

GEOHERMAL RESEARCH AND DEVELOPMENT PROGRAM

SECOND ANNUAL TECHNICAL REPORT

July 1991 through June 1992

RECEIVED
MAR 04 1993
OSTI

Work Performed Under Grant No. DE-FG07-90ID12934

For
U. S. Department of Energy
Office of Industrial Technologies
Washington, D.C.

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

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

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

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

SGP-TR-140

**Stanford Geothermal Program
Second Annual Technical Report**

**Geothermal Research and
Development Program**

Principal Investigators:

H. J. Ramey, Jr.

Roland N. Horne

F. G. Miller

October 1992

**Department of Energy Grant No.:
DE-FG07-90ID12934. For the period of
July 1, 1991 through June 30, 1992.**



**Stanford Geothermal Program
Interdisciplinary Research in
Engineering and Earth Sciences
STANFORD UNIVERSITY
Stanford, California**

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

for

Annual Report for July 1991 - June 1992

Stanford Geothermal Program
Stanford University

October 8, 1992

1 ADSORPTION OF WATER VAPOR ON RESERVOIR ROCKS

This experimental project is under the direction of Research Associate Dr. Shubo Shang, and Prof. Henry J. Ramey, Jr. The focus of the work is the experimental investigation of adsorption of water onto geothermal reservoir rocks.

Introduction

In vapor-dominated geothermal systems, it has been proposed that liquid might exist as adsorbed liquid in micropores (White, 1973). Evidence from both laboratory studies and field data indicates that storage of liquid as micropore fluid is likely (Ramey, 1990). Measurement of adsorption/desorption of water vapor on reservoir rocks is a crucial step in determining whether adsorption is the storage mechanism for these systems.

Status of the experimental apparatus

A fully automated sorptometer by Porous Material, Inc. (PMI) has been employed in this work. Different versions of the software have been investigated and problems associated with the appropriate application of the sorptometer in the present work have been identified. With the cooperation of PMI, the sorptometer is now believed to function properly up to a pressure of 40 psia for the adsorption of steam. However, there is difficulty in reaching pressures higher than 40 psia with an instrument temperature of 150 ° C. This problem is currently under investigation in PMI.

DISCLAIMER

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

Effort was made to measure the surface area of the rock samples using BET (after Brunauer, Emmett and Teller) methods. However, due to the small surface area of the rock sample, N_2 adsorption failed. Kr was subsequently employed. Unfortunately, the software used for the Kr adsorption test, which is different from that for N_2 since Kr has a much lower saturation pressure at liquid N_2 temperature, does not appear to work successfully. PMI is looking into this problem.

Experimental Results

Results for the measurement of the adsorption/desorption isotherm of water on Unocal shallow reservoir core are summarized here. The size of the rock sample used in the adsorption/desorption test has an equivalent diameter of about 3mm. The volume of the sample used in the tests is approximately 5.6 cm^3 . Knowing the complexity of the adsorption process, it is important to ensure that the rock surface has the same condition prior to each adsorption/desorption isotherm test. This was achieved by heating the sample at 180°C under vacuum for about 4 hours. Reproducible isothermal adsorption curves were obtained after this pretreatment.

The effect of pressure on the amount of steam adsorbed is shown in the adsorption/desorption isotherms. To determine the effects of temperature on adsorption, it is necessary to measure adsorption/desorption isotherms at different temperatures. Figures 1 to 4 show the isotherms obtained on the Geysers shallow reservoir core at 80, 100, 120 and 140°C , respectively. The well and temperature zone of the reservoir where the core was taken was unknown to us.

Discussion

It is interesting to note the shape of the isothermal adsorption curves and the rapid changes at high relative pressures (the ratio of system pressure relative to the saturation vapor pressure). At least two tests were made for each temperature, and different final equilibrium pressures were used. With the adsorption isotherm ending at a low relative pressure, the contribution of adsorption to the total retention of water on the rock is shown clearly (Figures 1 and 2). Upto a relative pressure of around 0.9 at 80°C , and a relative pressure of around 0.85 at 100°C , the amount of water adsorbed increases gradually with increase in pressure due to the building up of the multilayers on the rock surface. For those runs with an adsorption isotherm

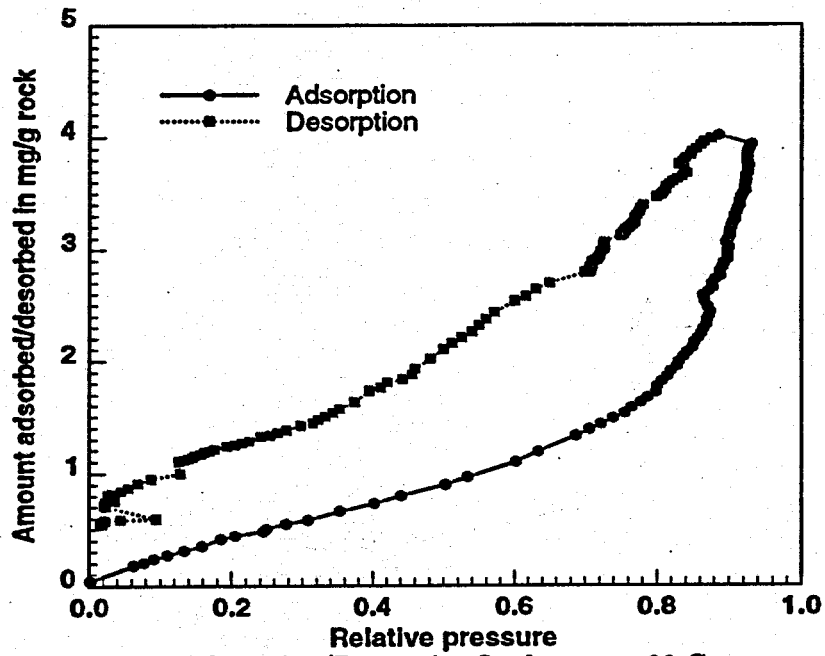


Figure 1: Adsorption/Desorption Isotherms at 80 C

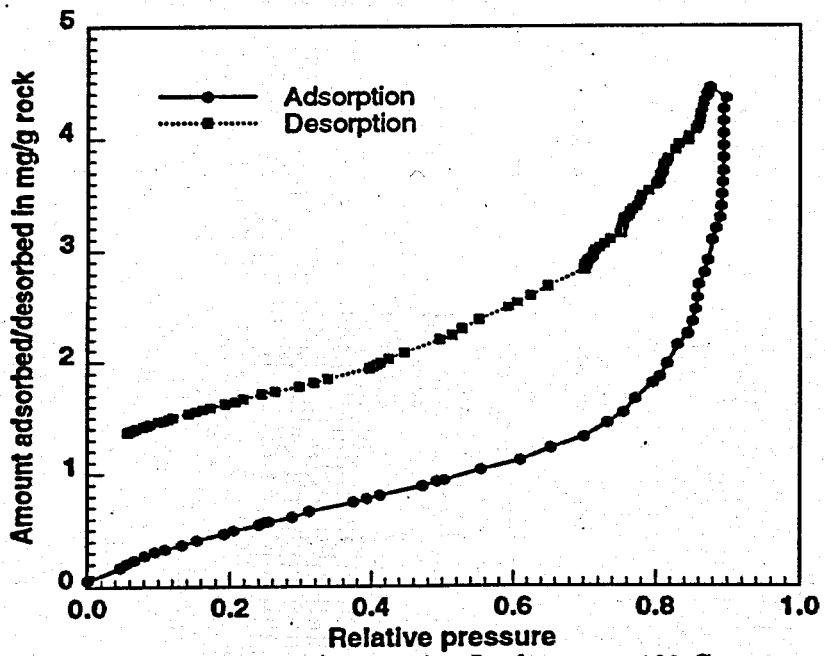


Figure 2: Adsorption/Desorption Isotherms at 100 C

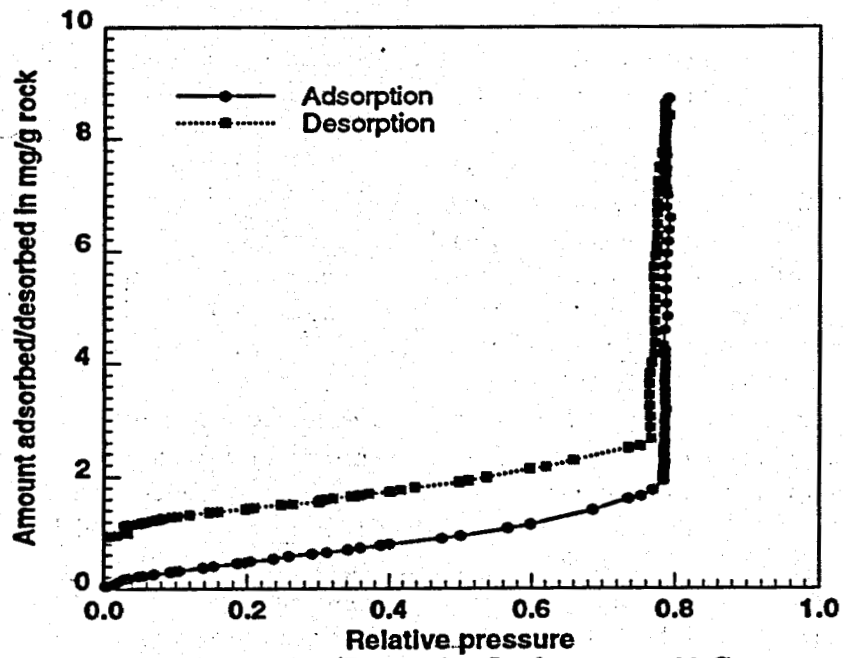


Figure 3: Adsorption/Desorption Isotherms at 120 C

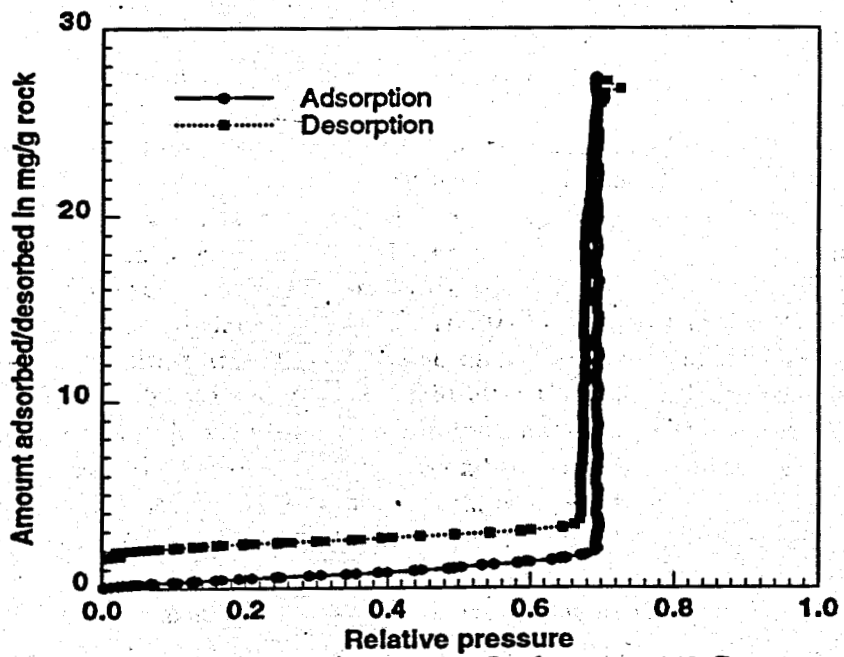


Figure 4: Adsorption/Desorption Isotherms at 140 C

ending at a high relative pressure, the contribution of condensation to the total water retention is significant (Figures 3 and 4). With heating and outgassing before each run, adsorption isotherms are reproducible. However, the desorption isotherms are affected by the final state of adsorption. It is logical to suggest that the system is adsorption dominated at low relative pressures, and changes to capillary condensation dominated at higher relative pressures. Adsorption is a surface phenomena while capillary condensation is related to the geometry of the porous media. These processes are similar in nature i.e they both cause vapor to condense on to the solid, and the two processes affects each other in a complicated manner. Thus, the results of an adsorption test do show a lower vapor pressure than the standard saturation pressure of water. However, it is hard to determine the cause of this vapor pressure lowering since the status of the rock surface, e.g. chemical composition and geometrical structure, is largely unknown.

Both Hsieh and Ramey (1983) and Herkelrath et al. (1983) reported temperature insensitivity of adsorption on some rock samples. If this can be generalized for all geothermal rock materials, considerable laboratory work can be avoided. However, adsorption does appear to depend on temperature for the sample shown here, at least at high relative pressures. Figure 5 compares the adsorption isotherms at the four temperatures tested. The relative pressure at which the adsorption isotherm has a dramatic change decreases as temperature increases. This is an unexpected observation and further investigation is planned.

Significant hysteresis exists for steam adsorption/desorption on the Geysers Shallow Reservoir rocks. Physical heterogeneity of the rock must be responsible for the presence of the hysteresis at high relative pressures. Scanning Electron Micrographs (SEM) show the complexity of the physical structure. However, at very low pressures, there appears to be irreversible adsorption. Figure 6 shows two sets of isotherms obtained at 120°C. The first set was obtained according to the normal procedure, while the second set was obtained by starting the test right after the completion of the first test without going through the normal pretreatment. As shown in Figure 6, the amount adsorbed is smaller in the second test and the amount retained at the end of the second desorption isotherm is also reduced.

Adsorption is important in geothermal reservoirs, not only in itself but also in inducing condensation to take place easier than in the absence of adsorption. Experimental desorption isotherms are affected by the final state of the adsorption run. Understanding of these phenomena will certainly assist the design of a reinjection process.

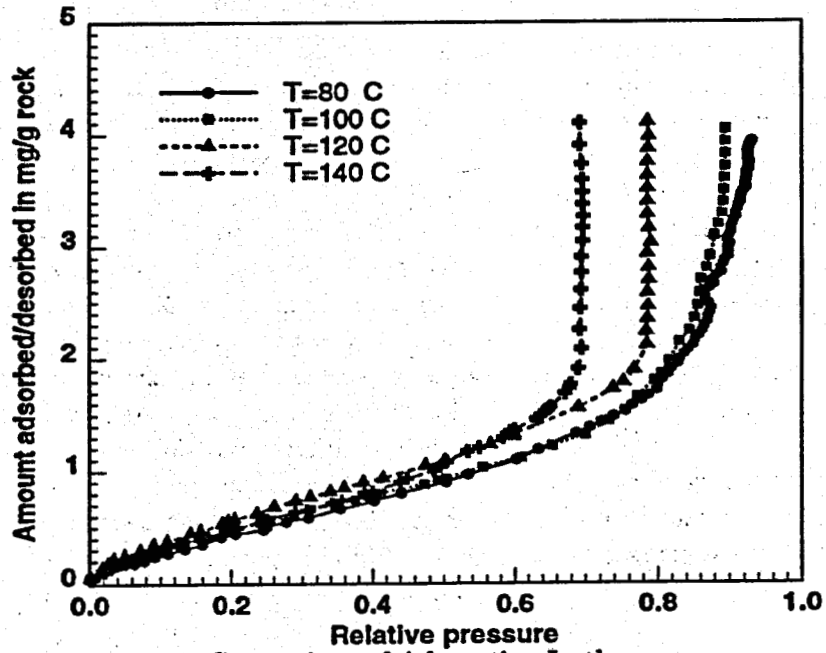


Figure 5: Comparison of Adsorption Isotherms

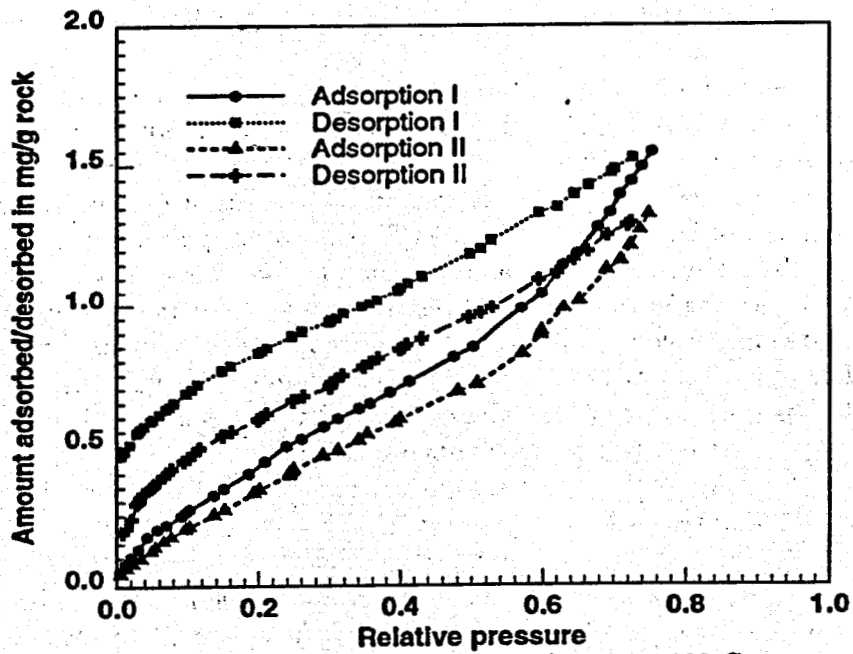


Figure 6: Adsorption/Desorption Isotherms at 120 C

Future Work

The ultimate goal of this project is to collect sufficient experimental adsorption/desorption data for various geothermal reservoir rocks to be able to extrapolate the laboratory data to field conditions so that one can compute reservoir performance in a correct manner.

Currently, we have a number of samples for testing. Two pieces of Geysers graywacke (Unocal well NEGU-17) are available from UURI. Ten samples from well cuttings were sent by ENEL, Italy. In addition, we have samples from Iceland and Mexico. Adsorption tests similar to the ones described will be performed on the samples available.

Additional work will be undertaken to investigate the possibility of running adsorption tests at temperatures higher than 140°C so that we can simulate field reservoir temperature and pressure conditions.

Measurement of the surface area of the rocks will be made once the problems in the software used for the test are fixed by PMI. Scanning electron micrographs of the rock samples will be taken so that a comparison of the structural effect on the hysteresis can be made.

2 DRAWDOWN AND BUILDUP PRESSURE ANALYSIS IN MULTIWELL RESERVOIRS

This is the continuing work of the reservoir interpretation project performed by research assistant Xianfa Deng and Professor Roland N. Horne.

The objective of this study is to investigate how the neighboring wells affect the buildup pressure data in the test well if the neighboring wells are producing during the testing. The study is the preliminary part of a broader project, which will look at the simultaneous analysis of data not only from different wells, but also from different types of geothermal well tests (for example, pressure transient and tracer tests). Before embarking on the broader study, it has been necessary to first complete the current understanding of some aspects of multiwell pressure transient tests. In particular, the common use of superposition to create the effect of closed drainage areas is not fully accurate in the case of buildup tests, since the apparent "image" wells do not replicate the closing of the testing well. The tested well is shut in, but the neighboring wells continue to produce.

If there are an infinite number of wells, the testing well is producing at constant rate q first and at constant rate 0 after t_{pD} , and if all the

neighboring wells are producing at the constant rate q all the time, then the pressure solution in Laplace space for the infinite system is:

$$\bar{p}_D(r_{1D}, r_{2D}, \dots, t_{pD}, z) = \frac{r_{eD}(1 - e^{-st_{pD}/r_{eD}^2})K_0(r_{1D}\sqrt{z}/r_{eD}) + \sum_{n=2}^{\infty} K_0(r_{nD}\sqrt{z}/r_{eD})}{z^{\frac{3}{2}}(K_1(\sqrt{z}/r_{eD}) + C_D\sqrt{z}/r_{eD}K_0(\sqrt{z}/r_{eD}))}$$

where r_{nD} is the distance between observation well 0 and well n . The derivation of this solution makes use of the commonly invoked assumptions, namely single phase flow into line source wellbores from a homogeneous and isotropic porous medium.

As examples, for the six-well and infinite-well systems illustrated in Figure 7, Figures 8 and 9 show a comparison of drawdown and buildup curves. The distances in x direction and in y direction between any two neighboring wells are 500 feet, and the testing well and observation well are located at $(0,0)$, so the pressure response due to the production of infinite neighboring wells is

$$\sum_{m=1}^{\infty} \sum_{n=1}^{\infty} [f(r_{m,n}) + f(r_{m,-n}) + f(r_{-m,n}) + f(r_{-m,-n})] + \sum_{m=1}^{\infty} [f(r_{m,0}) + f(r_{-m,0}) + f(r_{0,m}) + f(r_{0,-m})]$$

where

$$f(r_{m,n}) = \frac{K_0(r_{m,n}\sqrt{z}/r_{eD})}{z^{\frac{3}{2}}(K_1(\sqrt{z}/r_{eD}) + C_D\sqrt{z}/r_{eD}K_0(\sqrt{z}/r_{eD}))}$$

and

$$r_{m,n} = \sqrt{(m * a - x_w)^2 + (n * b - y_w)^2} * \frac{1}{r_w}$$

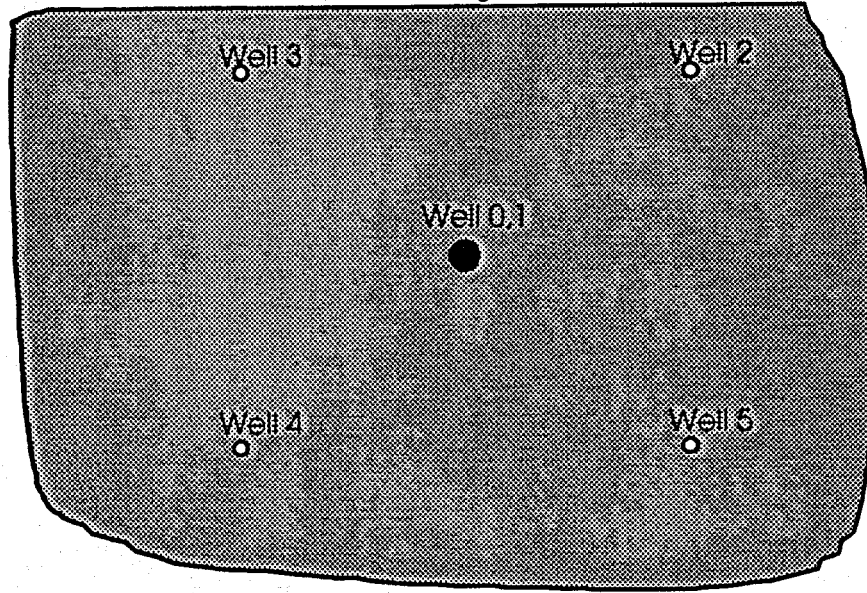
with $a = b = 500.0$ feet, $x_w = y_w = 0.0$ feet and $r_w = 0.3$ feet. Figures 10 and 11 show the buildup part of these two different systems. It can be seen that in the infinite-well system the pressure drops rapidly at long time due to depletion.

With slight modification, the formula above can be used to express the pressure responses (drawdown or drawdown and buildup) for a well in a rectangle with either a closed boundary or a constant pressure boundary.

Drawdown case

$$\bar{p}_D(r_{1D}, r_{2D}, \dots, C_D, s) = \frac{(1 - e^{-st_{pD}}) \sum_{n=0}^{\infty} K_0(r_{nD}\sqrt{s})}{s^{\frac{3}{2}}(K_1(\sqrt{s}) + C_D\sqrt{s}K_0(\sqrt{s}))}$$

Six-well System



Infinite-well System

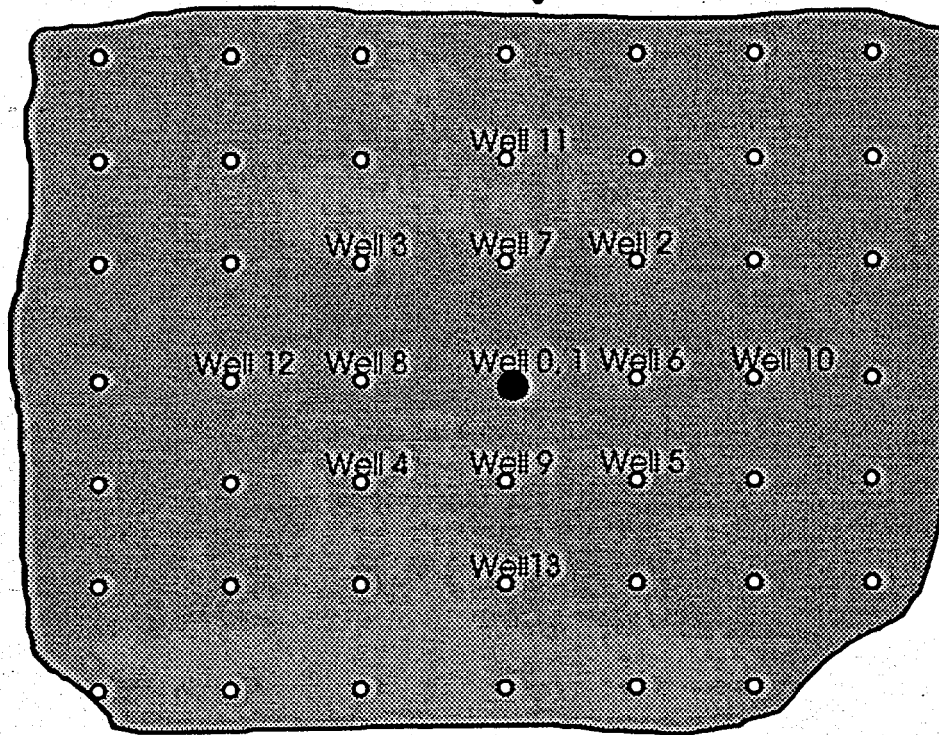


Figure 7: Configuration of six well and infinite array systems

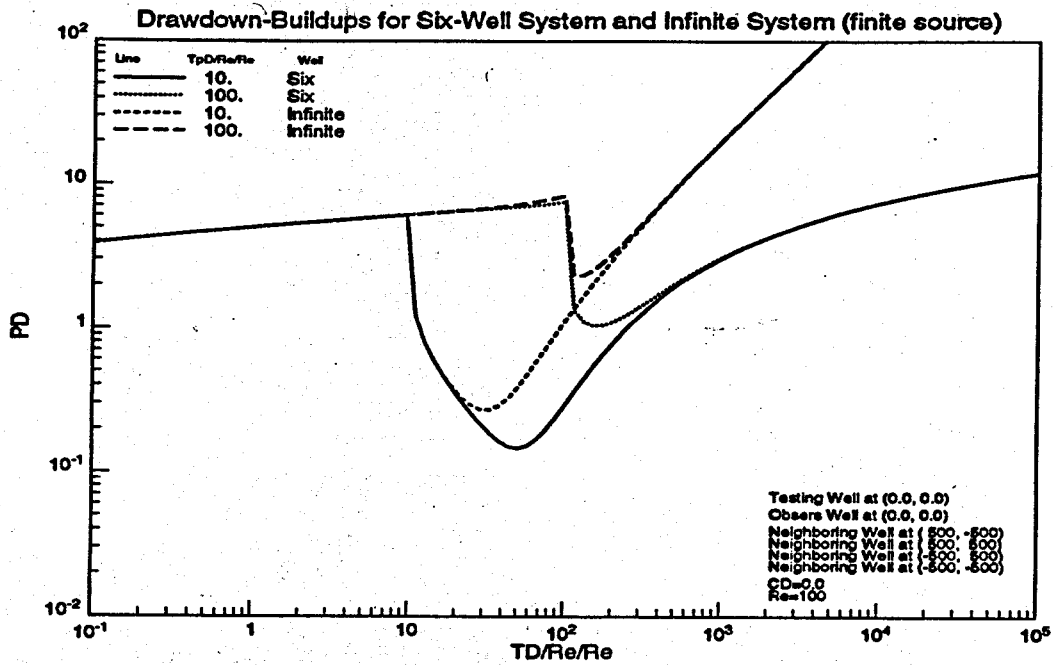


Figure 8: Pressure response vs production time with no wellbore storage

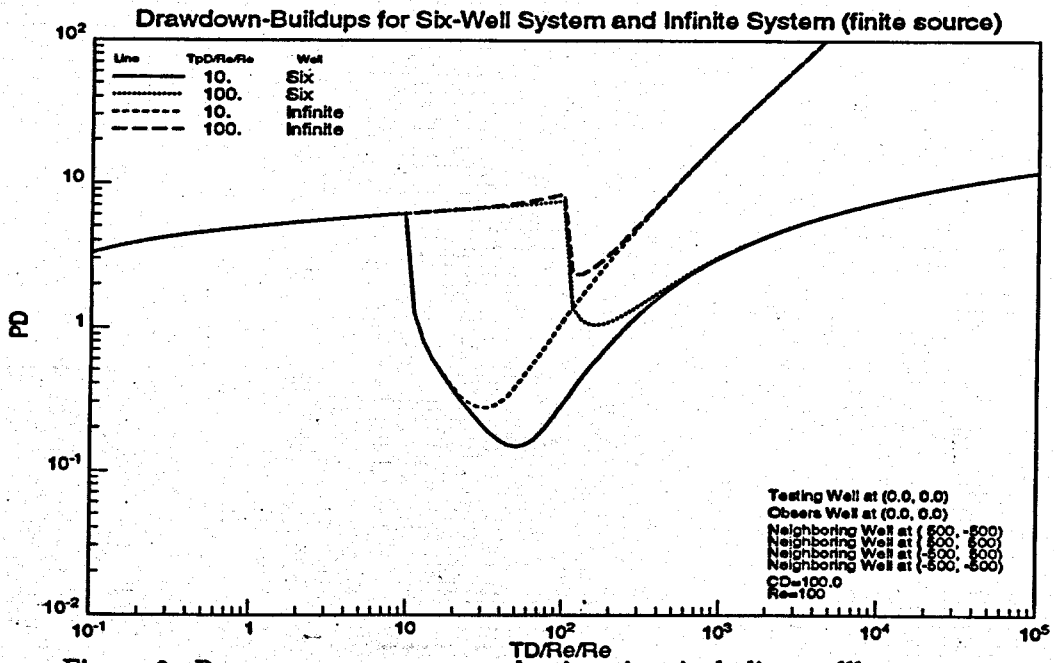


Figure 9: Pressure response vs production time including wellbore storage effect

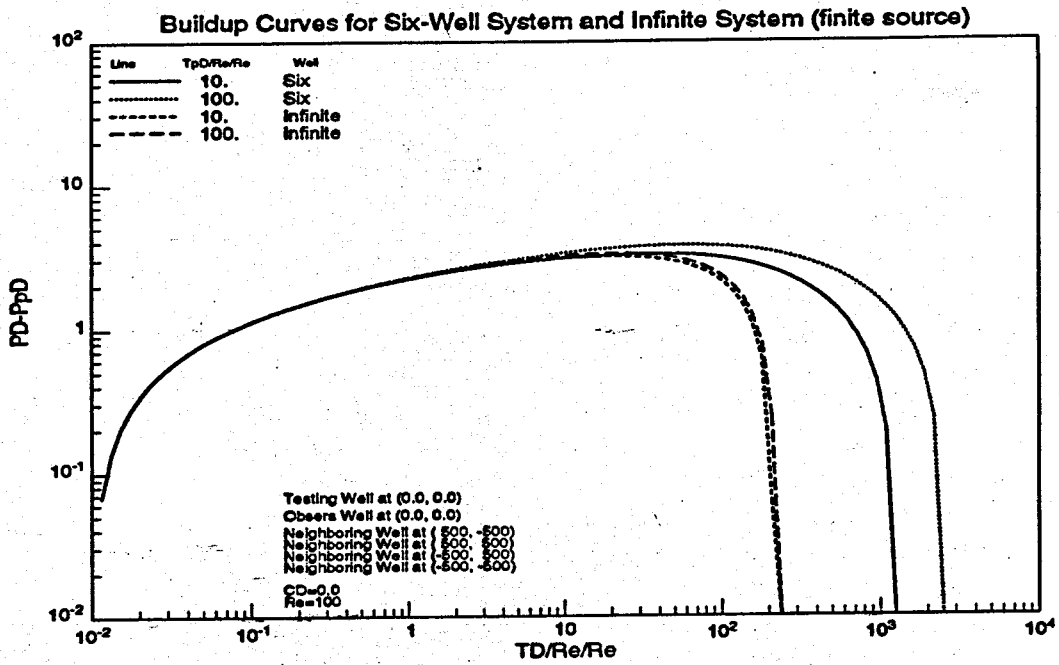


Figure 10: Pressure buildup response vs time after shut-in with no wellbore storage

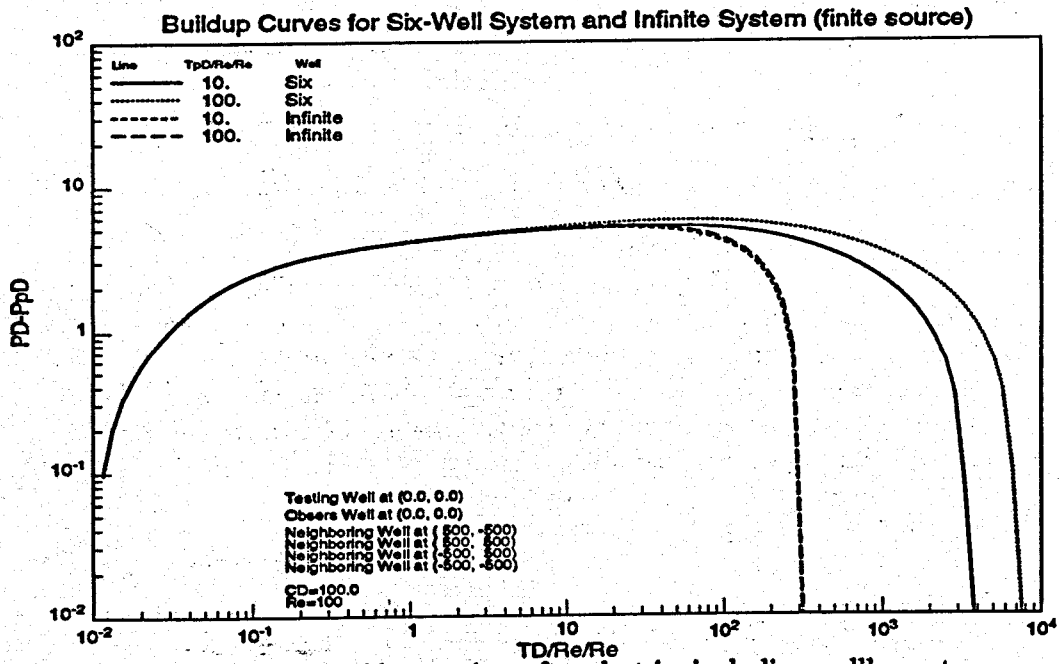


Figure 11: Pressure buildup vs time after shut-in, including wellbore storage effect

Drawdown and buildup case

$$\bar{p}_D(r_{1D}, r_{2D}, \dots, t_{pD}, C_D, z) = \frac{r_{eD}(1 - e^{-z t_{pD}/r_{eD}^2}) \sum_{n=0}^{\infty} K_0(r_{nD}\sqrt{z}/r_{eD})}{z^{3/2}(K_1(\sqrt{z}/r_{eD}) + C_D\sqrt{z}/r_{eD}K_0(\sqrt{z}/r_{eD}))}$$

where r_{0D} is the distance between testing well and observation well, and r_{nD} represents the distance between the observation well and any image well or neighboring well. Similar expressions can be written for a partial penetration well in a reservoir with no flow or constant pressure boundary where superposition by images is applicable, as discussed in a personal communication from Al-Hussainy[1991]. As an example, the pressure responses are presented in Figure 12 and Figure 13 for different conditions in a rectangular reservoir of 800 × 500 feet, thickness 50 feet, permeability 100 md in both radial and vertical directions, testing well and observation well at (100 feet, 100 feet), well radius 0.3 feet. The well partially penetrates the upper $\frac{3}{5}$ of the thickness and the pressure is measured both at the bottom of the well and at the top of the completion interval. The difference of pressure responses between partial penetration and full penetration exists from early time through late time. So if the partial penetration effect is not considered, the permeability of the reservoir might not be correctly interpreted.

3 ADSORPTION PARAMETERS FROM EXPERIMENTAL DATA

This project is being performed by research assistant Ming Qi, together with Professors Roland N. Horne and Henry J. Ramey, Jr..

The objective of the work is to develop the means to infer adsorption and desorption isotherms from reservoir performance history matching, both in the field and also in transient laboratory experiments. In the current stage of the project, we have recently started collecting data from the transient adsorption experiments. Having developed a parameter estimation program consisting of a simulation part and a regression part, the transient experimental data can be used to estimate a pair of constants needed for the Langmuir equation.

However, only a small number of vapor pressure transient experimental data are available. Harr (1991) carried out an experimental study on the laboratory measurement of sorption in porous media. A series of equilibrium sorption measurement were made by using the PMI Sorptometer

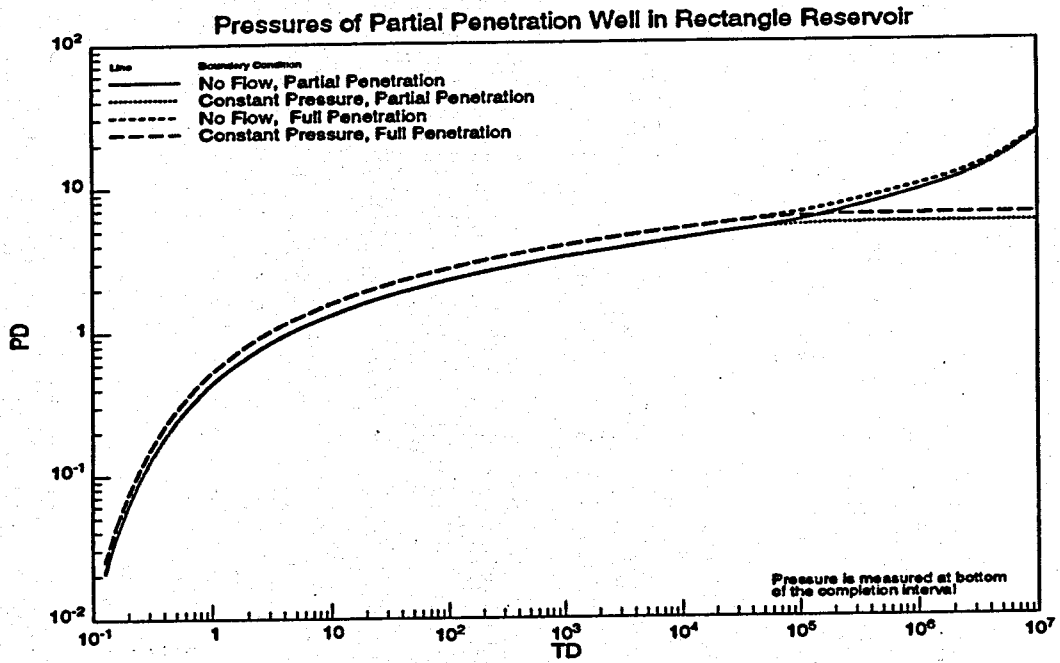


Figure 12: Drawdown pressure response vs production time

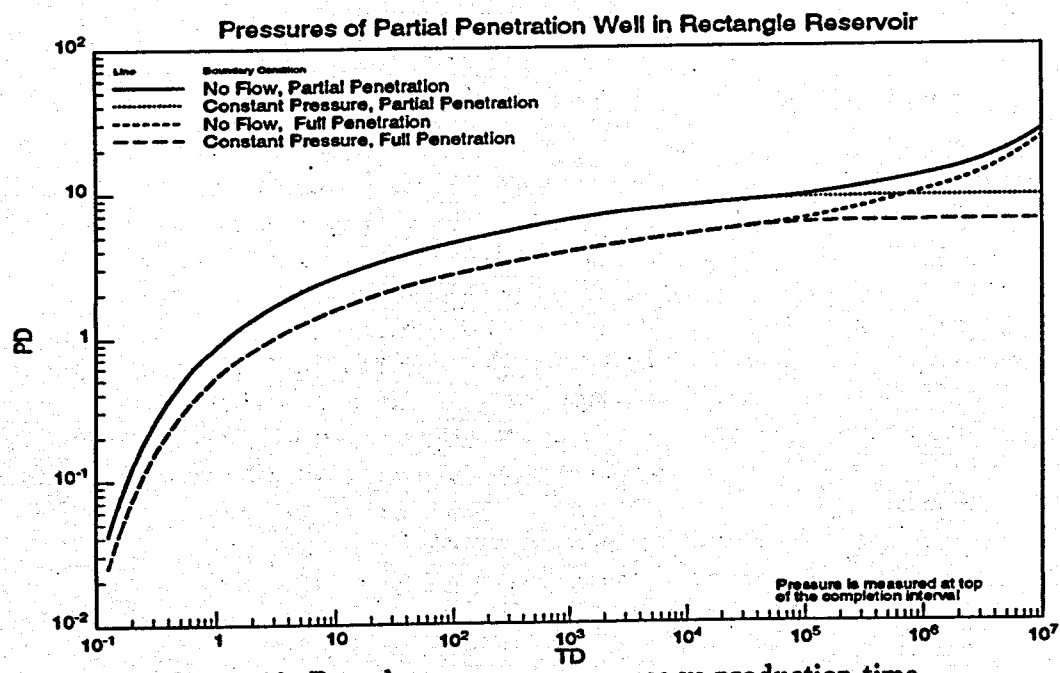


Figure 13: Drawdown pressure response vs production time

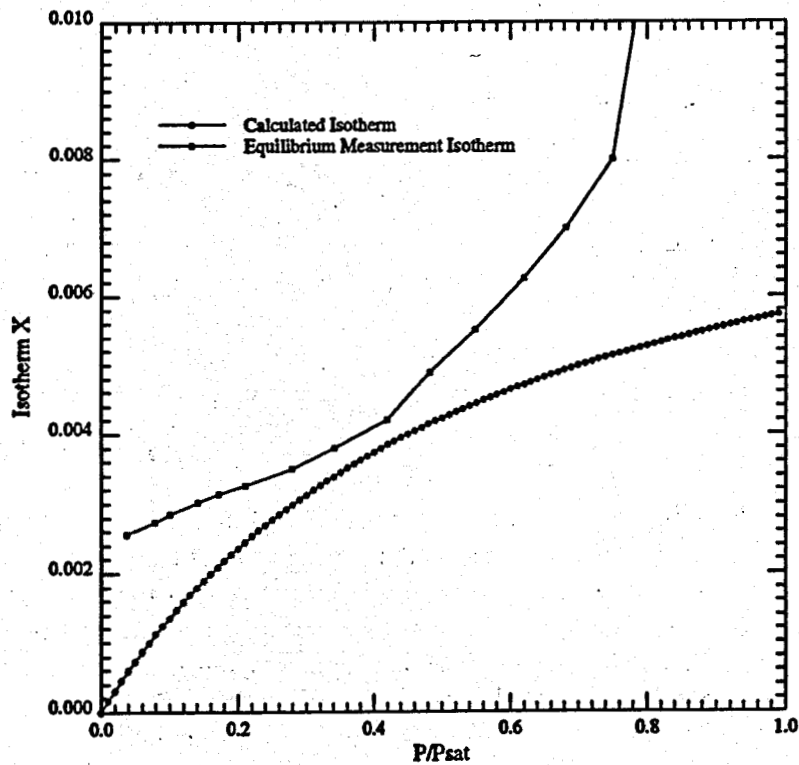


Figure 14: Comparison of Calculated and Measured Isotherms

but only four transient desorption measurements were made due to limited time. All four set of results have been studied and used to test the parameter estimation program. From that preliminary study it was shown that the program could give a reasonably good match of the transient pressures (these results were reported in the Stanford Geothermal Program quarterly report for Jan.-Mar. 1992). Two estimated constants could thus be used to calculate the isotherm. However, a comparison of the calculated isotherm with the experimental isotherm obtained from equilibrium measurements showed large disagreement in some cases (Figure 14).

To further study the problem, more experimental results are needed. Also, the disagreement of calculated isotherm and the isotherm of equilibrium measurement indicates that the pressure decline curve may not be sensitive to the two parameters being estimated. Alternatively, the Langmuir equation may not be an appropriate model of the adsorption isotherm in the cases studied and other forms of the isotherm will be tested. Currently,

the work is focusing on the pressure transient experiment. The equipment being used is the same as that used by Harr (1991), namely the transient adsorption apparatus on loan from the U.S. Geological Survey. One initial run has recently been made and the results are being analyzed. As soon as the adjustments of the equipment are finished, a series of transient pressure experiments will be performed and the results will be available for further analysis.

4 TRITIUM TRACER MOVEMENT AT THE GEYSERS

This project, by research assistant John W. Hornbrook, and Prof. Roland N. Horne, is intended to aid understanding of the characteristics of injection of water into vapor-dominated geothermal reservoirs by investigating long-term observations of tritium tracer movement at the Geysers. The project has begun with the development of analytical solutions for the flow of vapor through porous material with adsorption effects included. After considering various options, the method of Fitzgerald and Woods presented at the 1992 Stanford Workshop on Geothermal Engineering appears to be at least a useful approach to the problem. In this method, a nonlinear diffusion equation is solved by similarity, with the nonlinearity contained in the diffusion coefficient. In the work so far, we have rederived the diffusion equation including adsorption effects and are preparing to investigate the effects of adsorption on injection of water into and production of vapor from various geothermal systems.

Derivation of the nonlinear diffusion equation including adsorption effects begins with the material balance:

$$\frac{\partial \rho_v (1 - S_w)}{\partial t} + \rho_w \frac{\partial S_w}{\partial t} + \nabla(u_v \cdot \nabla \rho_v) = 0 \quad (1)$$

The second term in this equation accounts for the mass adsorbed. Adsorption is related to liquid saturation by the following expression:

$$S_w = \frac{1 - \phi}{\phi} \frac{\rho_r}{\rho_w} X \quad (2)$$

After substituting Eqn. (2) into Eqn. (1) and rearranging, we obtain:

$$\left[\left(1 - \left(\frac{1 - \phi}{\phi} \right) \frac{\rho_r}{\rho_w} X \right) + \left(\frac{\partial X}{\partial \rho_v} \left(\frac{1 - \phi}{\phi} \rho_r - \left(\frac{1 - \phi}{\phi} \right) \frac{\rho_r \rho_v}{\rho_w} \right) \right) \right] \frac{\partial \rho_v}{\partial t} + \nabla(u_v \cdot \nabla \rho_v) = 0 \quad (3)$$

After including Darcy's law for the velocity term in Eqn. (3) and rearranging, we obtain the following expression by following the method of Fitzgerald and Woods (1992):

$$\frac{\partial p}{\partial t} - \alpha \nabla \cdot ((p_1 + p) \nabla p) = 0 \quad (4)$$

where:

$$p = (p - p_{\infty}) / (p_{sat}(T_{\infty}) - p_{\infty}) \quad (5)$$

$$p_1 = p_{\infty} / (p_{sat}(T_{\infty}) - p_{\infty}) \quad (6)$$

$$\alpha = \frac{k(p_{sat}(T_{\infty}) - p_{\infty})}{\beta \mu \phi} \quad (7)$$

$$\beta = \left[\left(1 - \left(\frac{1-\phi}{\phi} \right) \frac{\rho_r}{\rho_w} X \right) + \left(\frac{\partial X}{\partial \rho_v} \left(\frac{1-\phi}{\phi} \rho_r - \left(\frac{1-\phi}{\phi} \right) \frac{\rho_r \rho_v}{\rho_w} \right) \right) \right] \quad (8)$$

The time for pressure and vapor diffusion is dependent upon α , and, therefore, upon the amount and rate of adsorption as shown in Eqn. (8). Currently, we are evaluating the β term with the Langmuir and BET isotherms used as a basis for calculation. Once the β term is evaluated over a range of pressures, we will proceed in determining the rate of pressure and vapor diffusion in geothermal reservoirs. This work will extend the work of Fitzgerald and Woods (1992) and will provide solutions which include both adsorption and desorption effects.

5 ADSORPTION MODELING

This project is being undertaken by research assistant, Richard Holt, and Prof. Henry J. Ramey, Jr. The objective is to develop methods to include adsorption effects into standard geothermal reservoir simulators.

Physical adsorption of steam has increasingly become recognized as an important phenomenon in vapor-dominated geothermal reservoirs. A method was developed which allows the effects of adsorption to be modeled using TETRAD, a commercially available geothermal simulator. The method consists of replacing the standard steam table with a modified steam table. This new steam table was generated by combining the Langmuir isotherm adsorption model with an energy and mass balance. The TETRAD simulator, when run with the pseudo steam table, approximately matches the pressure, production, and saturation behavior of a desorbing geothermal system.

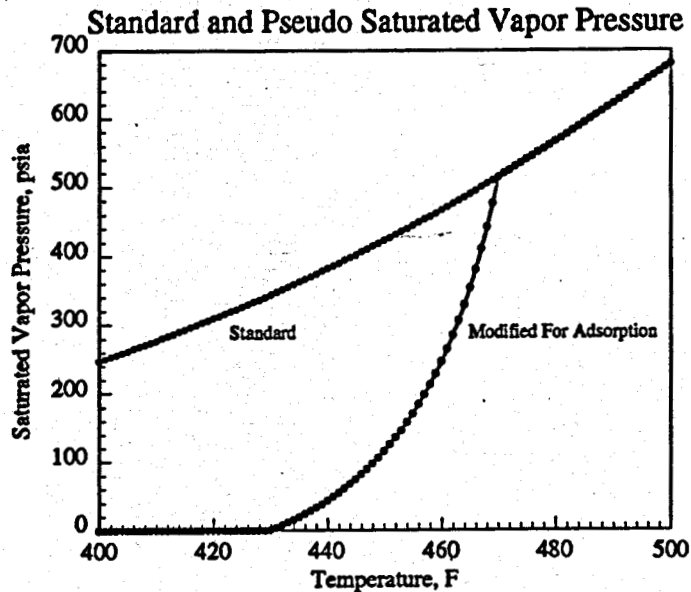


Figure 15: Comparison of the standard and pseudo steam tables.

Adsorption can be described as the existence of an immobile layer of liquid on the surfaces within a porous medium, at pressures below saturation pressure. The presence of an adsorbed liquid water layer in rocks has been shown experimentally to lower the vapor pressure at a given temperature. The pseudo steam table accounts for this vapor pressure lowering. Figure 15 shows saturated vapor pressure versus temperature for both the standard and pseudo steam tables. Notice that a geothermal system which follows the pseudo steam table will have large changes in pressure for modest changes in temperature.

A research project on the subject of adsorption and desorption phenomena in rock systems is presently in its beginning stages. The goal of this new study is to perform and analyze adsorption experiments on rock samples under varying conditions, in order to be able to generalize the kind of pseudo steam table approach already completed.

This work will use the PMI sorptometer. The PMI system is computer controlled and allows sorption experiments to be done rapidly. Experiments can be performed on a wide range of materials over a wide range of temperature.

The results of these experiments will be analyzed in a theoretical manner. Predictive correlations can be generated for various materials under various

conditions. In addition, adsorption and desorption behavior may provide a useful method of understanding porosity and microporosity structure of rocks. Finally, insight gained from the experiments and analysis will be cast into a form which can be used in reservoir simulation.

6 EFFECTS OF EARTH TIDES ON DOWN-HOLE PRESSURES

This study, by research assistant Edgar Dias and Prof. Henry J. Ramey, Jr., has recently been initiated. The objective is develop methods to use the phase shifts observed between tidal forces and downhole pressure measurements in geothermal and water wells.

So far, a literature survey has been completed to understand the current work in this field. Most practical methods involved the use of "efficiency factors" to account for the response of the reservoir to earth tides. The study will continue by attempting to derive the basic equations governing the physical process at the reservoir level, from first principles. This will involve integrating the mechanics of soil structure and its dilatation, into the governing equations. Hopefully, this will lead to a tractable mathematical model, which will highlight the effects of various reservoir parameters on amplitude and phase of the response. Ultimately, reservoir parameters such as permeability and porosity may be estimated.

Nomenclature

a	=	equal distance between wells in x direction
b	=	equal distance between wells in y direction
C_D	=	dimensionless wellbore storage coefficient
K_0, K_1	=	modified Bessel functions
p	=	pressure
p_{sat}	=	saturation pressure
p_∞	=	pressure at infinity
p_D	=	dimensionless pressure response at observation well
q	=	flow rate of testing well before shut-in
r_{eD}	=	dimensionless reference distance
r_{nD}	=	dimensionless distance between observation and neighboring wells
r_w	=	wellbore radius
$t_{p,D}$	=	dimensionless producing time before shut-in at testing well
S_w	=	water saturation
T	=	temperature
T_∞	=	temperature at infinity
u_v	=	vapor velocity
X	=	mass adsorbed per mass of rock
z	=	Laplace variable
well 0	=	observation well
well 1	=	testing well
well n ($n > 1$)	=	neighboring well or image well
ρ_v	=	vapor density
ρ_r	=	rock density
ρ_w	=	water density
ϕ	=	porosity

References

- Herkelrath, W.N., Moench, A.F. and O'Neal II, C.F., Laboratory Investigation of Steam Flow in a Porous Medium, *Water Resources Research*, Vol. 19, No. 4, 931-937 (1983).
- Hsieh, Chih-Hang and Ramey, H.J., Jr., Vapor-Pressure Lowering in Geothermal Systems, *SPEJ*, 23(1), 157-167 (1983).
- Harr, M.S., Laboratory Measurement of Sorption in Porous Media,

MS report, Stanford University, 1991. SGP-TR-138.

- Ramey, H.J., Jr., Adsorption in Vapor-Dominated Systems, Geothermal Program Review VIII, April 18-20, 1990, San Francisco, CA.
- Fitzgerald, S.D. and Woods, A.W., The injection of water into and extraction of vapor from a geothermal reservoir, *Geothermics*, submitted (1992).
- White, D.E., Characteristics of Geothermal Resources, Ch. 4, Geothermal Energy, Eds Kruger and Otte, Stanford Press, p.69 1973.
- Stanford Geothermal Program: Quarterly Report for January, February and March, 1992.
- Al-Hussainy, R., personal communication to Roland N. Horne, August 1991.