductivity	$2.16 \frac{\text{W}}{\text{m} \cdot ^\circ\text{C}}$	$(1.25 \frac{\text{Btu}}{\text{hr} \cdot \text{ft} \cdot ^\circ\text{F}})$
Rock Thermal Capacity	$2.62 \frac{\text{MJ}}{\text{m}^3 \cdot ^\circ\text{C}}$	$(39.1 \frac{\text{Btu}}{\text{ft}^3 \cdot ^\circ\text{F}})$
Operating Conditions		
Nominal Pressure	5070 kPa	(50 atm)
Air Flow Rate		
Injection	$5.45 \frac{\text{kg}}{\text{s}}$	$(12.0 \frac{\text{lbm}}{\text{s}})$
Extraction	$7.17 \frac{\text{kg}}{\text{s}}$	$(15.8 \frac{\text{lbm}}{\text{s}})$
Percent of Air Cycled		12%
Injection Temperature	232°C	(450°F)
Earth Surface Temperature	21.1°C	(70°F)
Geothermal Gradient	0.0017°C/m	(0.001°F/ft)
Initial Reservoir Temperatures Determined by Geothermal Conditions		

- one-dimensional reservoir analyses^(1,2). The following discussion is provided to avoid confusion regarding the definition of these parameters.

The desired nominal reservoir pressure was 5070 kPa (50 atm). Based on a hydrostatic head of 9.73 kPa/m (0.43 psi/ft), the depth required to conform to the nominal pressure was approximately 518.2 m (1700 ft). Numerically, the vertical center of the porous zone is fixed at reservoir depth.

The percent of air cycled is the variation between the weekly maximum and minimum values of the stored air mass in the reservoir. It is defined as

$$\lambda = \frac{M_{\max} - M_{\min}}{M_{\max}} \quad (37)$$

The injection and extraction air flow rates are determined to provide the appropriate air cycling based on the weekly cycle which is described in the next section.

The surface temperature of the earth and the geothermal gradient are based on values in two references that dealt with wellbore heat transfer.^(4,5)

4.2 WEEKLY CAES CYCLE

Included in the reference conditions is the specification of a weekly operating cycle that defines when the reservoir is to be charged or discharged and when there is no air flow to the reservoir. The operating cycle is nearly identical to that used for the one-dimensional analysis of dry reservoirs. The development of the cycle is described in the report issued on that analysis.⁽¹⁾

The weekly reservoir pressure cycle applied to the reference case of this analysis is shown in Figure 3. The weekly cycle begins and ends on Friday at 8:00 p.m. The fraction of the weekly stored mechanical energy supplied to the reservoir on the weekend is specified

FIGURE 3. Reference Weekly Reservoir Pressure Cycle

as approximately 0.40. The duration of the daily charge and discharge cycles is 10 hours each. The reservoir is closed for 2 hours between each daily cycle. On the weekend, a 10-hour charging cycle begins on Friday at 8:00 p.m. It is followed in order by 18 hours of no flow, 16 hours of charging and 16 hours of no flow which ends on Monday morning at 8:00 am. This cycle approximates the availability and demand cycle for the CAES facility.

4.3 WELLBORE HEAT TRANSFER

Heat losses between the wellhead and the reservoir can have a significant impact on thermal energy recovery, thermal cycling, and thermal distributions. From a performance viewpoint the thermal energy recovery is possibly the most important of these parameters. For previous analyses with a one-dimensional radial flow model, thermal energy recovery efficiencies of 77% in the first week of cycling and

85% after one year of cycling were reported.⁽⁶⁾ These values suggested that porous-media reservoirs would perform as very efficient thermal energy storage devices. However, these optimistic numbers were based on the built-in assumption that the path between the compressor and the reservoir was perfectly insulated. Since it would be difficult to approach this insulated condition, the magnitude of these recovery efficiencies are probably not realistic. (Given the assumption, comparative results of that study are still valid.) It follows that if heat losses are expected in the wellbore, then the previously reported temperature distributions and the extremes of thermal cycling should also be affected. While the temperature distributions and thermal cycling do not directly involve determining the thermal efficiency of the CAES facility, they are extremely important in terms of the integrity of the underground portion of the system. Thermal cycling in the wellbore and well casing could lead to problems including air leakage around the caprock penetration, fatiguing of casing joints, and damage to completion cements. Temperature distributions and thermal cycling in the reservoir and caprock impact the structural integrity of the storage zone. In terms of the flow response of the system, the underground thermal behavior is important because of the temperature effect on viscosity, and, therefore, the pressure differentials required to drive the system.

To evaluate the effect of wellbore heat transfer on thermal energy recovery, thermal cycling and temperature distributions, it would be most appropriate to use analytic solutions already available in the literature. The information that is available provides solutions for quasi-steady-state thermal conditions for constant flow to or from a reservoir. The solutions were generated for application to geothermal sources⁽⁴⁾ and to thermal recovery techniques in oil production⁽⁵⁾, specifically steam injection. The solutions would be difficult, if not impossible, to apply to the cyclic conditions involved in CAES. Therefore, the computer model was used to evaluate the wellbore heat transfer problem.

Four parameters related to wellbore heat transfer were identified as having the potential to affect the thermal behavior of the underground system. These included wellbore insulation, preheating, air storage volume, and porous zone depth. Wellbore insulation involves the modeling of an annular region of insulating material around the wellbore. Preheating refers to the development of the cushion air storage bubble using heated air. The air storage volume will affect the optimum air mass flow rates, and, therefore, the thermal energy entering the underground system. The depth of the porous zone similarly affects the air mass flow rates in addition to establishing the length over which wellbore heat transfer may occur.

To characterize the thermal response associated with each of the parameters mentioned above, six cases were defined for analysis. These cases are given in Table 2. Each case was simulated for 1 year of air mass cycling. The results of these analyses are presented in the remainder of this section.

TABLE 2. Parametric Cases for Wellbore Heat Transfer Analysis

<u>Case</u>	<u>Initial Thermal Conditions</u>	<u>Wellbore Insulation</u>	<u>Reservoir Depth (m)</u>	<u>Reservoir Thickness (m)</u>	<u>Other Conditions</u>
1	Geothermal	No	518.2	30.5	Reference
2	Preheated	No	518.2	30.5	"
3	Geothermal	No	518.2	61.0	Double Air Mass Flow Rates
4	Geothermal	Yes	518.2	30.5	Reference
5	Preheated	Yes	518.2	30.5	"
6	Geothermal	No	1036.3	30.5	Double Air Mass Flow Rates

A summary of the results characterizing the thermal energy recovery is given in Figure 4. In addition to results for the six cases defined in Table 2, the results obtained by the one-dimensional analysis are also presented. The one-dimensional result essentially represents a perfectly insulated wellbore. The comparison suggests the significant potential for wellbore heat losses to reduce the recovered thermal energy.

FIGURE 4. Effect of Wellbore Heat Transfer on Thermal Energy Recovery

In addition to comparing the results on the basis of thermal energy recovery, the effects of insulation, preheating, air storage volume, and depth on thermal cycling in the wellbore are also presented. For the reference case, which is defined by the reference conditions of Table 1 and includes no insulation or preheating, the thermal cycling in the wellbore during the first week and after 1 year of simulated mass cycling is shown in Figures 5 and 6, respectively. These results are similar to the results reported for the one-dimensional analyses^(1,2) in that the well boundary of the reservoir is subjected to decreasing extremes of temperatures although the temperatures are generally higher as thermal development proceeds. A significant result of wellbore heat transfer is that the highest temperatures and the largest amplitudes of temperature cycling are observed in the wellbore very near the earth surface. While

FIGURE 5. Thermal Cycling of the Air in the Wellbore for the Reference Conditions, Week 1

FIGURE 6. Thermal Cycling of the Air in the Wellbore for the Reference Conditions, Week 52

wellbore heat losses decrease the recovery thermal energy, it offers the advantage of subjecting the reservoir to less severe thermal conditions. The other results will be compared against these results obtained for the reference conditions.

4.3.1 Insulation

For a given set of operational conditions, the results shown in Figure 4 suggest that the parameter having the greatest impact on thermal energy recovery is the wellbore insulation. The comparison of curves 1 and 7 in Figure 4 show, for the conditions of this analysis, that about half of the thermal energy that is recoverable from the reservoir can be lost due to heat transfer through an uninsulated wellbore. The benefit of a moderate amount of insulation is shown by curve 4.

The insulated condition represented here involves an annular region of insulation material applied to the outside of the wellbore. The annular spacing was 10.16 cm (4.0 in.) and it allowed for a well tubing wall thickness of 1.27 cm (0.5 in.). Thus, the outer diameter of the insulation was 40.64 cm (16.0 in.). The insulation material used in the model was perlite. This material was referred to by Ramey for an application to wellbore insulation.⁽⁴⁾ The relevant properties of perlite include conductivity (0.216 W/m-°C (0.125 Btu/hour-ft-°F)), density (721.5 kg/m³ (45.0 lbm/ft³)) and specific heat (1004 J/kg-°C (0.24 Btu/lbm-°F)).⁽⁷⁾

Thermal cycling for the insulated wellbore is shown in Figures 7 and 8 for the first week and after 1 year of simulated reservoir operation, respectively. These results show the decrease in the extremes of thermal cycling and the generally increased temperatures occurring as thermal

FIGURE 7. Thermal Cycling of the Air in an Insulated Wellbore, Week 1

FIGURE 8. Thermal Cycling of the Air in an Insulated Wellbore, Week 52

development proceeds. However, it is obvious that the overall thermal behavior of the insulated condition is unique by comparison to the reference case. While insulation dramatically improves the thermal energy recovery, it does so at the expense of exposing the wellbore and reservoir to generally higher temperatures and greater extremes of thermal cycling.

A surprising condition observed for these results of thermal cycling is that during reservoir closure, the air temperature in the insulated wellbore decreases more than that for the uninsulated wellbore. This behavior deserves explanation. The numerical model dictates that the heat transfer between the air and the wall of the wellbore during reservoir closure is based on the conductivity of the air since the convective heat transfer coefficient is zero for the no-flow condition. Heat transfer away from the wall is based on the conductivity of the

insulation. Numerically, this forms a series thermal resistance which is the basis for the heat conductance term in Eq. 27. When the conductivity of the air is less than that of the insulator cell, which would generally be the case, the radial heat transfer is controlled by the conductivity of the air and is almost independent of the conductivity of the insulator cell. As long as the thermal resistance is controlled by the conductivity of the air, then the heat transfer during closure is dependent primarily on the temperature gradient at the wellbore, regardless of the conductivity of the insulation. The insulated wellbore shows more heat loss than the uninsulated wellbore during closure because the temperature gradients are steeper for the insulated case. The steeper temperature gradients result because, during the reservoir charging cycle, the heat transfer from the air to the wall is based on the forced convection heat transfer coefficient. This coefficient is of such magnitude that now the conductivity of the insulator cell dominates the thermal resistance. Thus, during the charging cycle, the insulation reduces the heat transfer, subsequently maintaining a steeper temperature gradient at the wellbore.

This explanation suggests the factors controlling the exhibited thermal behavior. However, the behavior is based on the results obtained from the numerical model, subject to the assumptions and resolution of the grid spacing. In particular, the numerical cell adjacent to the wellbore includes the well casing, the insulation, and a portion of the surrounding rock. Thus, on a local basis, the thermal behavior could be significantly different than the bulk effects shown here. Also, some of the behavior can be attributed to the lower heat capacity of the insulation material. And finally, the thermal cycling is shown for the air in the wellbore. Because of the greater thermal inertia of the surrounding material there is actually very little thermal cycling in the material adjacent to the wellbore, above the reservoir.

A final observation to be made is that for the insulated case the computer model predicts that heat is lost from the air to the wellbore throughout the discharge cycle as well as during the charging cycle. That is, there is no recovery of the thermal energy that is lost to the

overburden and caprock during the charging cycle. This result occurs because of the higher temperatures of the air leaving the reservoir and the existing radial temperature gradients adjacent to the wellbore and above the reservoir. For the uninsulated wellbore some thermal recovery is exhibited above the reservoir during the discharge cycle.

4.3.2 Preheating

Preheating of the underground system was intended to simulate the thermal condition resulting from the injection of heated air during bubble development. Preheating was accomplished by continuously injecting heated air until the nominal stored air mass of the system had been injected. The resultant thermal condition was found to be very sensitive to the air mass injection rates. For the reference cyclic mass injection rate of 5.45 kg/s (12 lbm/s), the nominal stored air mass of a single well could be injected into the reference reservoir in 198 hours. The temperature of the air in the wellbore during this simulated bubble development is shown by Figure 9. The effect of flow rate is demonstrated by comparison of this result to Figure 10 for which the flow rate was lowered an order of magnitude, resulting in a bubble development time of 1980 hours.

To quantify an appropriate air mass flow rate to use to develop the preheated thermal condition, a method described by Katz and Coats was used.⁽⁸⁾ Calculations using their model showed that the bubble development air mass injection rate would be about twice the reference cyclic injection rate used in this analysis. As the bubble expands and the number of wells inside the bubble increases, the average injection rate per well decreases. However, the Katz and Coats model does not take into account the potential to enhance the bubble growth rate by producing aquifer water from wells just outside the air-water interface. This would allow the average air mass injection rate per well to be higher than that predicted by their model. Thus, whatever the flow rate that is used for preheating, it is, at best, an order of magnitude approximation. As a result of this deliberation, the air mass injection

FIGURE 9. Air Temperature at Depth in the Wellbore During Simulated Bubble Development, Air Mass Flow Rate = 5.45 kg/s (12 lbm/s)

FIGURE 10. Air Temperature at Depth in the Wellbore During Simulated Bubble Development, Air Mass Flow Rate = .545 kg/s (1.2 lbm/s)

rate used to develop the preheated thermal condition for cases 2 and 5 of Table 2 was chosen as 5.45 kg/s (12 lbm/s), the reference value cyclic injection rate.

The effect of preheating on the thermal energy recovery is shown in Figure 4, where cases 2 and 5 should be compared to the results of cases 1 and 4, respectively, for which there was no preheating. The results show that in the first few weeks of reservoir operation the effect of preheating is to significantly improve the thermal energy recovery. However, the thermal condition established by preheating is rapidly dissipated, becoming nearly indistinguishable from the comparative cases after only 20 weeks.

This speedy diffusion of the preheat thermal energy suggests that the selection of the air mass flow rate used to develop the preheated condition was not terrifically important. Another factor that diminishes the significance of the flow rate is that it is possible that a considerable delay will occur between the conclusion of air injection at a particular well and the initial reservoir operation. This would happen if the bubble development injection wells were those at the air-water interface while the wells in the interior of the bubble were closed or merely provided pressure maintenance. In the event of such a delay, the thermal condition due to preheating would diffuse. In Figure 11, the thermal energy recovery in the first week of reservoir operation is shown as a function of the delay time. These results were established for the case of no wellbore insulation. These results and Figure 4 indicate that if a delay of 6 weeks or more occurs then the influence of preheating on thermal energy recovery should be almost unnoticable.

The effect of preheating on thermal cycling is shown by comparison of Figures 12 and 13 to Figures 5 and 7, respectively. This reveals that preheating significantly reduces the thermal cycling in the wellbore during the initial weeks of reservoir operation. However, the process of diffusion of the preheat thermal energy, which is openly displayed by the significantly increased heat losses in the wellbore during the

FIGURE 11. Thermal Recovery Efficiency in the First Week of Reservoir Operation as a Function of the Delay Between Preheating by Bubble Development and the Start of Reservoir Operation

FIGURE 12. Thermal Cycling of the Air in the Wellbore for a Preheated Reservoir, Week 1

FIGURE 13. Thermal Cycling of the Air in an Insulated Wellbore for a Preheated Reservoir, Week 1

extraction cycles, causes the thermal cycling to approach that of the non-preheated cases. As a result, the thermal cycling for the noninsulated and insulated cases at the end of 1 year is independent of the preheated initial condition and is, therefore, indistinguishable from the thermal cycling shown by Figures 6 and 8, respectively.

4.3.3 Air Mass Flow Rate

The air mass flow rate is important to the wellbore heat transfer problem because it determines the total thermal energy injected to the reservoir. If the weekly cycle is fixed, then the air mass flow rates are based only on the nominal stored air mass in the reservoir. This air mass depends on the air storage volume and air density. The effect of these two parameters on the air mass flow rate and, thereby, the wellbore heat transfer problem is discussed below.

4.3.3.1 Air Storage Volume

Based on the fixed weekly cycle, the air mass flow rates for a reservoir at a given depth are linearly proportional to the air storage volume. For a given depth, which establishes the nominal air density, and a given wellbore diameter, the air mass flow rates subsequently define the air velocity in the wellbore. Therefore, the air mass flow rate determines the total thermal energy injected into the wellbore, and the air velocity determines the heat transfer coefficient and the residence time for the air in the wellbore. In this way, the wellbore heat transfer is established.

In Figure 4, curve 3 is drawn for the case of doubled air mass flow rate that is based upon a doubled reservoir thickness. Comparison of curves 1 and 3 in Figure 4 shows that increasing the air mass flow rate at the reference pressure results in a significant increase in thermal energy recovery. This result is expected in consideration of the combined effects of the energy input, flow velocity, and heat transfer coefficient. As with other cases that show improved thermal energy recovery, the thermal cycling of the air in the wellbore at reservoir depth for case 3 is greater than that for case 1. The thermal cycling for case 3 in the first week of reservoir operation is shown in Figure 14. While the extremes of thermal cycling and the temperatures are generally higher, the fundamental characteristic of the cycling for case 3 are very similar to those of case 1. The same is true for the results after 1 year of reservoir operation.

4.3.3.2 Air Density

The nominal air density is based upon the nominal reservoir pore pressure at depth. Because the nominal reservoir pressure is linearly dependent on the depth, then so too is the stored air mass for a fixed reservoir volume. To conform to the reference weekly cycle the air mass flow rates must be similarly dependent on depth. Thus, for a change of air density, which implies a change of reservoir depth, the flow velocities and the heat transfer coefficients in the wellbore are essentially unaffected. Thus, the constraint of a fixed weekly cycle implies that the wellbore heat transfer problem is independent of depth.

FIGURE 14. Thermal Cycling of the Air in the Wellbore for Doubled Air Mass Flow Rates, Week 1

In case 6, defined in Table 1, the depth was doubled. The nominal reservoir pressure was, therefore, doubled except for a small influence of the geothermal gradient. While the air mass flow rates were doubled, the flow velocities in the wellbore were not affected because of the effect of pressure on air density. The wellbore heat transfer coefficients were, as a result, identical to those for the reference case. While doubling the air mass flow rates doubled the thermal energy input to the underground system, the air was essentially in transit in the wellbore twice as long. Thus, the overall heat transfer was nearly unaffected. As shown by Figure 4, the thermal energy recoveries for cases 1 and 6 are identical. The thermal cycling characteristics for cases 1 and 6 are similarly identical. Thus, the thermal solution is essentially independent of reservoir depth if the flow rates are constrained to a given weekly cycle and the air storage volume is fixed.

4.4 RESERVOIR ANALYSIS

The reservoir analysis using the two-dimensional model was restricted to the characterization of the fluid and thermal response of the reservoir to conditions that were encountered in the porous zone by virtue of inclusion of the vertical dimension. The principal measure of the fluid response was the quasi-steady-state difference between the wellbore boundary pressure and the reservoir average pressure. The thermal response that was of interest was the temperature distribution. In general, factors which perturb the flow field and the resultant quasi-steady-state pressure difference also affect the temperature distributions because the primary mode of energy transport is by convection.

The results of the wellbore heat transfer analysis permitted the fluid and thermal solutions for the reservoir to be decoupled from the wellbore solutions. Since pressure losses are additive, the decoupling represented no sacrifice for the flow solution. The pressure losses in the porous zone were independent of pressure losses in the wellbore. In contrast, the air temperature in the wellbore at the top of the porous zone during the charging cycle was observed to be very dependent on upstream conditions. However, to decouple the thermal solution in the reservoir from that in the wellbore, it was necessary to use an approximate boundary temperature. From the results for the insulated wellbore heat transfer analysis, shown by Figures 7 and 8, an air temperature of 400°F was chosen for the boundary condition during the charging cycle. Those figures show that the accuracy lost by using a constant boundary temperature rather than tracing the predicted boundary temperature should not be significant.

The porous zone and the confining strata can be further decoupled without loss of distinguishable accuracy. By assumption, there is no mass transport through the vertical boundaries. A preliminary analysis was done to test the assumption of no heat transport through the vertical boundaries. The result showed that this assumption had no definable effect on the pressure response. However, the temperatures in the

porous zone along the boundaries are affected slightly. But after 1 week of simulated reservoir operation with both thermally insulated and uninsulated vertical boundaries, the thermal energy recovery from the porous zone varied by less than 0.1% between the two cases. Thus, the reservoir analysis was performed without the conduction heat transfer to the vertical boundaries. Checks were made and discrepancies in the assumption are pointed to in the discussion on the thermal response. In general, however, the loss of accuracy is very small, while the assumption allows costly numerical resolution along the boundary to be avoided. Furthermore, for this analysis the temperature distributions in the reservoir were secondary in importance to the pressure response, thus lending added justification to the assumption.

4.4.1 Pressure Response

The pressure response of the porous zone is developed by initially considering the weekly cycle for the reservoir average pressure as shown by Figure 3. When this cycle was applied to the reference reservoir, the wellbore pressure at the top of the porous zone behaved as shown in Figure 15. When the reservoir is closed the fluid pressure stabilizes to a uniform value. In the subsequent charge or discharge cycles there is an initial transient in the vicinity of the wellbore where the compressibility of the air is important. Following this transient, the air pressure in the wellbore and the reservoir pressure change at nearly identical rates. This quasi-steady-state condition is observed when the curves for the well pressure and reservoir pressure become parallel. This quasi-steady-state pressure difference is important because, as a pressure loss, it represents the additional compression power required to charge a reservoir at the specified air mass flow rates and subject to the flow resistance of the reservoir. It similarly represents power losses during discharge.

In addition to representing the work required to charge the reservoir, the quasi-steady-state pressure difference also adds to the total pressure swing that the reservoir experiences each week. From Figure 15 the variation

FIGURE 15. Weekly Cycle of the Wellbore and Reservoir Average Pressure for the Reference Conditions

in reservoir average pressure over the week is about 621 kPa (90 psi). The system pressure losses on both the charge and discharge cycles must be added to this to determine the total pressure swing seen by the above-ground equipment. Matching the system performance to above-ground equipment will be more restrictive for large pressure swings. Therefore, it is important to be able to predict the contribution of porous zone pressure losses to the total system losses.

It is observed in Figure 15 that the pressure response for each charge or discharge cycle is essentially identical. Thus, to evaluate comparative quasi-steady-state pressure differences, it was only necessary to consider the initial charge cycle. Furthermore, a preliminary analysis with the two-dimensional model showed that the fundamental characteristics of the pressure response were independent of the thermal condition. This agreed with a conclusion reached for a similar situation using the

one-dimensional model.⁽¹⁾ It implies that the conclusions that would result from a comparison of pressure responses obtained by variation of reservoir parameters would not be dependent on the thermal condition for which the responses were obtained. Thus, it is of no consequence to this analysis that the initial thermal state for the charge cycle is based on geothermal conditions.

The parameters that were encountered in the reservoir by the inclusion of the vertical dimension and that were expected to have an effect on the quasi-steady-state pressure difference were the producing length of the wellbore, the permeability ratio, and stratification of permeability. The producing length of the wellbore represents the minimum flow area through which the air entering or leaving the porous zone must pass. The permeability ratio is a term used to describe the ratio of the vertical to horizontal permeability. Stratification of permeability deals with horizontal layers within the porous zone that exhibit permeability that is different from the surrounding layers, although within a given layer the permeability is isotropic.

4.4.1.1 Producing Length of the Wellbore

The producing length of the wellbore represents the minimum flow area through which the air entering or leaving the porous zone must pass. For a given air mass flow rate and air density, this flow area determines the maximum air velocity in the porous zone. Since the pressure gradient is dependent upon the velocity, the producing length of the wellbore is largely responsible for determining the quasi-steady-state pressure difference in the reservoir.

The results presented show that it is most desirable, with respect to the pressure response, to have the producing length of the wellbore extend entirely through the porous zone. However, there are conditions for which the wellbore may not or should not extend to the bottom of the porous zone. An example of likely occurrence is that the region underlying the porous zone contains liquid water. Completion of the wellbore to this boundary could result in infiltration of water into the wellbore

during the production cycle. With such possibilities it was necessary to evaluate the sensitivity of the pressure response to the producing length of the wellbore so that the proper amount of control can be exercised while establishing this length during the well completion process.

The pressure response for various producing lengths is shown in Figure 16. The reference conditions were applied to the analysis. The only variation is the producing length. The response of the reservoir average pressure is the same for all cases. The pair of lines including

FIGURE 16. Reservoir Inlet Pressure versus Time for Various Producing Length (m (ft)), Reservoir Thickness = 30.5 m (100 ft)

the 30.5-m (100-ft) producing length and the reservoir pressure are the same as those shown for the first 10 hours of Figure 15. The producing length is measured from the top of the 30.5-m- (100-ft-) thick porous zone. This result shows how the pressure transient develops for each case. After about 2 hours of charging, quasi-steady-state is reached. Figure 17 provides the variation of the quasi-steady-state pressure difference as a function of the producing length.

It was not at first evident that the mechanism for the behavior of the quasi-steady-state pressure difference was determined, to a large extent, by the flow area at the wellbore. The issue was confused by the nonlinear behavior of the function shown in Figure 17. Two cases were run that led to the observation. In the first, the producing length of the wellbore was 15.2 m (50 ft), with the producing section beginning 6.72 m

FIGURE 17. Quasi-Steady-State Pressure Difference Versus Producing Length, Reservoir Thickness = 30.5 m (100 ft)

(25 ft) below the top of the reservoir. The reservoir pressure loss was 294.4 kPa (42.7 psi). For the same case with the producing section beginning at the top of the reservoir, the pressure loss was 302.7 kPa (43.9 psi). The case of lower pressure drop apparently results because the high-velocity flows near the wellbore dissipate more rapidly because the air mass can spread upward as well as downward once it has passed through the wellbore. In a second case, the reservoir thickness was set at 15.2 m (50 ft) and the porosity at 0.40. Such a reservoir would have the same storage volume as the reference reservoir and, therefore, could be subjected to the same weekly cycle and air mass flow rates. With the producing section of the wellbore extending through the 15.2-m- (50-ft-) thick porous zone, the resultant reservoir pressure loss was 337.9 kPa (49.0 psi). In this case, the extra pressure loss was apparently due to the fact that the air mass could not spill out vertically after passing through the wellbore. As a result, flow velocities and, therefore, the pressure loss are generally higher. These results suggested that it was the flow area at the wellbore, rather than the downstream conditions, that controlled the quasi-steady-state pressure loss. The non-linear behavior displayed in Figure 17 is, however, created by the so-called downstream flow. As the producing length decreases, the air velocities in the vertical direction must increase. These vertical flows result in additional pressure losses.

While it is obvious from these results that the producing length of the wellbore can dramatically affect the pressure loss in the reservoir, the significance of the magnitude of the loss cannot be fully judged until total system performance and costs are simultaneously considered. However, some numbers are available for comparison. Katz and Lady⁽⁹⁾ discuss a design for which the weekly pressure swing at the reservoir is 855.0 kPa (124 psi) for a system with a nominal pressure of 4054 kPa (40 atm). The pressure cycle at the plant is 1055 kPa (153 psi), the additional amount being the result of friction losses in the delivery lines and in the wellbore. Since their analysis considered total system performance and cost, these numbers may be considered typical. By

comparison, the results of this analysis show weekly extremes of wellbore pressure that differ by 979.1 kPa (142 psi) for a 30.5-m (100-ft) producing length and 1965 kPa (285 psi) for a 7.62-m (25-ft) producing length, both in a 30.5-m- (100-ft-) thick reservoir. The comparison suggests that the producing length of the wellbore is very important and that this length should be maximized. The comparison of the results of this analysis and those of Katz and Lady is justified because the weekly cycle and other factors applied in this analysis were designed, in part, by consideration of their work.

4.4.1.2 Permeability Ratio

The permeability ratio is used to describe the ratio of the vertical to horizontal permeability. It has been observed in laboratory measurements at PNL that the vertical permeability through a porous zone may be substantially lower than the horizontal permeability. As shown by Figure 18, large reductions in vertical permeability have relatively little effect on the fluid pressure response in the reservoir. For a producing length of 30.5 m (100 ft) there is essentially no effect of permeability ratio. This is undoubtedly due to the predominance of radial flow in the reservoir. For this case the radial mass flux is five orders of magnitude greater than the vertical mass flux. There simply are no significant vertical velocities to contribute to the pressure loss. As the producing length of the wellbore decreases, vertical velocities increase, although they remain small. For a wellbore producing length of 7.62 m (25 ft) the pressure losses due to low vertical permeabilities and increased vertical velocities are still a small portion of the total.

4.4.1.3 Permeability Stratification

To study the potential consequences of permeability stratification, a layer of reduced permeability was created in the reference reservoir. The layer was 3.81 m (12.5 ft) thick. The top of the layer was 15.2 m (50 ft) from the top of the porous zone. The permeability of this layer was set at 100 md while the permeability of the surrounding layers were

FIGURE 18. Quasi-Steady-State Pressure Difference Versus the Permeability Ratio for Various Producing Lengths (m (ft)), Reservoir Thickness = 30.5 m (100 ft)

set at the reference value of 500 md. Within each layer the permeability ratio was unity. Of particular interest was the effect that permeability stratification would have on the pressure response if the producing section of the wellbore penetrated to a position above or below the low-permeability layer.

As might be guessed from the results on the permeability ratio, the effect of the stratified permeability on the quasi-steady-state pressure response was minimal. The pressure differences are compared in Table 3 for the homogeneous reservoir and the stratified reservoir. The dominant factor in determining the pressure drop is the flow area at the wellbore which is determined by the producing length. The values given for the reference case were those used to draw Figure 17.

TABLE 3. Effect of Stratified Permeability on the Quasi-Steady-State Pressure Difference

Producing Length of Wellbore m (ft)	Reference ΔP		Stratified ΔP	
	kPa	(psi)	kPa	(psi)
7.62 (25)	583.	(84.6)	589.	(85.4)
15.2 (50)	303.	(43.9)	314.	(45.5)
19.1 (62.5)	244.	(35.4)	296.	(43.0)
22.9 (75)	205.	(29.7)	236.	(34.3)
30.5 (100)	159.	(23.1)	177.	(25.7)

For well completions above the low permeability layer, i.e., producing lengths ≤ 15.2 m (50 ft), a large portion of the pressure loss is incurred by the flow through the wellbore region. Subsequent vertical flow apparently occurs at such low velocity, due to the expanded flow area, that there is little contribution to the pressure loss even though the air must pass through a low-permeability layer. Actually, this situation is less severe than that shown by Figure 18 for a permeability ratio of 0.20 where the vertical flow is subjected everywhere to a permeability of 100 md. Thus, the results for the stratified case are not surprising.

For well completions below the top of the low permeability layer, i.e., producing lengths ≥ 15.2 m (50 ft), a portion of the radial flow through the wellbore encounters the increased resistance. Thus, the effect of the layer on the pressure response is more significant for these cases. The most severe case occurs for a producing length of 19.1 m (62.5 ft), which implies wellbore completion to the bottom of the low-permeability layer. This case results in an increase in the reservoir

pressure loss of about 20%. It must be that the bottom of the wellbore becomes the bottleneck for the portion of the air mass that is distributed below the completion of the wellbore. If the resultant higher velocity in this region is met by higher flow resistance, the effect on pressure drop is most significant.

These results further enhance the observation that it is most appropriate to maximize the producing length of the wellbore with respect to the pressure response of the reservoir. However, completion of the wellbore to the top of a low-permeability layer will reduce the potential for water influx due to coning.

4.4.2 Thermal Response

The thermal behavior of the porous zone is determined predominantly by the mass transport. Disturbances of the otherwise uniform radial flow will result in similar deviations in the temperature distributions. One of the principal factors affecting the radial uniformity of the flow was shown in to be the producing length of the wellbore. Another important factor involving the mass transport that was identified to cause non-uniform thermal distributions was the presence of stratified permeability. In addition, phenomena are present, even in homogeneous reservoirs with producing lengths equal to the reservoir thickness, that add to the maldistribution of thermal energy in the reservoir. These include natural circulation, heat losses to the vertical boundaries, and non-uniform flow distribution from the wellbore.

With respect to the performance of a CAES facility, the thermal distributions within the porous zone are not particularly important by comparison to the thermal energy recovery. The analysis of the wellbore heat transfer has shown that the thermal performance of the system is largely determined by the events occurring in the wellbore above the reservoir. In contrast, results are presented which show that potential thermal energy recovery from the reservoir itself is nearly independent of the thermal distributions in the reservoir. It still remains necessary to quantify these thermal distributions. The specific thermal behavior

within the reservoir will affect the structural and geochemical stability of the reservoir. Thus, the results presented will provide, or will indicate the capability to provide, important thermal information to researchers in those other areas.

4.4.2.1 Non-Uniform Fluid Flow

By far the most dramatic deviations from uniform thermal distribution in the reservoir will occur due to non-uniform air flow in the vicinity of the wellbore. Net heating beyond an inner 10- to 20-ft radius from the wellbore occurs primarily by conduction. This was demonstrated by the studies of thermal behavior using the one-dimensional models.^(1,2) As a result, any flow disturbances outside the near-wellbore region will not likely affect a large non-uniform distribution of thermal energy. Two sources have been identified that would result in non-uniform radial flow. These are:

- If the producing length of the wellbore does not extend completely through the reservoir, then significant vertical flows result.
- Stratified permeability restricts the radial flow in the low-permeability layers.

Many cases of flow disturbances were examined to evaluate their effect on the pressure response. Examples are presented here to exhibit the effect of the flow disturbance on the thermal distribution. In Figure 19 the solid lines represent vertical temperature distributions for the given radii in meters (feet) from the wellbore center for the reference case conditions. The dashed lines drawn for the same radii represent a case for which the producing section of the wellbore extends only 7.62 m (25 ft) below the top of the reservoir. These results were taken after 44 hours of the first weekly cycle. At this point in the weekly cycle the stored thermal energy in the reservoir is maximum. The most obvious effect of this flow disturbance is the creation of some fairly steep thermal gradients in the porous zone. Also, this type of disturbance can lead to large concentrations of thermal energy rather than having it

FIGURE 19. Vertical Temperature Distributions to Various Radii (m (ft)) for Producing Lengths of 30.5 m (100 ft) (Solid Lines) and 7.62 m (25 ft) (Dashed Lines).

uniformly distributed as with the reference case. In spite of the different thermal solutions for the two cases shown in Figure 19, the potential thermal energy recovery for them is different by only 1.6%.

To check the validity of the assumption of no heat transfer to the vertical boundaries, the two cases shown in Figure 19 were repeated with heat transfer permitted to constant-temperature boundaries. This is a worst case because heat transfer to the boundaries would otherwise decrease the temperature gradients and, therefore, the subsequent heat losses. This check showed the thermal recovery for the reference case to drop by 0.08% and that for the comparative case to drop by 0.18%. The maximum effect on temperature was less than 2°F, and this occurred only near the wellbore at the top of the reservoir. These variations are small enough to justify the assumption.

The results for the temperature distributions for a case with permeability stratification are shown by Figure 20. The same conditions apply to this

FIGURE 20. Vertical Temperature Distributions at Various Radii (m (ft)) for the Reference Reservoir (Solid Lines) and a Stratified Reservoir (Dashed Lines).

figure as were stated for Figure 19. The solid lines represent the solution for the reference case. The dashed lines are for a 100-md layer that is 3.81 m (12.5 ft) thick, the top of which is 15.2 m (50 ft) below the top of the reservoir. The remainder of the reservoir has a permeability of 500 md. This result shows that the thermal energy is deposited according to the preferred fluid flow paths. Due to the restricted flow in the low-permeability layer, there is an increase in radial and flow above and below the layer accounting for slightly greater heating in those regions.

The reference case results in Figures 19 and 20 provide a small indication that even for fully homogeneous reservoirs where the wellbore extends totally through the porous zone, there is some non-uniform flow distribution into the reservoir. The results from the computer model show that for this reference case, during the charge cycle, the radial mass flux at the wellbore was almost 5% greater at the top of the reservoir than at the bottom. On the extraction cycle the radial mass flux at the

bottom of the wellbore was about 2.5% greater than at the top. Since the extraction cycle flow apparently adds to the nonuniform thermal distribution, it is best to look at the results after some simulation time has elapsed. In Figure 21 the solid lines show temperatures at the various radii after 1 week. The dashed lines show the results after 5 weeks. The maximum vertical temperature gradient stabilizes at about $0.273^{\circ}\text{C}/\text{m}$ ($0.15^{\circ}\text{F}/\text{ft}$) although the location of the maximum gradient moves radially outward as thermal development proceeds. While this effect is relatively small compared to the effect of major flow disturbances, it nevertheless adds to the total for all of the cases.

In a previous paper published on the two-dimensional analysis it was reported that vertical temperature gradients were virtually non-existent.⁽³⁾ This occurred because the wellbore/reservoir coupling was not complete in the computer model when those results were obtained. Rather than flow being introduced in the wellbore at the top of the reservoir, a uniform pressure was specified along the length of the

FIGURE 21. Vertical Temperature Distributions at Various Radii (m (ft)) in the Reference Reservoir After 1 Week (Solid Lines) and After 5 Weeks (Dashed Lines)

wellbore adjacent to the porous zone. Those pressures were based on the boundary pressures required to achieve a constant mass flow boundary condition with the one-dimensional model. As a result, there was no wellbore/reservoir coupling. While those reported two-dimensional temperature solutions are not wrong in consideration of how they were developed, they, nevertheless, do not exhibit the temperature distributions that would likely result due to non-uniform flow from the wellbore. Also, heat losses from the wellbore between the top and bottom of the reservoir reduce the temperature of the air entering the bottom of the reservoir as compared to that at the top of the reservoir. Thus, vertical temperature gradients in the wellbore are likely to exist, which is a revision to those previous results.

4.4.2.2 Natural Circulation (and Other Heat Transfers)

When the well is closed to mass flow a natural circulation flow is established within the reservoir. While the buoyant forces creating this flow are always active, the natural flow is not distinguishable during the reservoir charge or discharge cycles when the forced flows are dominant. Although the natural flow is relatively small, it was necessary to quantify its effect on the thermal solution because the magnitude of this effect was previously unknown.

The basic pattern of the natural circulation is shown in Figure 22. The length of the arrows in the wellbore and perpendicular to the wellbore indicate the strength of the mass flow in that region. The other arrows indicate the general path of the circulation flow. The effect of the natural circulation on the thermal solution is controlled by the relatively small magnitude of these flows. In the wellbore the natural flow is about two orders of magnitude lower than the reference forced flows. Following a charging cycle, there is a concentration of thermal energy in the vicinity of the wellbore. During the subsequent closure, the buoyant flows are about 50% greater than the buoyant flows that result during the closure after a discharge cycle when the reservoir is at a state of minimum thermal energy. During the two long periods of

FIGURE 22. Natural Circulation Paths in a Closed Reservoir with the Distribution of Mass Flows in and Along the Wellbore Indicated by the Length of the Arrows

closure on the weekends, the buoyant flow, once established, remains nearly constant, providing evidence that the effect of the flows is small. If there were a large transport of thermal energy, the forces driving the flow would be dissipated. The whole character of the buoyant flow is dominated by the flow in the wellbore. Vertical flows in the porous material that are due to buoyancy are five to seven orders of magnitude less than the buoyant flows in the wellbore.

The effect of the natural circulation flow on the thermal solution is to decrease the temperatures along the full length of the wellbore while heating occurs away from the wellbore at the top of the reservoir.

This results because the radially inward flow in the lower half of the reservoir and the vertical flow in the wellbore occur in the direction of increasing temperatures. Thus, this entire region is cooled because the upstream temperature is lower than the temperature at any specific location. Heating occurs where the radially outward flow at the top of the reservoir is in the direction of decreasing temperatures.

The computer results verify the small effect expected from buoyant flows. However, it is difficult to isolate the heat transfer due to these flows from other heat transfers that occur simultaneously. During reservoir closure, the main source of thermal transport is eliminated, this being the termination of forced flow. During closure, the heat transfer mechanisms that remain active include heat transfer to the vertical boundaries, conduction heat transfer within the storage zone, and heat transfer due to flows resulting from pressure equalization, as well as the buoyant flows. Any combination of these processes can be eliminated to isolate and quantify the heat transfer due to buoyant flows. To eliminate flows from pressure equalization, the results have to be taken during a long period of closure. The time required for pressure equalization depends on the pressure distribution when closure is initiated and on the flow resistance. The 2-hour closures between daily cycles are sufficiently long to promote total equilization for the conditions of the reference reservoir. To exclude the other heat transfer processes requires that the thermal conductivity and the acceleration of gravity be set to zero. To determine the contribution to the heat transfer from each component, the reference case was repeatedly evaluated, with each successive simulation deleting one of the heat transfer mechanisms, until only gravity was active. This resulted in the data provided in Table 4. The data is the temperature change that occurs between hours 50 and 52 of the first week of reservoir operation. Since closure of the reservoir occurs at 44 hours, pressure equalization is essentially complete. Data for adjacent radial node positions are given. This data applies to the top numerical layer in the reservoir where the nodes are 1.91 m (6.25 ft) below the top of the reservoir. For example, at a

TABLE 4. Contributions to Temperature Change, in °C (°F), During Reservoir Closure Between Hours 50 and 52 of the First Week of Reservoir Operation

Radius (m (ft))	0.30 (1.0)	0.55 (1.8)	0.98 (3.2)	1.6 (5.4)	2.8 (9.2)
Vertical H.T.	-0.083 (-0.149)	-0.076 (-0.136)	-0.052 (-0.093)	-0.027 (-0.048)	-0.004 (-0.008)
Conduction in Rock	-0.923 (-1.662)	-1.327 (-2.388)	-1.057 (-1.903)	0.154 (0.277)	0.116 (0.209)
Conduction in Air	-0.001 (-0.001)	-0.004 (-0.007)	-0.004 (-0.008)	0.001 (0.001)	0.000 (0.000)
Gravity	0.000 (0.000)	0.003 (0.005)	0.091 (0.164)	0.129 (0.232)	0.027 (0.048)
Total	-1.007 (-1.812)	-1.404 (-2.526)	-1.022 (-1.840)	0.257 (0.462)	0.139 (0.249)

radius of 0.55 m (1.8 ft) from the wellbore center the temperature drops 1.403°C (2.526°F) between hours 50 and 52 of the first week of operation. When conduction to the vertical boundaries is eliminated, the temperature drop is 1.328°C (2.390°F), suggesting that vertical heat transfer accounted for 0.076°C (0.136°F) of the total. When, in addition, conduction in the rock was eliminated, the temperature drop was 0.001°C (0.002°F), suggesting that conduction through the rock accounted for 1.327°C (2.388°F) of the remaining total. When conduction through the air was eliminated, leaving only gravitationally induced flow as a heat transfer mechanism, the temperature increased by 0.003°C (0.005°F), suggesting that conduction through the air accounted for a temperature drop of 0.004°C (0.007°F). In this way the components at each radii were evaluated.

The specific magnitude of these numbers in Table 4 suggests that the total heat transfer during reservoir closure is actually quite small. The relative magnitudes suggest that the conductivity of the rock controls these minor heat transfer contributions. The magnitude of these temperature changes compared to those incurred during forced flow

can be judged by Figure 23, which shows the thermal cycling at four of the radial node points during the first week of reservoir operation. These results support the conclusion drawn for the one-dimensional analysis that thermal cycling is significant only inside a radius of about 3.05 m (10 ft). Within this region, thermal transport by forced convection dominates, while outside this region net heating is basically a function of the rock conductivity.

Some additional results were obtained to further characterize the behavior of buoyant flows. The results presented above show that it is difficult to define the buoyant effects in terms of temperature changes, since these are very small and are dependent on location and time. Thus, results for other cases are compared on the basis of the magnitude of the wellbore buoyant flow, which appears to be the most obvious characteristic of the buoyancy effect.

FIGURE 23. Thermal Cycling at Various Radii (m (ft)) in the Porous Zone of the Reference Reservoir

Observing that the principal vertical flow due to buoyancy occurs in the wellbore, the wellbore diameter was tested for its effect on the flow. For the reference case the wellbore diameter was 17.8 cm (7 in). For the same conditions, except with a wellbore diameter of 61.0 cm (24 in), the buoyant flow increased by about 50%.

The effect of the permeability ratio, i.e., the ratio of vertical to horizontal permeability, was tested by setting the ratio to a value of 0.1. For this case the vertical permeability was 50 md. Since the primary vertical flow path for buoyancy is the wellbore, the reduced vertical permeability of the porous rock had little effect. The flows decreased by 15% relative to the reference case.

The effect of porous zone thickness was evaluated by comparing results for the reference case and a reservoir with a thickness of 61.0 m (200 ft). The impact of doubling the thickness was to increase the buoyant flows by a factor of about 3.6 following an extraction cycle and 3.7 following an injection cycle. The results obtained for the study of the producing length of the wellbore suggest that reservoir thickness is not the controlling factor in this buoyant effect. Rather, it is the length of the flow path in the wellbore that controls the total flow while the total vertical flow path, i.e., the thickness, plays a lesser role. The location of the producing length in the reservoir also has some effect. If the producing section of the wellbore does not extend entirely through the porous zone, then there is a concentration of thermal energy in the vicinity of the producing section. If this concentration of thermal energy is at the top of the reservoir, then the driving force for buoyant flow is reduced relative to a situation where the thermal energy may be concentrated at lower levels in the reservoir. For such conditions a cold region may overlie a heated region, thereby enhancing the buoyant flow.

From this discussion, it is apparent that natural circulation has little effect on the thermal distributions in the reservoir. Now that its magnitude has been documented, it can be placed low on a list of potential operational pitfalls.

5.0 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS FOR FURTHER STUDY

The results of the computer analysis have led to quantification and characterization of certain behavior of the underground CAES system that could only be addressed by a multi-dimensional model. According to the results obtained by the numerical modeling, the following statements can be made regarding the effects of the vertical parameters of the reservoir. With regard to wellbore heat transfer:

- The recovery of thermal energy can be significantly reduced by the heat losses in the wellbore.
- Wellbore thermal insulation was shown to provide significant potential for improving thermal energy recovery.
- Heat losses in an uninsulated wellbore result in reduced thermal cycling as well as lower temperatures in the porous zone.
- While wellbore insulation improves thermal energy recovery, the porous zone is exposed to greater extremes of thermal cycling and higher temperatures. Also, the insulation was shown to cause increased thermal cycling of the air in the wellbore for certain conditions.
- Preheating the reservoir by injecting heated air during bubble development may result in significantly improved thermal energy recovery and reduced thermal cycling during the initial weeks of reservoir operation.
- The effects of preheating dissipate rapidly. After about 20 weeks of reservoir operation, the thermal condition of a preheated reservoir is essentially indistinguishable from a reservoir that was not preheated.
- Thermal energy recovery is strongly dependent on the residence time of the air in the wellbore. The residence time is, in turn, established by the flow velocity in the wellbore and by reservoir

depth. The reservoir air storage volume (which is determined by porosity, diameter, and thickness), the reservoir depth, and the applied weekly operating cycle are all interrelated to determine the residence time.

With regard to thermal behavior in the porous zone:

- The most important factor in determining the thermal distribution in the porous zone is the forced-convection flow field. Producing lengths that are less than the porous zone thickness result in concentrations of thermal energy that intensify vertical temperature gradients.
- When forced convection flow is terminated, the remaining heat transfer mechanisms are conduction in the air and porous rock, conduction to the vertical boundaries, and natural circulation. The contribution of the conductivity of the rock was shown to be the most important of these parameters.
- Natural convection flow contributes relatively little to the distribution of thermal energy.
- Heat losses to the vertical boundaries can be neglected if the thermal behavior of the porous zone is of principal concern.

With regard to the fluid behavior in the porous zone:

- The producing length of the wellbore is extremely important to the total pressure loss of the porous zone. For a given wellbore diameter, the producing length fixes the minimum flow area through which the air entering or leaving the porous zone must pass. This establishes the maximum air velocity in the porous zone and, thereby, strongly influences the total pressure drop in the reservoir.
- Air flow in the vicinity of the wellbore is predominantly radial. Therefore, reduced vertical permeability does not significantly affect the overall pressure loss in the porous zone.

- Stratification of permeability has a greater effect on pressure loss in the reservoir when the producing section extends through the layer. That is, for a given producing length, if a low-permeability layer exists below the well bottom, the effect on pressure loss will be less than if the layer is above the well bottom. This results from the dependence of the pressure drop on the permeability in the vicinity of the wellbore.

These results add to a growing knowledge of the fundamental behavior of the fluid and thermal response of a CAES porous-media reservoir. The increased analysis capability of the two-dimensional model was also demonstrated.

The results of this investigation lead to the next phase of model development. The importance of the producing length of the wellbore with regard to reservoir pressure loss was shown. For porous zones having a liquid-phase water boundary below the air storage zone, the producing length will necessarily be less than the storage zone thickness. This will be required to prevent the production of water in the wellbore due to water coning. The degree of water coning will depend on such parameters as producing length, air mass flow rates, permeability/saturation relationships, storage zone thickness, and water zone thickness. Development of the model and the analysis of these and other subsequently identified parameters will constitute the next step of this research effort.

REFERENCES

1. G. C. Smith, L. E. Wiles, and W. V. Loscutoff, Numerical Analysis of Temperature and Flow Effects in a Dry, One-Dimensional Aquifer Used for Compressed Air Energy Storage. PNL-2546, Pacific Northwest Laboratory, Richland, WA 99352, February 1979.
2. L. E. Wiles, The Effects of Water on Compressed Air Energy Storage in Porous Rock Reservoirs. PNL-2869, Pacific Northwest Laboratory, Richland, WA 99352, March 1979.
3. L. E. Wiles, C. A. Oster, "Fluid Flow and Thermal Analysis for CAES in Porous Rock Reservoirs," Proceedings of the 1978 Mechanical and Magnetic Energy Storage Contractor's Review Meeting. CONF-781046, Luray, VA, 1978.
4. H. J. Ramey, Jr., "Wellbore Heat Transmission," Journal of Petroleum Technology, Vol. 14, April 1962.
5. A. Sater, "Heat Losses During Flow of Steam Down a Wellbore," SPE Reprint Series, No. 10, Thermal Recovery Techniques. SPE of AIME, 1972.
6. G. C. Smith, and L. E. Wiles, "Analysis of Underground Porous Reservoirs for Compressed Air Energy Storage," 1978 Compressed Air Energy Storage Symposium Proceedings. CONF-780599, Vol. 1, Pacific Grove, CA, 1978.
7. CRC Handbook of Tables for Applied Engineering Science, 2nd ed., Chemical Rubber Company, 1973, p. 530.
8. D. L. Katz and K. H. Coats, Underground Storage of Fluids. Ulrich's Books, Inc., Ann Arbor, MI, 1968.
9. D. L. Katz and E. R. Lady, Compressed Air Storage. Ulrich's Books, Inc., Ann Arbor, MI, 1976.

DISTRIBUTION

<u>No. of Copies</u>		<u>No. of Copies</u>	
	<u>OFFSITE</u>	5	Saul Strauch DOE Division of Energy Storage Systems Advanced Physical Methods Branch 600 E Street, Room 416 Washington, DC 20585
	A. A. Churm DOE Chicago Patent Group Chicago Operations Office 9800 South Cass Avenue Argonne, IL 60439		J. H. Swisher Division of Energy Storage Systems U.S. Department of Energy Washington, DC 20585
27	DOE Technical Information Center B. J. Mueller Department of Energy Chicago Operations Office 9800 S. Cass Avenue Argonne, IL 60439 Chief, APMBR Division of Energy Storage Systems U.S. Department of Energy Washington, DC 20585 Dan Hall P.O. 635 Fairvault, MN 55021 Royal B. Newman Soyland Power Cooperative, Inc. PO Box A1606 Decatur, IL 62525 G. D. Pezdirtz, Director Division of Energy Storage Systems U.S. Department of Energy Washington, DC 20585		D. W. Boehm Division of Environmental Control Technology U.S. Department of Energy Washington, DC 20585 Assistant Director for Major Projects Division of Solar Energy U.S. Department of Energy Washington, DC 20585 Assistant Director for Thermal Power Systems Division of Solar Energy U.S. Department of Energy Washington, DC 20585 DOE Library U.S. Department of Energy Mail Station G-043 Washington, DC 20585
5	Gabor D. Karadi Department of Energy Division of Energy Storage 600 E Street, Room 416 Washington, DC 20545		R.F. Kimberlin DOE Library U.S. Department of Energy Room 1223 Washington, DC 20585

No. of
Copies

D. Willett
Acres American, Inc.
Liberty Bank Building
Main at Court
Buffalo, NY 14202

L. A. Wilson
Middle South Services
P.O. Box 61000
New Orleans, LA 70161

G. T. Flynn
Energy Systems Engineer
MIT/Lincoln Laboratory
Lexington, MA 02173

J. P. Joyce
NASA Lewis Research Center
21000 Brookpark Road
Cleveland, OH 44135

Division of Advanced Energy
Research and Technology
National Science Foundation
Room 1140
1800 G Street, NW
Washington, DC 20550

C. G. Nelson
Manager, Storage Operations
Northern Illinois Gas
Company
P.O. Box 190
Aurora, IL 60507

P. E. Schaub
Potomac Electric Power
Company
1900 Pennsylvania Avenue
Washington, DC 20006

T. McCafferty
Public Service Company
of Indiana
1000 E. Main Street
Plainfield, IN 46168

No. of
Copies

2 Technical Library
Department 3141
Sandia Laboratory
Albuquerque, NM 87115

J. Rasmussen
PEPCO
1900 Pennsylvania Avenue, N.W.
Washington, DC 20068

S. Serata
Serata Geomechanics, Inc.
1229 Eighth Street
Berkeley, CA 94710

Energy Research Section
Tennessee Valley Authority
1360 Commerce Union Bank Bldg.
Chattanooga, TN 37401

Gerald Phillips
Tennessee Valley Authority
1150 Chestnut, Tower 2
Chattanooga, TN 37401

E. Berman
Technical Library
TRW Energy Systems Group
7600 Colshire Drive
McLean, VA 22101

E. H. King
Underground Design Consultants
820 Cascade Bldg.
Portland, OR 97204

A. I. Giramonti
United Technologies Research
Center
Silver Lane
East Hartford, CT 06108

H. J. Pincus
University of Wisconsin
Department of Geological
Sciences
Sabin Hall and Greene Museum
P.O. Box 413
Milwaukee, WI 53201

No. of
Copies

D. Ayers
Manager, Fluid Systems
Laboratory
Westinghouse Electric
Corporation
1291 Cumberland Avenue
West Lafayette, IL 47906

American Public Power
Association
2600 Virginia Avenue, NW
Washington, DC 20037

2 J. M. Clinch
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439

Manager, Research and
Development
Bonneville Power
Administration
P.O. Box 3621
Portland, OR 97208

Research Library,
Reference Section
Information Division
Brookhaven National
Laboratory
Upton, NY 11973

Stanley Stys
Vice President, American
Brown Boveri Corporation
New Brunswick, NJ 08902

Director of Research
Cincinnati Gas and
and Electric Company
139 East Fourth Street
Cincinnati, OH 45202

D. E. DeViney
Commonwealth Edison
Company
1319 South First Avenue
Maywood, IL 60153

No. of
Copies

R. A. Bell
Consolidated Edison Company
4 Irving Place
New York, NY 10003

T. Schneider
Electric Power Research
Institute
Box 10412
Palo Alto, CA 94303

D. Anderson
Fenix and Scisson, Inc.
P.O. Box 15609
Tulsa, OK 74115

Director of Research
GPU Service Corporation
260 Cherry Hill Road
Parsippany, NJ 07054

A. H. Barber
Director of Marketing
Harza Engineering Company
150 S. Wacker Drive
Chicago, IL 60606

Library
Lawrence Berkeley Laboratory
University of California
Bldg. 50, Room 134
Berkeley, CA 94720

3 Technical Information
Department, L-3
Lawrence Livermore Laboratory
University of California
P.O. Box 808
Livermore, CA 94550

Director of Research
Louisiana Power and Light
142 Delaronde Street
New Orleans, LA 70174

No. of
Copies

I. Glendenning
Head of Long-Term Studies
Marchwood Engineering Labs
Southampton, England

A. Ferreira
Electric Power Research
Institute
NEPLAN
174 Brush Hill Avenue
West Springfield, MA 01089

W. Stevens
Project Manager
Electric Power Research
Institute
3412 Hillview Avenue
PO Box 10412
Palo Alto, CA 94303

Fred Ahrens
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439

Paul Gnirk
Re/Spec Inc.
PO Box 725
Rapid City, SD 57701

Donald L. Katz
Department of Chemical
Engineering
The University of Michigan
2042 E. Engr. Bldg.
Ann Arbor, MI 48109

Bob Holliday
Project Manager
Department of Energy
600 "E" Street
Washington, D.C. 20545

R. L. Thoms
Louisiana State University
Institute for Environmental
Studies
Room 42, Atkinson Hall
Baton Rouge, LA 70803

No. of
Copies

O.C. Farquhar
U. of Massachusetts
Dept. of Geology & Geography
Morrill Science Center
Amherst, MA 01003

T. L. Brekke
University of California
Department of Civil Engineering
1847 Yosemite Road
Berkeley, CA 94707

H. Lorenzen
PB-KBB Inc.
Subservice Systems & Technology
800 Commerce Road West
Harahan, LA 70123

A. H. Warnke
Vice President Power Supply
Central Illinois Public Service Co.
607 East Adams Street
Springfield, IL 62701

Mr. G. E. Huck
Manager of Planning
Illinois Power Company
500 South 27th St.
Decatur, IL 62525

Mr. W. C. Walke
Project Manager
Sargent & Lundy Engineers
55 East Monroe Street
Chicago, IL 60603

T. J. Maiman
Sta. Mech. Engr. Dept. Manager
Commonwealth Edison Co.
36 FN West
PO Box 767
Chicago, IL 60690

E. M. Mabuice
Manager-Applied Research
Corporate Planning Dept.
Union Electric Co.
PO Box 149
St. Louis, MO 63166

No of
Copies

W. F. Kobett
CAES Project Manager
Westinghouse Electric Corp.
Combustion Turbine Sys. Div.
Long Range Development-Lab 100
PO Box 251
Concordville, PA 19331

J. C. Smith
Division of Electrical Energy
Systems
Department of Energy
20 Massachusetts Ave, Room 2205
Washington, DC 20545

J. Gahimer
Department of Energy
600 "E" Street
Washington, DC 20545

C. Holt
Battelle Columbus Laboratories
505 King Avenue
Columbus, OH 43201

T. Barlow
Lawrence Livermore Laboratory
PO Box 808
Livermore, CA 94550

M. Dodd
Organization 5743
Sandia Labs
Albuquerque, NM 87115

R. O. Woods
Sandia Laboratories
Org. No. 4715
Albuquerque, NM 87115

J. L. Nash-Webber
MIT
Energy Lab
Cambridge, MA 02139

No. of
Copies

ONSITE

DOE Richland Operations
Office

D. K. Jones
H. E. Ransom

Pacific Northwest Laboratory

R.D. Allen
R.T. Allemann
M.C.C. Bampton
J.M. Bates
H.J. Bomelburg
D.B. Cearlock
T.J. Doherty
D.W. Dragnich
M.K. Drost
R.L. Erikson
J.A. Fort
J.R. Friley
P.J. Gutknecht
A.J. Haverfield
J.J. Jacobson
L.D. Kannberg
W.V. Loscutoff (30)
R.A. McCann
M.A. McKinnon
L.T. Pedersen
R.W. Reilly
R.P. Smith
J.A. Stottlemire
A.M. Sutey
D.S. Trent
R.A. Walter
L.E. Wiles (8)
Technical Information (5)
Publishing Coordination (2)