GEOHERMAL RESEARCH AND DEVELOPMENT PROGRAM

QUARTERLY TECHNICAL REPORT

September - December 1992

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For
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Office of Industrial Technologies
Washington, D.C.

By
Stanford Geothermal Program
Stanford University
Stanford, California 94305-2220

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Stanford University

January 25, 1993

1 ADSORPTION OF WATER VAPOR ON RESERVOIR ROCKS

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Figures 1 and 2 show the adsorption/desorption isotherms obtained at 100° and 120°C on this sample. As shown in the figures, significant hysteresis exists in water vapor adsorption/desorption in the Montiverdi #2 sample, similar to those reported previously. The origin of the hysteresis is not yet clear to us.

Figure 3 compares the adsorption isotherms obtained at temperatures of 80°, 100°, 120° and 140°C. Clearly, temperature has an effect on the amount of water adsorbed on this particular rock sample. Examination of the adsorption isotherms suggests that for the range of relative pressures studied, the adsorption isotherms can be well approximated by linear relationships. However, due to the problem of nonuniform heating, we were not able to

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Currently, work is in progress to install a new heater. Hopefully, the new heating system will eliminate the temperature problem we have had and enable us to run adsorption/desorption tests at near saturation pressures for various temperatures. Continuous effort will be made on the development of a model to describe the adsorption-capillary condensation process.

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2.1 Introduction

In order to design effective injection and production programs for geothermal reservoirs, the physics of the flow in the reservoirs must be understood. Geothermal reservoirs are, in general, highly fractured and heterogeneous, and the transport of fluids is influenced strongly by heat diffusion and also by adsorption or capillary retention effects.

In the Sept. 1992 Quarterly Report, an overview of this topic was discussed. The current report emphasizes the research undertaken on one aspect of the topic over the last two months, specifically the perturbation expansion describing flow through porous media with adsorption present.

2.1.1 Perturbation Expansion

A new approach to the perturbation expansion has been taken. The method described below varies from the one described in the last quarterly report in that the entire solution has been obtained in Laplace space.

The equation describing flow in porous media is:

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1. $p(0,t) = p_w$
2. $p(L,t) = p_i$
3. $p(x,0) = p_i$

The linear diffusion term may be expressed as:

$$A = A_w [1 + \beta(p - p_w)] \quad (4)$$

where, $A_w = A(p)$ at $p = p_w$. Dimensionless quantities may be defined as follows:

$$p_d = \frac{p - p_i}{p_w - p_i} \quad (5)$$

$$x_d = x/L \quad (6)$$

$$t_d = \frac{A_w t}{L^2} \quad (7)$$

$$\varepsilon = \beta(p_i - p_w) = \frac{A_i - A_w}{A_w} \ll 1.0 \quad (8)$$

After inserting dimensionless quantities, Eqn. (3) becomes:

$$\frac{\partial p_d}{\partial t_d} = (1 + \varepsilon p_d) \frac{\partial^2 p_d}{\partial x_d^2} \quad (9)$$

with boundary and initial conditions:

1. $p(0, t_d) = 1$
2. $p(1, t_d) = 0$
3. $p(x_d, 0) = 0$

Eqn. (9) may be transformed into Laplace space:

$$[s\bar{p}_d - p_d(x_d, 0)] = (1 + \varepsilon\bar{p}_d)\frac{\partial^2 \bar{p}_d}{\partial x_d^2} \quad (10)$$

After making use of the initial condition, the problem in Laplace space may be written:

$$(1 + \varepsilon\bar{p}_d)\frac{\partial^2 \bar{p}_d}{\partial x_d^2} - s\bar{p}_d = 0 \quad (11)$$

with boundary conditions:

1. $\bar{p}_d(x_d = 0) = 1/s$
2. $\bar{p}_d(x_d = 1) = 0$

Eqn. (11) may be expanded in a perturbation series of the form:

$$\bar{p}_d = \bar{p}_{d0} + \varepsilon\bar{p}_{d1} + \varepsilon^2\bar{p}_{d2} + \dots \quad (12)$$

To solve for the first term in this expansion, ε is set to zero in Eqn. (11) and the resulting linear equation is solved. The first term in the perturbation expansion, $\bar{p}_{d0}$, is:

$$\bar{p}_{d0} = \frac{e^{\sqrt{s}(1-x_d)} - e^{-\sqrt{s}(1-x_d)}}{s(e^{\sqrt{s}} - e^{-\sqrt{s}})} \quad (13)$$

The equation to be solved for the second term in the perturbation expansion, $\bar{p}_{d1}$, is:

$$\frac{\partial^2 \bar{p}_{d1}}{\partial x_d^2} - s\bar{p}_{d1} = -\bar{p}_{d0} \frac{\partial^2 \bar{p}_{d0}}{\partial x_d^2} \quad (14)$$

with boundary conditions:

1. $\bar{p}_{d1}(x_d = 0) = 0$
2. $\bar{p}_{d1}(x_d = 1) = 0$

Eqn. (14) yields the following expression for $\bar{p}_{d1}$:

$$\begin{aligned} \bar{p}_{d1} = & \frac{e^{2\sqrt{s}(-2+x)}}{3(-1+e^{-2\sqrt{s}})^2 s^2} + \frac{1}{3e^{2\sqrt{s}x}(-1+e^{-2\sqrt{s}})^2 s^2} + \quad (15) \\ & \frac{2e^{2\sqrt{s}}}{(-1+e^{2\sqrt{s}})^2 s^2} + \frac{e^{\sqrt{s}(2-x)}(1-7e^{\sqrt{s}}-e^{2\sqrt{s}}-e^{3\sqrt{s}})}{3(-1+e^{\sqrt{s}})^2(1+e^{\sqrt{s}})^3 s^2} + \\ & \frac{e^{\sqrt{s}x}(-1-e^{\sqrt{s}}-7e^{2\sqrt{s}}+e^{3\sqrt{s}})}{3(-1+e^{\sqrt{s}})^2(1+e^{\sqrt{s}})^3 s^2} \end{aligned}$$

So, the solution for pressure in Laplace space is:

$$\begin{aligned} \bar{p}_d = & \frac{e^{\sqrt{s}(1-x_d)} - e^{-\sqrt{s}(1-x_d)}}{s(e^{\sqrt{s}} - e^{-\sqrt{s}})} + \quad (16) \\ \varepsilon [& \frac{e^{2\sqrt{s}(-2+x)}}{3(-1+e^{-2\sqrt{s}})^2 s^2} + \frac{1}{3e^{2\sqrt{s}x}(-1+e^{-2\sqrt{s}})^2 s^2} + \frac{2e^{2\sqrt{s}}}{(-1+e^{2\sqrt{s}})^2 s^2} + \\ & \frac{e^{\sqrt{s}(2-x)}(1-7e^{\sqrt{s}}-e^{2\sqrt{s}}-e^{3\sqrt{s}})}{3(-1+e^{\sqrt{s}})^2(1+e^{\sqrt{s}})^3 s^2} + \frac{e^{\sqrt{s}x}(-1-e^{\sqrt{s}}-7e^{2\sqrt{s}}+e^{3\sqrt{s}})}{3(-1+e^{\sqrt{s}})^2(1+e^{\sqrt{s}})^3 s^2}] \end{aligned}$$

This development has only recently been achieved. In the coming quarter, the terms will be evaluated and the implications to geothermal transport determined.

2.2 Nomenclature

Variable	Description	Units
A	Nonlinear term	dimensionless
c	Compressibility	1/kPa
k	Permeability	md
L	Characteristic length	m
p	Pressure	bar
q	Flow rate	kg/s or m ³ /s
s	Laplace constant	dimensionless
t	Time	s
X	Adsorbed mass	g _a /g _r
x	Distance	m
β	Slope of adsorption isotherm	dimensionless
μ	Viscosity	cp
φ	Porosity	dimensionless
ρ	Density	g/cc

Subscript	Meaning
d	Dimensionless
i	initial
l	Liquid
p	Pressure or Constant pressure
r	Rock
t	Total
w	wellbore
∞	Infinity

3 EARTH-TIDE EFFECTS ON DOWNHOLE PRESSURES

This project is being undertaken by Research Assistant Edgar Dias under the guidance of Prof. Henry J. Ramey, Jr. The aim of the project is to develop a method to derive reservoir parameters by utilizing the phase-shifts observed between exciting tidal forces, and the downhole pressure response to these forces.

3.1 Derivation of Phase shift expression

Using an element of the earth, we derived an expression relating the incremental pressure and reservoir parameters. This differential equation contained a general expression of the stress function due to earth tides.

$$\frac{K}{\rho g} \nabla^2 \sigma = (\alpha + \phi \beta') \frac{\partial \sigma}{\partial t} + \alpha F(t, z) + \alpha C \exp i\omega t \quad (17)$$

where :

$$\alpha = \frac{1}{\lambda + \mu}$$

$F(t, z)$ is a constant of integration

3.2 Mathematical Description

We model the reservoir as circular disk. The outer radius is R and the well of radius a is at the center of the disk. The reservoir thickness is h , and the top of the reservoir is at a depth H . For convenience we position the origin of the frame of reference at the center of the circular disk, h is small relative to H , the overburden height.

Rewriting the mathematical definition of the problem, we have the governing equation of flow:

$$\frac{K}{\rho g} \nabla^2 \sigma = (\alpha + \phi \beta') \frac{\partial \sigma}{\partial t} + \alpha F(t, z) + \alpha C \exp i\omega t \quad (18)$$

where:

$$\alpha = \frac{1}{\lambda + \mu}$$

$F(t, z)$ is a constant of integration

Assuming impermeable boundaries on the top and bottom, we get:

at $z = \pm \frac{h}{2}$:

$$\frac{\partial \sigma}{\partial z} = 0$$

and an oscillating flow at the inner boundary

at $r = a$:

$$\frac{\partial \sigma}{\partial r} = \frac{Q \rho g}{2\pi K a h}$$

for $t > 0$
 and an outer impermeable boundary
 at $r = R$:

$$\frac{\partial \sigma}{\partial r} = 0$$

The initial conditions assumed are:

at $t = 0$: $C = 0$; and $F = 0$

let $Q = Q_0 \exp i(\omega t + \psi)$: where ψ is the phase shift and where ω is the tidal frequency being considered.

The governing equation is nonlinear due to the $F(t, z)$ and C functions on the right side. In order to solve it we first solve the homogeneous equation and expand the nonhomogenous terms as an infinite series of the eigenfunctions of the homogenous problem.

The homogenous governing equation may written as:

$$\frac{K}{\rho g(\alpha + \phi \beta')} \nabla^2 \sigma = \frac{\partial \sigma}{\partial t} \quad (19)$$

This may be written as:

$$\zeta \nabla^2 \sigma = \frac{\partial \sigma}{\partial t} \quad (20)$$

where ζ includes the constant terms, with the original boundary conditions, and the initial conditions.

The initial conditions indicate that earth-tidal effects started at time $t = 0$. This leads us to a transient response and a steady-state response. We will concentrate on the steady-state response, which contains the desired information.

So, let the solution be denoted as:

$$\sigma = \sigma_t(r, z, t) + \sigma_s(r, z, t)$$

where σ_t is the transient solution, and σ_s is the steady-state solution.

We will write the steady-state solution as:

$$\sigma_s = \sigma_s(r, z) \exp i(\omega t + \psi)$$

The problem subdivides into transient and steady-state parts as follows:

Steady-State Problem:

$$\zeta \nabla^2 \sigma_s = \frac{\partial \sigma_s}{\partial t} \quad (21)$$

$$\sigma_s(z, r, t) = \sigma_s(r, z) \exp i(\omega t + \psi) \quad (22)$$

$$(23)$$

with the boundary conditions:

$$\frac{\partial \sigma_s}{\partial z} = 0$$

at $z = \pm \frac{h}{2}$ for $a < r < R$

$$\frac{\partial \sigma_s}{\partial r}(a, z, t) = Q' \exp i(\omega t + \psi)$$

for $t > 0$ and where: $Q' = \frac{Q_0 \rho g}{2\pi K a h}$

$$\frac{\partial \sigma_s}{\partial r}(R, z, t) = 0$$

for $-\frac{h}{2} < z < \frac{h}{2}$

Transient State Problem:

$$\zeta \nabla^2 \sigma_t = \frac{\partial \sigma_t}{\partial t} \quad (24)$$

for $a < r < R$ and $-\frac{h}{2} < z < \frac{h}{2}$, and $t > 0$

$$\frac{\partial \sigma_t}{\partial z} = 0$$

at $z = \pm \frac{h}{2}$

$$\frac{\partial \sigma_t}{\partial r} = 0$$

at $r = R$

$$\frac{\partial \sigma_t}{\partial r} = 0$$

at $r = a$
and

$$\sigma_t(r, z, 0) = -\sigma_s(r, z, 0)$$

For the solution to the steady-state problem, we have:

$$\sigma_s(r, z, t) = \sigma_s(r, z) \exp i(\omega t + \psi)$$

substituting in the governing equation:

$$\zeta \nabla^2 \sigma_s = \frac{\partial \sigma_s}{\partial t}$$

and differentiating both sides we get:

$$\zeta \nabla^2 \sigma_s(r, z) = i\omega \sigma_s(r, z)$$

where $\sigma_s(r, z) = R(r)Z(z)$

Then using cylindrical coordinates and substituting, we get by separation of variables

$$\frac{(rR')'}{r} Z + RZ'' = \frac{i\omega}{\zeta} RZ$$

dividing through by RZ we get:

$$\frac{(rR')'}{rR} - \frac{i\omega}{\zeta} = \frac{-Z''}{Z} = \beta^2$$

i.e.:

$$Z'' + \beta^2 Z = 0$$

and

$$(rR')' - rR(\beta^2 + \frac{i\omega}{\zeta}) = 0$$

now putting

$$\lambda^2 = \beta^2 + \frac{i\omega}{\zeta}$$

we have:

$$(rR')' - r h \lambda^2 = 0$$

the general solution to these two equations may be written as:

$$Z = C_1 \sin(\beta Z) + C_2 \cos(\beta Z)$$

and

$$R = C_3 I_0(\lambda r) + C_4 K_0(\lambda r)$$

Substituting the boundary conditions at $z = \pm \frac{h}{2}$ we get:

$$Z_n = C_n \cos\left\{\frac{(2n-1)\pi(z - \frac{h}{2})}{h}\right\}$$

for

$$n = 1, 2, \dots$$

and:

$$R_n = C_{4n} \left\{ \frac{K_1(\lambda_n R)}{I_1(\lambda_n R)} I_0(\lambda_n r) + K_0(\lambda_n r) \right\}$$

These eigenfunctions are orthogonal and we can write:

$$\sigma_{en}(r, z, t) = \sum_{n=1}^{\infty} R_n(r) Z_n(z) \exp i\omega t$$

Now we go back to the nonlinear equation and express the nonlinear terms as infinite series of the eigenfunctions derived above.

Coming back to our original governing equation:

$$\zeta \nabla^2 \sigma = \frac{\partial \sigma}{\partial t} + \frac{\alpha}{\alpha + \phi \beta'} F(t, z) + \frac{\alpha}{\alpha + \phi \beta'} C \exp i\omega t \quad (25)$$

where:

$$\alpha = \frac{1}{\lambda + \mu}$$

σ will be written as σ_a , which denotes an average value of σ over h .

This equation may be written as:

$$\zeta \left\{ \frac{\partial^2 \sigma}{\partial r^2} + \frac{1}{r} \frac{\partial \sigma}{\partial r} + \frac{\partial^2 \sigma}{\partial z^2} \right\} = \frac{\partial \sigma}{\partial t} + \chi F(t, z) + \chi C \exp i\omega t \quad (26)$$

where:

$$\chi = \frac{\alpha}{\alpha + \phi\beta'}$$

and using average values over h we get by integrating from $z = -\frac{h}{2}$ to $z = \frac{h}{2}$:

$$\zeta\left\{\frac{\partial^2 \sigma_a}{\partial r^2} + \frac{1}{r} \frac{\partial \sigma_a}{\partial r} + \frac{\partial \sigma}{\partial z} \Big|_{\frac{h}{2}} - \frac{\partial \sigma}{\partial z} \Big|_{-\frac{h}{2}}\right\} = \frac{\partial \sigma_a}{\partial t} + \chi F_a(t) + \chi C_a \exp i\omega t \quad (27)$$

Using:

$$\frac{\partial \sigma}{\partial z} \Big|_{-h/2} = 0$$

and

$$\frac{\partial \sigma}{\partial z} \Big|_{h/2} = 0$$

we get :

$$\zeta\left\{\frac{\partial^2 \sigma_a}{\partial r^2} + \frac{1}{r} \frac{\partial \sigma_a}{\partial r}\right\} = \frac{\partial \sigma_a}{\partial t} + \chi F_a(t) + \chi C_a \exp i\omega t \quad (28)$$

Now expressing the right hand side as an infinite series of the eigenvalues obtained from the homogenous equations, we get:

$$\chi F_a(t) + \chi C_a \exp i\omega t = \sum_{i=1}^n q_n(t) R_n(r) \quad (29)$$

where $R_n(r)$ is the eigenfunction derived earlier. Then by orthogonality we can find $q_n(t)$ by integrating between $r = a$, to $r = R$

$$q_m(t) = \int_a^R \{\chi F_a(t) + \chi C_a \exp i\omega t\} R_m(r) \partial r$$

Substituting the derived values in the initial condition at $r = a$ will allow the extraction of ψ in terms of known reservoir parameters.

As seen from the procedure above, we will need to obtain characteristic expression which describe $F(t, z)$ and C realistically in order to obtain the value for ψ . This will involve an analysis of soil mechanics and a simplification to obtain descriptions which are realistic but easy to manipulate.

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2. $\bar{p}_d(x_d = 1) = 0$

Eqn. (11) may be expanded in a perturbation series of the form:

$$\bar{p}_d = \bar{p}_{d0} + \varepsilon\bar{p}_{d1} + \varepsilon^2\bar{p}_{d2} + \dots \quad (12)$$

To solve for the first term in this expansion, ε is set to zero in Eqn. (11) and the resulting linear equation is solved. The first term in the perturbation expansion, $\bar{p}_{d0}$, is:

$$\bar{p}_{d0} = \frac{e^{\sqrt{s}(1-x_d)} - e^{-\sqrt{s}(1-x_d)}}{s(e^{\sqrt{s}} - e^{-\sqrt{s}})} \quad (13)$$

The equation to be solved for the second term in the perturbation expansion, $\bar{p}_{d1}$, is:

$$\frac{\partial^2 \bar{p}_{d1}}{\partial x_d^2} - s\bar{p}_{d1} = \bar{p}_{d0} \frac{\partial^2 \bar{p}_{d0}}{\partial x_d^2} \quad (14)$$

with boundary conditions:

1. $\bar{p}_{d1}(x_d = 0) = 0$
2. $\bar{p}_{d1}(x_d = 1) = 0$

Eqn. (14) yields the following expression for $\bar{p}_{d1}$:

$$\begin{aligned} \bar{p}_{d1} = & \frac{e^{2\sqrt{s}(-2+x)}}{3(-1+e^{-2\sqrt{s}})^2 s^2} + \frac{1}{3e^{2\sqrt{s}x}(-1+e^{-2\sqrt{s}})^2 s^2} + \quad (15) \\ & \frac{2e^{2\sqrt{s}}}{(-1+e^{2\sqrt{s}})^2 s^2} + \frac{e^{\sqrt{s}(2-x)}(1-7e^{\sqrt{s}}-e^{2\sqrt{s}}-e^{3\sqrt{s}})}{3(-1+e^{\sqrt{s}})^2(1+e^{\sqrt{s}})^3 s^2} + \\ & \frac{e^{\sqrt{s}x}(-1-e^{\sqrt{s}}-7e^{2\sqrt{s}}+e^{3\sqrt{s}})}{3(-1+e^{\sqrt{s}})^2(1+e^{\sqrt{s}})^3 s^2} \end{aligned}$$

So, the solution for pressure in Laplace space is:

$$\begin{aligned} \bar{p}_d = & \frac{e^{\sqrt{s}(1-x_d)} - e^{-\sqrt{s}(1-x_d)}}{s(e^{\sqrt{s}} - e^{-\sqrt{s}})} + \quad (16) \\ \varepsilon [& \frac{e^{2\sqrt{s}(-2+x)}}{3(-1+e^{-2\sqrt{s}})^2 s^2} + \frac{1}{3e^{2\sqrt{s}x}(-1+e^{-2\sqrt{s}})^2 s^2} + \frac{2e^{2\sqrt{s}}}{(-1+e^{2\sqrt{s}})^2 s^2} + \\ & \frac{e^{\sqrt{s}(2-x)}(1-7e^{\sqrt{s}}-e^{2\sqrt{s}}-e^{3\sqrt{s}})}{3(-1+e^{\sqrt{s}})^2(1+e^{\sqrt{s}})^3 s^2} + \frac{e^{\sqrt{s}x}(-1-e^{\sqrt{s}}-7e^{2\sqrt{s}}+e^{3\sqrt{s}})}{3(-1+e^{\sqrt{s}})^2(1+e^{\sqrt{s}})^3 s^2}] \end{aligned}$$

This development has only recently been achieved. In the coming quarter, the terms will be evaluated and the implications to geothermal transport determined.

2.2 Nomenclature

Variable	Description	Units
A	Nonlinear term	dimensionless
c	Compressibility	1/kPa
k	Permeability	md
L	Characteristic length	m
p	Pressure	bar
q	Flow rate	kg/s or m ³ /s
s	Laplace constant	dimensionless
t	Time	s
X	Adsorbed mass	g _a /g _r
x	Distance	m
β	Slope of adsorption isotherm	dimensionless
μ	Viscosity	cp
φ	Porosity	dimensionless
ρ	Density	g/cc

Subscript	Meaning
d	Dimensionless
i	initial
l	Liquid
p	Pressure or Constant pressure
r	Rock
t	Total
w	wellbore
∞	Infinity

3 EARTH-TIDE EFFECTS ON DOWNHOLE PRESSURES

This project is being undertaken by Research Assistant Edgar Dias under the guidance of Prof. Henry J. Ramey, Jr. The aim of the project is to develop a method to derive reservoir parameters by utilizing the phase-shifts observed between exciting tidal forces, and the downhole pressure response to these forces.

3.1 Derivation of Phase shift expression

Using an element of the earth, we derived an expression relating the incremental pressure and reservoir parameters. This differential equation contained a general expression of the stress function due to earth tides.

$$\frac{K}{\rho g} \nabla^2 \sigma = (\alpha + \phi \beta') \frac{\partial \sigma}{\partial t} + \alpha F(t, z) + \alpha C \exp i\omega t \quad (17)$$

where :

$$\alpha = \frac{1}{\lambda + \mu}$$

$F(t, z)$ is a constant of integration

3.2 Mathematical Description

We model the reservoir as circular disk. The outer radius is R and the well of radius a is at the center of the disk. The reservoir thickness is h , and the top of the reservoir is at a depth H . For convenience we position the origin of the frame of reference at the center of the circular disk, h is small relative to H , the overburden height.

Rewriting the mathematical definition of the problem, we have the governing equation of flow:

$$\frac{K}{\rho g} \nabla^2 \sigma = (\alpha + \phi \beta') \frac{\partial \sigma}{\partial t} + \alpha F(t, z) + \alpha C \exp i\omega t \quad (18)$$

where:

$$\alpha = \frac{1}{\lambda + \mu}$$

$F(t, z)$ is a constant of integration

Assuming impermeable boundaries on the top and bottom, we get:

at $z = \pm \frac{h}{2}$:

$$\frac{\partial \sigma}{\partial z} = 0$$

and an oscillating flow at the inner boundary

at $r = a$:

$$\frac{\partial \sigma}{\partial r} = \frac{Q \rho g}{2\pi K a h}$$

for $t > 0$
 and an outer impermeable boundary
 at $r = R$:

$$\frac{\partial \sigma}{\partial r} = 0$$

The initial conditions assumed are:

at $t = 0$: $C = 0$; and $F = 0$

let $Q = Q_0 \exp i(\omega t + \psi)$: where ψ is the phase shift and where ω is the tidal frequency being considered.

The governing equation is nonlinear due to the $F(t, z)$ and C functions on the right side. In order to solve it we first solve the homogeneous equation and expand the nonhomogenous terms as an infinite series of the eigenfunctions of the homogenous problem.

The homogenous governing equation may written as:

$$\frac{K}{\rho g(\alpha + \phi \beta')} \nabla^2 \sigma = \frac{\partial \sigma}{\partial t} \quad (19)$$

This may be written as:

$$\zeta \nabla^2 \sigma = \frac{\partial \sigma}{\partial t} \quad (20)$$

where ζ includes the constant terms, with the original boundary conditions, and the initial conditions.

The initial conditions indicate that earth-tidal effects started at time $t = 0$. This leads us to a transient response and a steady-state response. We will concentrate on the steady-state response, which contains the desired information.

So, let the solution be denoted as:

$$\sigma = \sigma_t(r, z, t) + \sigma_s(r, z, t)$$

where σ_t is the transient solution, and σ_s is the steady-state solution.

We will write the steady-state solution as:

$$\sigma_s = \sigma_s(r, z) \exp i(\omega t + \psi)$$

The problem subdivides into transient and steady-state parts as follows:

Steady-State Problem:

$$\zeta \nabla^2 \sigma_s = \frac{\partial \sigma_s}{\partial t} \quad (21)$$

$$\sigma_s(z, r, t) = \sigma_s(r, z) \exp i(\omega t + \psi) \quad (22)$$

$$(23)$$

with the boundary conditions:

$$\frac{\partial \sigma_s}{\partial z} = 0$$

at $z = \pm \frac{h}{2}$ for $a < r < R$

$$\frac{\partial \sigma_s}{\partial r}(a, z, t) = Q' \exp i(\omega t + \psi)$$

for $t > 0$ and where: $Q' = \frac{Q_0 \rho g}{2\pi K a h}$

$$\frac{\partial \sigma_s}{\partial r}(R, z, t) = 0$$

for $-\frac{h}{2} < z < \frac{h}{2}$

Transient State Problem:

$$\zeta \nabla^2 \sigma_t = \frac{\partial \sigma_t}{\partial t} \quad (24)$$

for $a < r < R$ and $-\frac{h}{2} < z < \frac{h}{2}$, and $t > 0$

$$\frac{\partial \sigma_t}{\partial z} = 0$$

at $z = \pm \frac{h}{2}$

$$\frac{\partial \sigma_t}{\partial r} = 0$$

at $r = R$

$$\frac{\partial \sigma_t}{\partial r} = 0$$

at $r = a$
and

$$\sigma_t(r, z, 0) = -\sigma_s(r, z, 0)$$

For the solution to the steady-state problem, we have:

$$\sigma_s(r, z, t) = \sigma_s(r, z) \exp i(\omega t + \psi)$$

substituting in the governing equation:

$$\zeta \nabla^2 \sigma_s = \frac{\partial \sigma_s}{\partial t}$$

and differentiating both sides we get:

$$\zeta \nabla^2 \sigma_s(r, z) = i\omega \sigma_s(r, z)$$

where $\sigma_s(r, z) = R(r)Z(z)$

Then using cylindrical coordinates and substituting, we get by separation of variables

$$\frac{(rR')'}{r} Z + RZ'' = \frac{i\omega}{\zeta} RZ$$

dividing through by RZ we get:

$$\frac{(rR')'}{rR} - \frac{i\omega}{\zeta} = \frac{-Z''}{Z} = \beta^2$$

i.e.:

$$Z'' + \beta^2 Z = 0$$

and

$$(rR')' - rR(\beta^2 + \frac{i\omega}{\zeta}) = 0$$

now putting

$$\lambda^2 = \beta^2 + \frac{i\omega}{\zeta}$$

we have:

$$(rR')' - r h \lambda^2 = 0$$

the general solution to these two equations may be written as:

$$Z = C_1 \sin(\beta Z) + C_2 \cos(\beta Z)$$

and

$$R = C_3 I_0(\lambda r) + C_4 K_0(\lambda r)$$

Substituting the boundary conditions at $z = \pm \frac{h}{2}$ we get:

$$Z_n = C_n \cos\left\{\frac{(2n-1)\pi(z - \frac{h}{2})}{h}\right\}$$

for

$$n = 1, 2, \dots$$

and:

$$R_n = C_{4n} \left\{ \frac{K_1(\lambda_n R)}{I_1(\lambda_n R)} I_0(\lambda_n r) + K_0(\lambda_n r) \right\}$$

These eigenfunctions are orthogonal and we can write:

$$\sigma_{en}(r, z, t) = \sum_{n=1}^{\infty} R_n(r) Z_n(z) \exp i \omega t$$

Now we go back to the nonlinear equation and express the nonlinear terms as infinite series of the eigenfunctions derived above.

Coming back to our original governing equation:

$$\zeta \nabla^2 \sigma = \frac{\partial \sigma}{\partial t} + \frac{\alpha}{\alpha + \phi \beta'} F(t, z) + \frac{\alpha}{\alpha + \phi \beta'} C \exp i \omega t \quad (25)$$

where:

$$\alpha = \frac{1}{\lambda + \mu}$$

σ will be written as σ_a , which denotes an average value of σ over h .

This equation may be written as:

$$\zeta \left\{ \frac{\partial^2 \sigma}{\partial r^2} + \frac{1}{r} \frac{\partial \sigma}{\partial r} + \frac{\partial^2 \sigma}{\partial z^2} \right\} = \frac{\partial \sigma}{\partial t} + \chi F(t, z) + \chi C \exp i \omega t \quad (26)$$

where:

$$\chi = \frac{\alpha}{\alpha + \phi\beta'}$$

and using average values over h we get by integrating from $z = -\frac{h}{2}$ to $z = \frac{h}{2}$:

$$\zeta \left\{ \frac{\partial^2 \sigma_a}{\partial r^2} + \frac{1}{r} \frac{\partial \sigma_a}{\partial r} + \frac{\partial \sigma}{\partial z} \Big|_{\frac{h}{2}} - \frac{\partial \sigma}{\partial z} \Big|_{-\frac{h}{2}} \right\} = \frac{\partial \sigma_a}{\partial t} + \chi F_a(t) + \chi C_a \exp i\omega t \quad (27)$$

Using:

$$\frac{\partial \sigma}{\partial z} \Big|_{-h/2} = 0$$

and

$$\frac{\partial \sigma}{\partial z} \Big|_{h/2} = 0$$

we get :

$$\zeta \left\{ \frac{\partial^2 \sigma_a}{\partial r^2} + \frac{1}{r} \frac{\partial \sigma_a}{\partial r} \right\} = \frac{\partial \sigma_a}{\partial t} + \chi F_a(t) + \chi C_a \exp i\omega t \quad (28)$$

Now expressing the right hand side as an infinite series of the eigenvalues obtained from the homogenous equations, we get:

$$\chi F_a(t) + \chi C_a \exp i\omega t = \sum_{i=1}^n q_n(t) R_n(r) \quad (29)$$

where $R_n(r)$ is the eigenfunction derived earlier. Then by orthogonality we can find $q_n(t)$ by integrating between $r = a$, to $r = R$

$$q_m(t) = \int_a^R \{ \chi F_a(t) + \chi C_a \exp i\omega t \} R_m(r) \partial r$$

Substituting the derived values in the initial condition at $r = a$ will allow the extraction of ψ in terms of known reservoir parameters.

As seen from the procedure above, we will need to obtain characteristic expression which describe $F(t, z)$ and C realistically in order to obtain the value for ψ . This will involve an analysis of soil mechanics and a simplification to obtain descriptions which are realistic but easy to manipulate.

3.3 Data Processing

While the first part of this project, as described in the previous section, concerns itself with obtaining a mathematical expression for the phase shift in terms of reservoir parameters, we have also started work on an actual set of data which showed the presence of earth-tides.

The aim of the data processing is the following:

1. To write a program which can calculate theoretical gravity variations due to earth-tides at the location of data acquisition.
2. To design a filter using Fourier analysis which can remove noise and barometric pressure changes from field data.
3. To compare the theoretical data with the filtered data and determine quantitatively phase shifts shown.

The present status of the data processing part is as follows. The data from Palm Valley which is being processed has been passed through a fast Fourier transform operation using the MATLAB program. The power spectrum of the raw signal shows peaks in the low frequency range.

The program to obtain theoretical data will use the equation of the earth-tide potential as derived by Melchior.

3.4 Nomenclature

r_w	=	Radius of well bore
T	=	Transmissivity of the reservoir
e	=	Volume strain
S_r	=	Fluid Saturation
ρ_b	=	Bulk density
K	=	Permeability coefficient
v_A	=	Displacement velocity of the solid medium
u_A	=	Displacement vector of the solid material
ϕ	=	Porosity
σ	=	Incremental stress

4 INJECTION OPTIMIZATION AT THE GEYSERS

This is a new project this quarter and is being undertaken by Research Assistant Zosimo Aunzo and Prof. Roland Horne.

The purpose of this work is to quantify the effects and optimize injection at the Geysers Geothermal Field.

The study will begin by collating all information regarding the injection and production history of the Geyser's Geothermal Field using the production database established by LBL. The data would be analyzed to determine the effect of injection into the reservoir. This would involve correlating injection with the production history of the field. Once a correlation has been established, we will attempt to describe the physics behind the field response.

The bulk of the work that will be done on the earlier part of the project will be on data collection, integration and analysis of production and injection history at the Geysers. After this is done, the field response to injection will be analyzed using techniques similar to those used earlier in analyzing the reinjection strategy of the Palomares Geothermal Field, Philippines.

5 EFFECTS OF SALINITY IN ADSORPTION EXPERIMENTS

This is another new project starting this quarter, and will be performed by Research Assistant Steve Palar and Profs. Roland N. Horne and Henry J. Ramey, Jr.

Past experiments of adsorption used only pure water. This project will analyze the effect of dissolved salts on adsorption using cores which have been previously soaked with brine. In addition, the role of temperature on transient pressure will be investigated.

Salinity may be quite significant, especially during reinjection. The reinjected water may contain salts and the subsequent effect of salinity is to reduce the vapor pressure. The thermodynamics of heat transfer and the production of steam may change with the introduction of increasing salt concentrations.

The objective of the experiment is to establish a relationship between the transient pressure drop after salts have been introduced onto the surfaces of geothermal cores.

The experiment will utilize the existing laboratory equipment, on loan from the USGS. Cores from the Geysers will be used.

6 INTERPRETING MULTIWELL PRESSURE DATA FROM OHAOKI

This investigation is being performed by Research Assistant, Xianfa Deng, and Prof. Roland N. Horne. The purpose of the study is to examine means of estimating reservoir heterogeneity using pressure transient and tracer tests. In the present stage of the project, we have undertaken a field study to reinterpret data from the Ohaaki geothermal using nonlinear regression by matching the pressure data from multiple interference tests, to see how reservoir heterogeneity affects the result.

6.1 Introduction

Using interference testing to evaluate reservoir heterogeneity and average transmissivity and storativity is a convenient and common method in geothermal fields. Twelve interference tests have been performed at Ohaaki geothermal field between six well pairs. Leaver et al [1988] analyzed those testing in an effort to identify a no-flow linear boundary using the inference ellipse method proposed by Vela [1977]. Leaver et al matched the pressure data only one pair at a time. The results are dominated by the local transmissivity and storativity between or around the two wells, so each matching gives a local average different from another. It is hard to say which estimated permeability value can be used as an average for the whole reservoir. Furthermore, by the inference ellipse method, there is considerable flexibility in deciding the location of linear boundary, since each two pairs of data give two ellipses which are sufficient to estimate a location of a linear boundary. A better way would be to match all the data pairs simultaneously, hopefully giving more consistent results.

6.2 Matching by Nonlinear Regression

The parameters matched are bulk transmissivity, kh/μ , storativity, $\phi c_i h$, the location of the linear boundary (two variables needed for identification), and the initial pressures of each active well. There are twelve sets of interference pressure data available, which means we have sixteen parameters to be matched. The theoretical drawdown and buildup curves used in the

analysis were similar to those developed by Eiper [1985], except that the linear boundary effect was included in the curves. To make this possible, a Cartesian coordinate is defined with *BR20* as the origin, so the location of each well is represented by a pair of numbers (x, y) as follows:

BR23 (0.0, 0.0)
 BR13 (-1079.9, -1977.3)
 BR23 (-521, -1230.31)
 BR31 (-1757.5, -878.8)
 BR34 (-2680.3, -2636.4)
 BR19 (-1318, -659.1)

We represent the linear boundary by another pair of (x, y) coordinates representing the point on the boundary which is nearest to the origin of our Cartesian coordinates. The algorithm used for this nonlinear regression problem is similar to the Gauss-Newton method except some corrections on the damping factor.

The results from Leaver et al [1988] are presented in Figure 4 and listed as follows (same units for all data below):

$$kh = 250(d-ft) \quad \phi c_t h = 0.008(ft/psi \cdot 1e4) \quad x_b = -1494(ft) \quad y_b = 2724(ft)$$

This interpretation gives an average residual of 1.999 psi per point (there are 1969 data points for all 12 wells). If we start from this result as an initial guess, after 11 iterations the algorithm finds a solution as shown in Figure 5:

$$kh = 547.92 \quad \phi c_t h = 0.0119 \quad x_b = -1981.07 \quad y_b = -1631.12$$

which gives an average residual of 1.4366 psi per point. Notice that tests *B7* and *B8* are worse than before, since they have less points and contribute less to the residual.

If we add the twelve initial pressures of the active wells as parameters, we can reduce the residual to 0.97 psi per point as shown in Figure 6 with estimated values as follows:

$$kh = 584.96 \quad \phi c_t h = 0.00473 \quad x_b = -3031.12 \quad y_b = -2076.63$$

$$p_i^{B1} = -7.11 \quad p_i^{B2} = -10.50 \quad p_i^{B3} = -53.15 \quad p_i^{B4} = 14.30$$

$$p_i^{B6} = -9.13 \quad p_i^{B7} = -117.83 \quad p_i^{B8} = -67.89 \quad p_i^{B9} = 297.20$$

$$p_i^{B10} = -32.76 \quad p_i^{C1} = 3.36 \quad p_i^{C2} = -24.25 \quad p_i^{C3} = -6.17$$

From Figure 6, we see that four sets of data $B6$, $B7$, $B8$ and $B9$ are not well-behaved. Excluding these four sets, the match was repeated with the remaining eight sets of pressure data. Figure 7 is the result without initial pressures as parameters but with weights to emphasize the early data. The result is

$$kh = 734.75 \quad \phi c_i h = 0.0052 \quad x_b = -1663.09 \quad y_b = -2883.21$$

With initial pressures as parameters without emphasis on early data, we have (Figure 8):

$$\begin{aligned} kh &= 659.31 \quad \phi c_i h = 0.0032 \quad x_b = -5067.12 \quad y_b = 18.74 \\ p_i^{B1} &= -4.88 \quad p_i^{B2} = -2.75 \quad p_i^{B3} = -54.73 \quad p_i^{B4} = 14.38 \\ p_i^{B10} &= -29.48 \quad p_i^{C1} = 12.12 \quad p_i^{C2} = -14.24 \quad p_i^{C3} = 14.83 \end{aligned}$$

With weights and initial pressures as parameters, we end up with

$$\begin{aligned} kh &= 630.98 \quad \phi c_i h = 0.0033 \quad x_b = -1506.85 \quad y_b = 2749.59 \\ p_i^{B1} &= -4.41 \quad p_i^{B2} = 0.379 \quad p_i^{B3} = -61.96 \quad p_i^{B4} = 17.10 \\ p_i^{B10} &= -34.01 \quad p_i^{C1} = 5.96 \quad p_i^{C2} = -28.81 \quad p_i^{C3} = 17.35 \end{aligned}$$

as shown in Figure 9.

All the data above are calculated with $h = 2297(ft)$ and $\mu = 0.34(cp)$.

Notice that in $B3$ of Figure 7, the calculated type curve is parallel and above the actual data and we could not shift it vertically without sacrificing the other matches. All the data matches affect each other here. When initial pressure is allowed to vary, the actual data of test $B3$ are increased by the same amount, resulting in a big jump in the early data as shown in the log-log graphs in Figures 7 and 8.

It is also worth mentioning that the location of the linear boundary is sensitive to the sets of data used. It is likely that there is a northwest/southeast trend of faults, and we always have a higher average permeability than $110(md)$ as suggested by Leaver et al [1988].

Based on these results, it seems likely that the data cannot be interpreted adequately in terms of a single average permeability, nor can the single linear fault model be used with much confidence. As a starting point of this work, this set of field examples demonstrates the need for the consideration of heterogeneity, which is the primary focus of the project.

Type-curve Match for Multi-well Pressure Data of Ohaaki Geothermal Field

Figure 4: Approximate Matching Results from Leaver

Type-curve Match for Multi-well Pressure Data of Ohaaki Geothermal Field

Figure 5: Matching Results without Weights and Initial Pressures as Parameters

Type-curve Match for Multi-well Pressure Data of Ohaaki Geothermal Field

Figure 6: Matching Results with Initial Pressures as Parameters

Type-curve Match for Multi-well Pressure Data of Ohaaki Geothermal Field

Figure 7: Matching Results with Weights Emphasizing Early Data

Type-curve Match for Multi-well Pressure Data of Ohaaki Geothermal Field

Figure 8: Matching Results with Initial Pressures as Parameters

Type-curve Match for Multi-well Pressure Data of Ohaaki Geothermal Field

Figure 9: Matching Results with Weights and Initial Pressures as Parameters

7 ESTIMATION OF ADSORPTION PARAMETERS FROM TRANSIENT EXPERIMENTS

This project is being performed by Research Assistant Ming Qi, together with Profs. Roland N. Horne and Henry J. Ramey, Jr..

During the quarter, we analyzed eight sets of water vapor pressure transient experiment data obtained during the previous quarter (July, August and September, 1992).

7.1 Estimation of the Sorption Isotherm

As mentioned in the previous report, all runs were made under the same conditions that Michael Harr used in 1991 and comparison with Harr's results Harr (1991) were made and discussed. With the newly measured data, we estimated the adsorption isotherm by nonlinear regression.

We first provide a pair of guessed values for A and B in the Langmuir adsorption isotherm and then run the one-dimensional steam flow simulator developed by Nghiem and Ramey (1991) to calculate the steam pressure changing with time. The pressure is matched to the experimental result using nonlinear regression. Having obtained estimates of A and B we can calculate the Langmuir isotherm from Eqn. 30:

$$X = \frac{p/p_{sat}}{A + Bp/p_{sat}} \quad (30)$$

The results of estimated isotherms are shown in Figure 10 through Figure 17.

7.2 Discussion

There are many factors affecting the result of the transient flow experiment and consequently the estimated isotherm. These factors include the temperature, the permeability, the porosity, particle size distribution, rock type, etc. The effects of permeability and porosity are discussed below.

Also the validity of the estimation procedure can be checked by comparing the results obtained by regression with the results obtained from other experiments. There are not many results available for the comparison. One useful set of comparable data is the isotherm measured from the equilibrium experiment by Shubo Shang, as described earlier in Section 1 of this report.

Figure 10: Geysers Unknown Well, Depth 5000 - 5200 Feet, 28-150 Mesh

Figure 11: Geysers Well OF52-11, Depth 5000 - 5200 Feet, 10-150 Mesh

Figure 12: Geysers Well OF52-11, Depth 5000 - 5200 Feet, 20-150 Mesh

Figure 13: Montiverdi Well No.2, 10-150 Mesh

Figure 14: Reykjanes Well No.9, 10-100 Mesh

Figure 15: Geysers Well Megu-15 ST2, Depth 8600 - 8800 Feet, 20-150 Mesh.

Figure 16: Geysers Well OF52-11, Depth 8000 - 8200 Feet, 30-80 Mesh

Figure 17: Geysers Well OF52-11, Depth 8000 - 8200 Feet, 30-150 Mesh

Figure 18: Isotherms from Different Experiments - Montiverdi 2

The same rock sample was used in both transient and equilibrium experiments. The two results are plotted together in Figure 18. The curves have very similar shape and the data are reasonably close. This is an encouraging sign although no firm conclusion can be made based on this single plot. As additional measurements are made, further comparisons will be possible.

7.3 Effect of Permeability

The samples were prepared by pouring the presieved sample into the core holder with the holder being tapped to consolidate the sample as much as possible to gain the largest weight. Permeability is measured after each transient run.

Three types of isotherm were observed as shown in Figures 10 through 17: convex to the pressure axis, concave to the pressure axis and straight line. To examine the effect of permeability on the shape of the isotherms, different permeabilities were used in the nonlinear regression model. The results are shown in Figures 19, 20 and 21. From these figures we can see that although permeability has an effect on the magnitude of the adsorption, the shape of the isotherm curve does not change. This means that even when

Figure 19: Effect of Different Permeability - Geysers Unknown Well

there is an error in permeability or when there is no accurate permeability data available, we can still use this method to estimate the correct shape of the isotherm curve.

7.4 Effect of Porosity

Porosities are calculated by knowing the volume of the sample holder and the weight of the samples. To check the effect of any measurement error, the program was run by using different porosity values. Again the results show that the porosity only affects the magnitude of the adsorption but has no effect on the shape of the isotherm curves. The results of the isotherm plot using different porosities are shown in Figures 22, 23 and 24.

7.5 Conclusions

- Using the one-dimensional steam flow simulator developed by Nghiem and Ramey (1991) combined with nonlinear regression, the Langmuir isotherm parameters can be estimated by matching the pressure transient experiment data.

Figure 20: Effect of Different Permeability - Geysers Well OF52-11

Figure 21: Effect of Different Permeability - Well Montiverdi 2

Figure 22: Effect of Different Porosity - Geysers Unknown Well

Figure 23: Effect of Different Porosity - Geysers Well OF52-11

Figure 24: Effect of Different Porosity - Well Montiverdi 2

- The permeability does not affect the shape of the isotherm curve obtained from the nonlinear regression method.
- The porosity does not affect the shape of the isotherm curve obtained from the nonlinear regression method.

7.6 Future Work

- Whenever possible, larger samples should be used to decrease the effect of the open space between the ends of the sample holder and the pressure transducers.
- The experiment procedure used in the experiment did not taking account the effect of the extra space mentioned above thus the pressures measured were lower than the "real" pressures before the sample holder's valves were opened. This procedure needs to be modified to give more accurate pressure measurement results.
- The pressure transient experiments using noncondensable gas and salt deposited onto the internal surfaces of the rock samples will be carried

out.

- The one-dimensional steam flow simulator considers only the material balance and not the energy balance. The energy balance needs to be added.

References

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