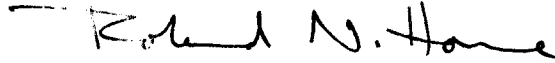# THE EFFECTS OF NON-CONDENSIBLE GAS AND SALINITY ON STEAM ADSORPTION

A REPORT
SUBMITTED TO THE DEPARTMENT OF PETROLEUM
ENGINEERING
OF STANFORD UNIVERSITY
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
MASTER OF SCIENCE

By
Steve Palar
June 1994

I certify that I have read this report and that in my opinion it is fully adequate, in scope and in quality, as partial fulfillment of the degree of Master of Science in Petroleum Engineering.

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Roland N. Horne
(Principal advisor)

Acknowledgements

Abstract

Water adsorption in geothermal reservoir materials was investigated by a transient flow technique using steam and CO_2 gas. Theoretical and experimental results indicate that water adsorption exists in the vapor-dominated type of reservoir, but experiments in the past have been limited to pure gases.

The common presence of CO_2, a non-condensible gas, in a geothermal reservoir necessitated a study of the effect of partial CO_2 concentration on adsorption. Experimental laboratory work using a crushed Geysers rock sample at low pressure was carried out. Transient pressure exerted by steam pressure inside the sample was measured against time during a desorption process. It was found that the partial presence of CO_2 did not significantly affect the adsorption of water.

A **5%** by weight of saline solution was added to the rock sample. Addition of salt to the sample enabled it to adsorb more mass of steam per unit mass of rock sample. This inference was obtained by means of a nonlinear regression program, which matched to the results of a one-dimensional geothermal simulator.

This series of experiment used different sizes of sample, which came from The Geysers geothermal wells.

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Section 1

INTRODUCTION

It is believed that vapor-dominated geothermal reservoirs (e.g. The Geysers) have liquid water in their pore space. The existence of the liquid water has been detected by using the following approaches:

- gravity & seismic method (Denlinger, 1979)
- material balance method (Ramey, 1990)

More steam production has been observed from The Geysers than can be accounted for by superheated vapor thermodynamics. Storage of the huge quantities of steam produced so far would require an improbably large reservoir thickness. Due to the density difference between water and steam, large quantities of steam can be stored by adsorption. The theory of adsorption provides a good explanation for the existence of the liquid water in this type of reservoir.

Surface adsorption plays a major role in the retention of liquid water in micropores at pressures below the saturation pressure. Since the density of liquid is approximately ten times greater than that of steam vapor, up to ten times the mass of the steam can be stored as adsorbed water in the same volume of reservoir.

The presence of adsorbed liquid water in a porous medium creates an apparent lowering of the saturated vapor pressure at a particular temperature. This explains the presence of the two-phase water and steam, under conditions that would normally be superheated. Adsorbed liquid water has properties different than normal liquid water.

Economides, et. al. (1982) wrote that properties, such as density, compressibility and viscosity might be different for the two waters.

Using kinetic theory, Langmuir (1916) investigated surface adsorption. His modified isotherm equation is:

$$X = \frac{\frac{P}{P_{sat}}}{A + B\frac{P}{P_{sat}}}$$

where:

X denotes the weight ratio of the adsorbate (steam) to the adsorbent (rock).

P / P_{sat} represents the ratio of pressure to the saturation pressure of steam at a particular temperature. Terms **A** and B are constants that determine the shape of the isotherm.

The limiting condition of this equation is that only one adsorption layer forms at each adsorption site. In practice this may not be true, however it has been found (Nghiem and Ramey, 1991) that this equation successfully matches experimental data over a wide range of saturation values.

A study of steam adsorption using transient flow experiments was performed by Herkelrath et al. from USGS (1983). Transient experiments using superheated steam were conducted by measuring the pressure of a porous sample during a sudden change in pressure. **A** delay in the pressure drawdown was observed in steam, compared to the drawdown in nitrogen. The delay was attributed to steam adsorption, since nitrogen is a non-adsorbing material.

A series of adsorption studies have been conducted by the Stanford Geothermal Program. In his study of vapor pressure lowering in porous media, Hsieh (1980) measured the water adsorbed on rock samples. He showed that the the mass of adsorbed steam was much more than that of pore steam.

Luetkehans (1988) investigated steam adsorption in geothermal reservoir rocks. Using specially constructed laboratory equipment to measure steam adsorption, she was able to observe adsorption. However the true magnitude of the adsorption was

questionable due to difficulties in establishing equilibrium.

Using the same equipment as in Herkelrath's study with slight modification, Harr (1991) experimented with steam.flow in porous media. His experiments indicated the effect of adsorption on steam flow. The sample holder used in the Harr's experiment was only 30-cm long, whereas the distance between the two pressure transducers was almost 90 cm. This effect was not taken into account. The current experiment used a longer core holder *(58.5* cm) to minimize the distance between the sample and the pressure transducers.

The most recent study was performed by Qi (1993), which incorporated a nonlinear regression program to infer the parameters of Langmuir isotherm equation. This involved performing transient flow experiments again using the same equipment as Harr (1991) and Herkelrath et al (1983).

Initially steam was supplied by an external steam generator, located outside the airbath. Problems with condensation in the connecting pipe between the airbath and the steam generator necessitated the use of a steam vessel inside the airbath. Qi (1993) modified the operating procedure to use the inside steam vessel. Hence the current experiment continued using steam generated from the inside of the airbath, except one single run for comparison purposes.

All the above studies used only pure steam in the sample. The current study incorporated a partial addition of CO_2 to the steam in order to determine any relationship between CO_2 and steam adsorption. The second part of this study investigated the effect of salt's addition to a geothermal rock sample. The purpose of the latter study was to determine the effect of salt on steam adsorption.

1.1   Effects of CO_2

Non-condensible gases are common in geothermal fields. The mole percentage of the non-condensible gases varies among reservoirs, apparently depending on the composition of rock. Organic matter in sedimentary reservoir rock will give more CO_2 than

volcanic rock.

The field concentrations of non-condensible gases **as** reported by Armstead (1978) are **as** follows:

Geothermal Field	Concentration by weight
Wairakei	0.35% to 0.5%
The Geysers	0.05% to 7.5%
Cerro Prieto	about 1.25%
Larderello	4.5% to 5%
Matsukawa	1.1%

The data for The Geysers has been revised to incorporate new data (Haizlip & Truesdell, 1991). Of the non-condensible gases, CO_2 forms the dominant component, 80 % to 97% by weight, with the remaining gases are H_2S, CH_4, N2, etc. (Armstead, 1978).

CO_2 was chosen to represent non-condensible gas in this experiment for the following reasons:

a. CO_2 is by far the most common non-condensible gas found in a geothermal field,
b. CO_2 is easily available in the market, sold in gas cylinders,
c. CO_2 gas is inexpensive, and is a safe gas to use in the laboratory.

In The Geysers, Truesdell et al. (1992) reported that the measured concentration of CO_2 in ppm by weight ranged as follows:

Northwest Geysers   7,450 - 55,500 ppm
Central & Southwest G.   2,080 - 11,500 ppm
Southeast Geysers   94.70 - 734   ppm

In comparison, the geothermal fluids from the Broadlands field in New Zealand had 10 % of CO_2.

CO_2 is characterized by its high saturation pressure. The presence of CO_2 in the binary mixture of CO_2 and water will elevate the saturation vapor pressure (dew point) of pure water at a given temperature. The single saturation pressure line of pure water is replaced by bubble point and dew point curves for the mixture.

Solubility of CO_2 in the adsorbed water and non-adsorbed water is not the same (Economides, et al. 1982). The equilibrium constant K, which is the ratio of vapor phase to liquid phase, for the adsorbed water is much larger than the non-adsorbed water. As a result, the solubility of CO_2 in the adsorbed water is much less.

Economides et al. calculated the solubility of CO_2 in the non-adsorbed water and found that the mole fraction of CO_2 would range from 0.0005 to 0.001 in a typical geothermal reservoir. The fraction of CO_2 in the adsorbed water would be even less. Thus the presence of CO_2, if any, is mainly in the pore space away from the adsorbed water. This was confirmed in the experiments here.

1.2 Effects of Salinity

One of the fluids present in a geothermal reservoir is hot saline brine. The saline brine may be at temperature higher than 300°C and may have a concentration between 10,000 to 80,000 ppm of brine. Concentration of chloride in steam is about a thousandth of the chloride concentration in liquid, provided that the temperature is high (about 350°C). At typical Geysers reservoir temperatures of 220 - 250°C, the chloride concentration in the steam becomes negligible due to its dissolution in steam condensate (Haizlip & Truesdell, 1988).

Measurement of salinity of geothermal steam is difficult. Chloride, coming from reservoir as HCl gas, dissolves quickly into any liquid present. Hence its concentration varies among separator outlets. It was reported by Haizlip and Truesdell (1988) that chloride concentrations in steam at the wellhead in high-chloride Geysers wells were between 10 and 120 ppm by weight, depending on locations and outlets.

High chloride concentration is detrimental to a geothermal well due to corrosion problems in subsurface and surface parts. Corrosion of well casing and steam-gathering system has been known in some parts of The Geysers fields.

Water, containing salt, has a lower vapor pressure than pure or less salt-concentrated water. Therefore, it was expected in this experiment that the transient pressure would be different from that of pure steam.

Section 2

APPARATUS AND PROCEDURE

The laboratory measurement of the transient flow experiment used a specially built equipment, on loan from the United States Geological Services (USGS).

This section will explain in detail the apparatus and the procedure used in the experiments.

2.1   Apparatus

The equipment for this experiment was designed by Herkelrath from the USGS. Only schematic drawings of this equipment are shown here. More detailed drawings are presented in Harr (1991).

The apparatus consists of three! main systems:

1. The Air Bath System

2. The Vacuum System

3. The Data Recording System

2.1.1 The Air Bath System

The air bath was made by Blue M Electric Company, model No. FA-1402EFG. Inside the air bath are a sample holder and a steam vessel, with several pneumatic valves and a manifold. The pneumatic valves are controlled from the outside.

This experiment uses a 58.5-cm. sample holder, having a 1.905-cm outside diameter and a 0.089-cm wall thickness. The volume of a fully packed sample is 137.066 cc.

The steam vessel has a volume of 1 liter and is partially filled with liquid water. The empty space is reserved for the formation of steam.

A sketch of this airbath system is shown in Figure 2.1.

2.1.2 The Vacuum System

A vacuum pump is used to evacuate air inside the sample prior to introducing steam or gas. In order to safeguard the pump, a cold liquid trap, filled with liquid nitrogen at a temperature below the freezing point of water, is used to trap moisture in the manifold, before reaching the pump. The presence of moisture is detrimental to the pump operation and its presence inside the pump reduces the vacuum that can be achieved.

A schematic diagram of the vacuum system is depicted in Fig. 2.2. Some valves were not shown here, since the valves were never operated but left in the open position only.

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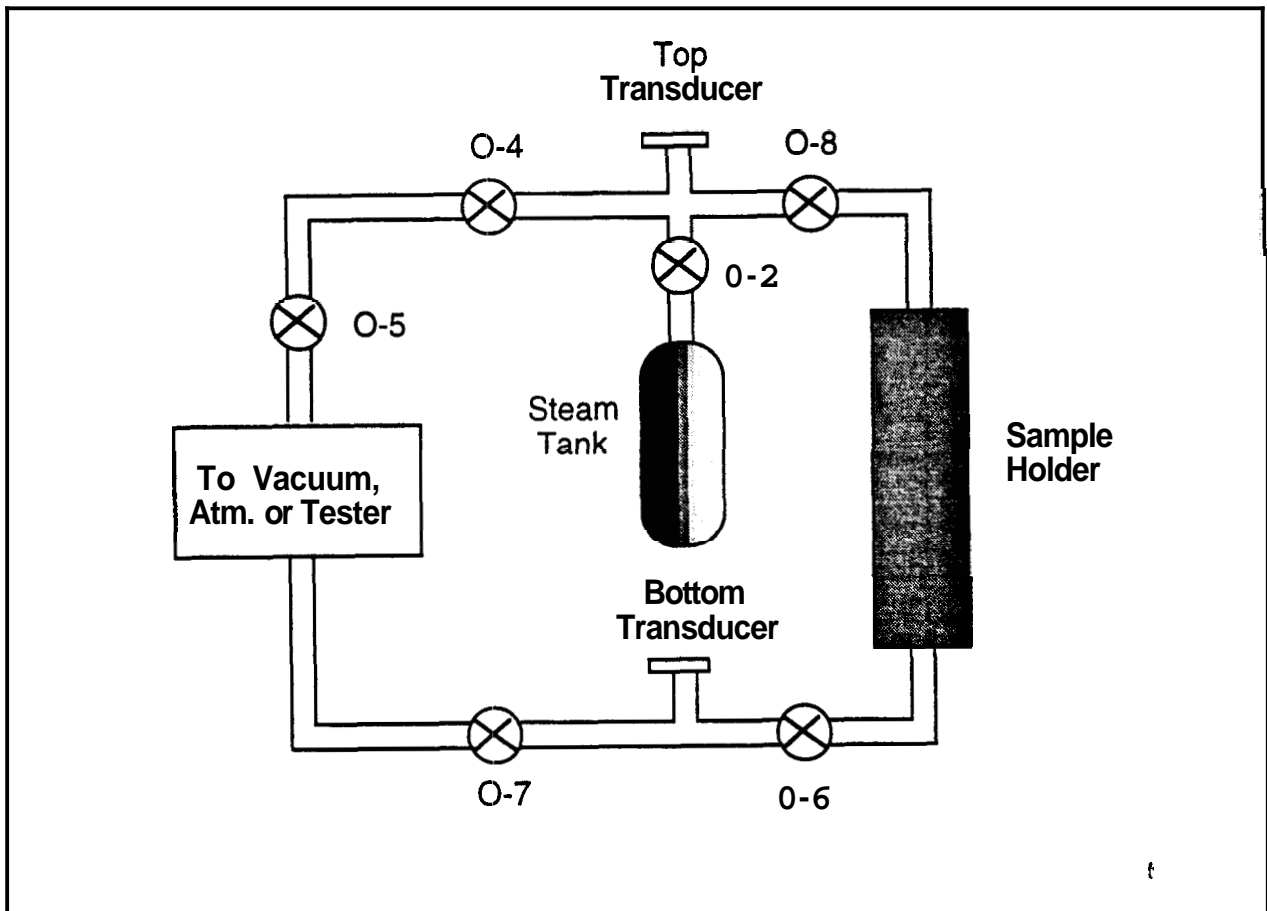
Figure 2.1: Diagram **of** the **Air** Bath System
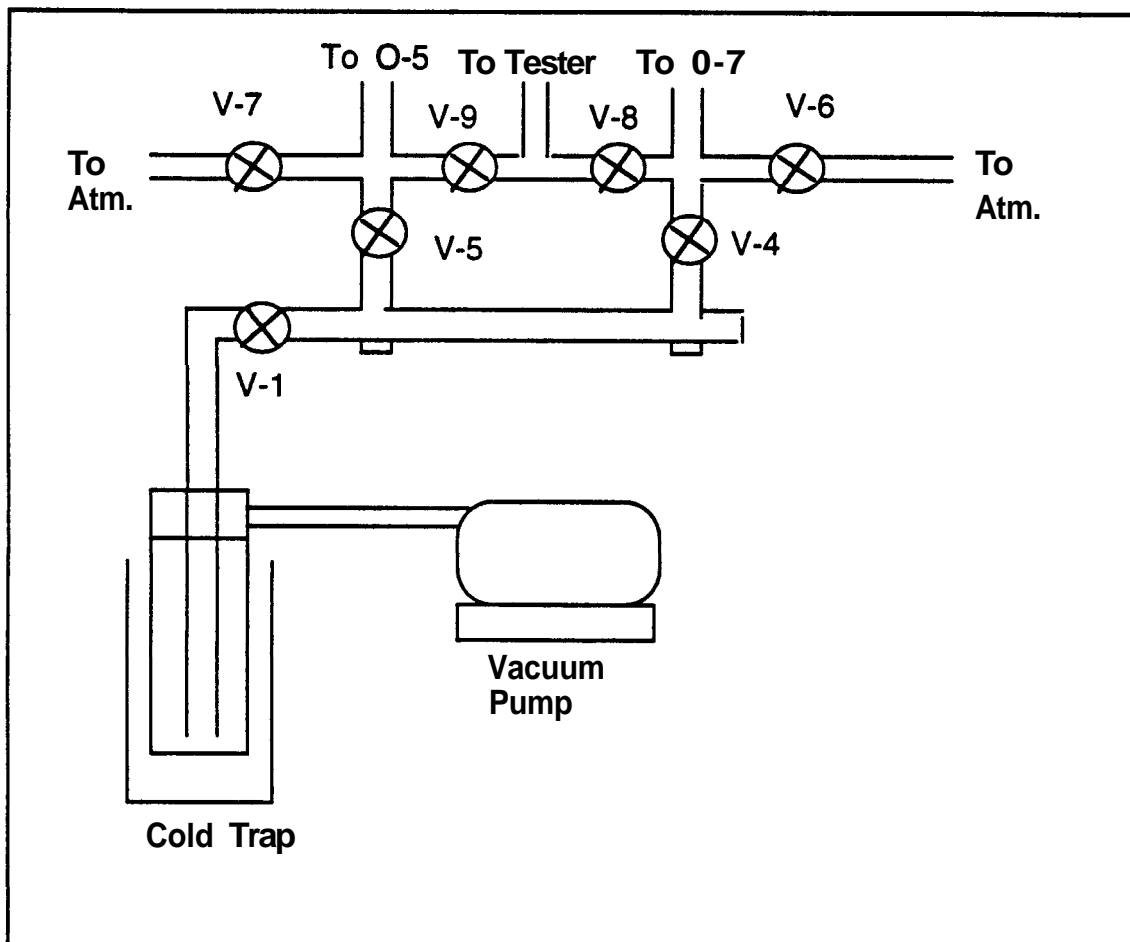
Figure **2.2: Diagram of the Vacuum System**

2.1.3   The Data Recording System

A computer system with specially designed software is employed for data acquisition and online reading of the pressure transducers.

The system consists of

- *o* Digital PDP-11 processor

- *o* Digital RXO2 floppy disk drive

- *o* Digital RL02 hard disk drive

- *o* Bell and Howell signal conditioner

- • VT105 monitor and keyboard

2.2   Sample Preparation

Core samples as well as well cuttings from a geothermal well need to be processed in order to achieve uniform size with sufficient surface area. Adsorption is dependent on the available surface area.

Whole cores or cuttings were crushed and subsequently sieved. Whole cores were first broken by a sledge hammer into small pieces and then fed into a rock crusher machine. The desired particle size can be achieved by means of a variable setting in the rock crusher machine. The pulverized sample was sieved gradually from large to fine particles. It then was poured into the 58.5 cm by 1.905 cm sample holder.! The holder was tapped lightly to compact the sample inside.

Care was always taken to pressure test the system prior to running the experiment to ensure a leak-free system. The pressure test of 20 psig was performed for at least **30** minutes or until it was reasonably sure that no visible leak was observed.

2.3   Procedure

The procedure of this experiment was slightly different from that used in the previous transient flow study, performed by Harr (1991). The previous method utilized a steam generator located outside the air bath, instead of using the steam vessel inside the air bath. This modified procedure was initiated by Qi (1993) and has been used since.

2.3.1   Using Steam

1. Fill the liquid nitrogen in the cold trap up to 4 liter capacity.
   Turn on the vacuum pump. Open the V-1 and V-2 valves. Leave for 5 minutes before opening the V-4 and V-5 valves. The vacuum reading indicator will slowly go down.

2. Open the **0-5,** 0-4, and 0-7 valves. Wait until the vacuum indicator dial goes down before opening the next sequence of valves: 0-6 and **0-8 .**
   These valves are in the closed position: 0-1, 0-3, V-6, V-7, V-8 and V-9.

3. Open and close the 0-2 valve quickly. Repeat a few times to ensure that no air remains in the water reservoir.

4. Turn on the air bath and the cooling fan.
   The air bath is already set at 125°C.

5. Wait for the system to reach equilibrium temperature for about 24 hours. Use longer equilibrium time for low permeability samples. The temperature inside the airbath can be read from a digital temperature recorder located outside.

6. Turn on the computer. Type 'kermit' at the C: prompt. Type 'DL' followed by DA DA-MON-YR and TI HR:MN at a dot prompt. DA-MON-YR and HR:MN are the date and time respectively. This is basically to specify the date and

time of the experiment. Enter the ADT program, by typing 'ADT' at a dot prompt. Answer '0' when prompted by a question "Which one of these?". A '0' will list a reading every **1000** data points.

7. Record the vacuum readings. Type 'S' to exit from the ADT program. Subsequent typing of 'Control-]' and 'C' at a dot prompt will exit to C:kermit prompt. Finally type 'quit' to return to the C: prompt.

8. Close the vacuum pump valves of **V-4** and **V-5.** Close the O-4, O-5, and *0-7* valves. Open the **0-2** valve. Steam will soak the sample.

9. Wait for at least **24** hours to reach equilibrium and to ensure the steam contacts all the sample surfaces. It is a good practice to extend the above time for low permeability samples.

10. Turn on the computer. Follow the procedure outlined above to go to ADT program. Record the saturation pressure and the initial pressure of the steam.

11. Close the *0-6* valve. Open the 0-7 and V-6 valves.

12. Stop the ADT program by typing 'S'. Start the PTDT program by typing PTDT at a dot prompt.

13. The PTDT program will ask a series of questions:
   1. Are '6' & '7' the data translation channels to be used? Answer **1.**   !
   2. Is **'50'** octal = **1/2** the data sample? Answer **1.**
   3. Is **'1005=1000'** x the log time factor? Answer **1.**
   4. Repeat A/D write cycle? Answer 0.

14. Record the name of the unformatted Data File.

15. Open the 0-6 valve. This starts the run.

    Running time varies depending on the log progression factor used and the permeability of the sample. Lower permeability requires longer running time. Suggested running time for low permeability sample is **3** hours. **A** 40-minute running time is sufficient for data acquisition of samples having permeability higher than **0.2** darcy.

16. Close the 0-6 and 0-8 valves. Open the **0-4,** 0-5, 0-7, V-6, and V-7 valves. Return to the ADT program. Measure the atmospheric pressure.

17. Close the V-7 and V-6 valves. Open the **V-4** and V-5 valves.

    Wait for about 10 minutes and measure the vacuum pressure after the run.

18. Calibrate the top and bottom pressure transducers.

    Connect a dead-weight tester to the dead-weight tester port.

19. Open the V-9, 0-4, and 0-5 valves for the top transducer.

    Apply 15 psig with the dead weight tester. Record the voltage reading on the computer screen.

20. Close the V-9 valve. Open the V-7 valve to bleed pressure.

21. Open the V-8 and *0-7* valves for the bottom transducer.

    Apply 15 psig with the dead weight tester. Record the voltage reading on the computer screen. Open the V-6 valve to bleed pressure.

22. Stop the ADT program and start the DRWDWN program.

    The air bath power can now be turned off.

23. Type in the required data. The data are from the top and bottom transducer readings. These data, except the raw ones, need to be subtracted from the vacuum readings after the run.

- *o* Steam charge in net volts?

- *o* Pzero in net volts?

- *o* Calibration voltage?

- *o* Calibration pressure in bar?

- *o* Raw atmospheric voltage?

- *o* Raw vacuum voltage?

- *o* Logtime progression factor? Answer **1005**

- *o* Samples per data point? Answer 40

24. End of experiment.

2.3.2   Using Non-Condensible Gas

Non-condensible gas needs to be introduced from a gas cylinder, outside the air bath. The sample needs to be evacuated first following the above procedures (using steam), Steps **1** to **7.** Steps 8 through 10 are replaced as follows:

8. Connect the gas cylinder to the **V-7** valve. Open the **V-4** and **V-5** valves to evacuate any entrapped air from the new connection tube, while the **0-5** and **0-7** valves are closed.

9. Inject gas into the system, while the pressures are monitored on the computer screen. Should the pressures be above the desired range of values (and most of the time they are), they can be reduced by opening and closing the vacuum valves.

10. Wait until equilibrium is achieved. Record the voltage pressures.

The next step follows from the steam procedure, starting from Step 11 until the end of the experiment, Step **24.**

2.3.3   Using Salt

The procedure starts with the connection of the sample holder, which contains the sample, to the vacuum pump and a beaker containing a saline solution, by means of a tee valve. After the sample is evacuated, the valve switches to connect the beaker with the sample, allowing the saline solution into the sample holder.

It is a good practice to have the sample evacuated for several hours to ensure an air-free condition. Furthermore, trapped air inside the plastic tube connecting the beaker and the valve must be removed prior to transfering the saline solution into the sample.

Salt is added to the sample in a form of saline solution. **As** much as **5%** of sodium chloride in water, properly and uniformly mixed, is forced into the vacuumed Sample and subsequently the water is evaporated inside the air-bath. The sample then contains salt particles inside its pores and is ready for another experiment.

The steps of the procedure are the same as the steps for using steam only, as described in Section **2.3.1.**

2.3.4   Measuring Permeability

Nitrogen gas **was** used to determine the permeability of the sample. Since gas flow is dependent of the differential pressure imposed on the sample, the mean pressure of the gas during the experiment must be calculated. This dependence on the mean pressure is termed the "Klinkenberg Effect".

The observed permeabilities obtained during the measurement must be adjusted to take this effect into account. Discussion on measuring the permeability can be found in Harr (1991) and in Amyx, et al. (1960). The latter also explained how to correct the observed permeabilites.

A calibration of the transducer is required in order to produce a graph showing a relationship between the pressure and the range of pressure reading. By knowing this, the corresponding differential pressure of the sample can be found. The observed permeability can then be calculated from the following equations:

$$\overline{V} = \frac{P_1 V_1}{\overline{P}}$$

$$\overline{Q} = \frac{\overline{V}}{t}$$

$$k = \frac{\overline{Q} L \mu}{A \Delta P}$$

where:

P_1	=	downstream pressure, set at atmospheric pressure
V_1	=	the cumulative volume of nitrogen
$\overline{P}$	=	the mean pressure
AP	=	the pressure difference
t	=	flowing time of nitrogen
μ	=	viscosity of nitrogen

This equation assumes laminar flow, which was a reasonable assumption since the flow rates used were slow enough. Trials with a turbulent flow equation did not give satisfactory results.

Nitrogen gas was used in this measurement. A controlled flow of nitrogen from a nitrogen gas cylinder was directed through the sample and the resulting volume was read from a wet test meter. Downstream pressure was kept at 0 psig (atmosphere)

and the upstream pressure could be measured by a pressure transducer. Flowing time was recorded by a stopwatch, hence the flow rate of nitrogen could be calculated.

2.3.5   Measuring Porosity

Laboratory measurement of porosity needs to determine only two of the three basic volume parameters, which are bulk volume, pore volume, and grain volume (Amyx et al., **1960).**

Bulk volume can be calculated easily, since the volume is simply the inside volume of the sample holder. Grain volume of the sample was calculated as the weight of the sample divided by the density of the sample, specified as 2.7 g/cm^3.

The pore volume of the sample is the difference of the bulk and grain volumes. Porosity is the ratio of pore volume to bulk volume.

Another method was employed in the calculation of the **45-150** Mesh and the second **20-45** Mesh size samples. Here water was used to find the pore volume of the sample. Water filled the sample and its weight was measured. The pore volume of the sample is the water weight divided by the water density.

Care has to be exercised prior to introducing water inside the sample holder. Should the pressure inside the sample be equal to atmospheric pressure, water would not go inside. Moreover the water would not occupy all the pore space since some of the pore space are occupied by air. Hence the sample needs to be evacuated first to ensure an air-free and low-pressure condition.

Section 3

EXPERIMENTAL RESULTS

The experiment used not only steam, but also non-condensible, non-adsorbing gases such as nitrogen and carbon dioxide. Steam could be generated either inside or outside the air bath. If generated outside, steam apparently condenses inside the connecting pipe between the steam generator and the air bath. Generating steam inside was preferred, since this method reduced the condensation effect.

This section includes graphs of each run followed by pertinent information about the run. The horizontal axis in these graphs shows the elapsed time in seconds after the run is started. The vertical axis depicts the pressure in bars, which had been subtracted from the vacuum pressure. This pressure was continuously recorded by the top transducer, located above the vertical sample holder, during the run. If the vertical axis shows a pressure ratio, it is simply the recorded pressure divided by the steam saturation pressure of that temperature.

The steam saturation temperature was calculated by the computer program based on the input data of steam saturation pressure inside the air bath. Although the air bath temperature was set at $125°C$, the steam temperature was slightly below this setting value, usually $4°C$ lower. The discrepancy could be either attributed to faulty electronic control or a bug in the computer program which transforms the voltage reading to bars and subsequently to the steam temperature in degrees Kelvin.

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The time for vacuum and for steam exposure were set to at least **24** hours. More time was allocated to allow the sample adsorb to steam properly. The vacuum pump sometimes did not work as well as expected, hence the vacuum time often was extended.

Steam was used for the adsorption experiment shown in Figure **3.1,** denoted as Run **1,** which is a semilog graph. The initial pressure of the steam was 2.05 bars, which was the steam saturation pressure at 121.2°C. The pressure started to decrease at time $= 0.6$ sec. It dropped to an atmospheric pressure of 1.1 bars in just 8 seconds.

It was initially concluded that the comparatively short core holder was responsible for the short desorption time. However later it was believed that the transient time depended mostly on the permeability of the sample. The short core holder would later be expanded; however, not enough of the existing sample was available. Later experiments using a longer core holder made use of a new sample.

In order to compare the effects of non-condensible gas and steam, two runs (Runs 2 and **3**) were performed using the same sample (from an unknown Geysers well) and the same sample holder. The run with steam, Run 2, also tried to duplicate a previous run, Run 1, performed a few days earlier. Figure **3.2** in Cartesian coordinates clearly shows that nitrogen, by virtue of its non-condensible properties, did have an earlier and steeper pressure drop. The rate of pressure drop in nitrogen is about six times faster than that in steam.

The replicate run with steam did show the same curve; however, the starting time of pressure drop (the breakthrough time) was slightly different. Run **2** had a starting time of 1 second, compared to 0.8 second for Run 1. The way the starting valve (0-6 Valve) was opened might contribute to this shift of 0.2 sec. Opening of this valve was sensed by the computer program in order to start collecting data.
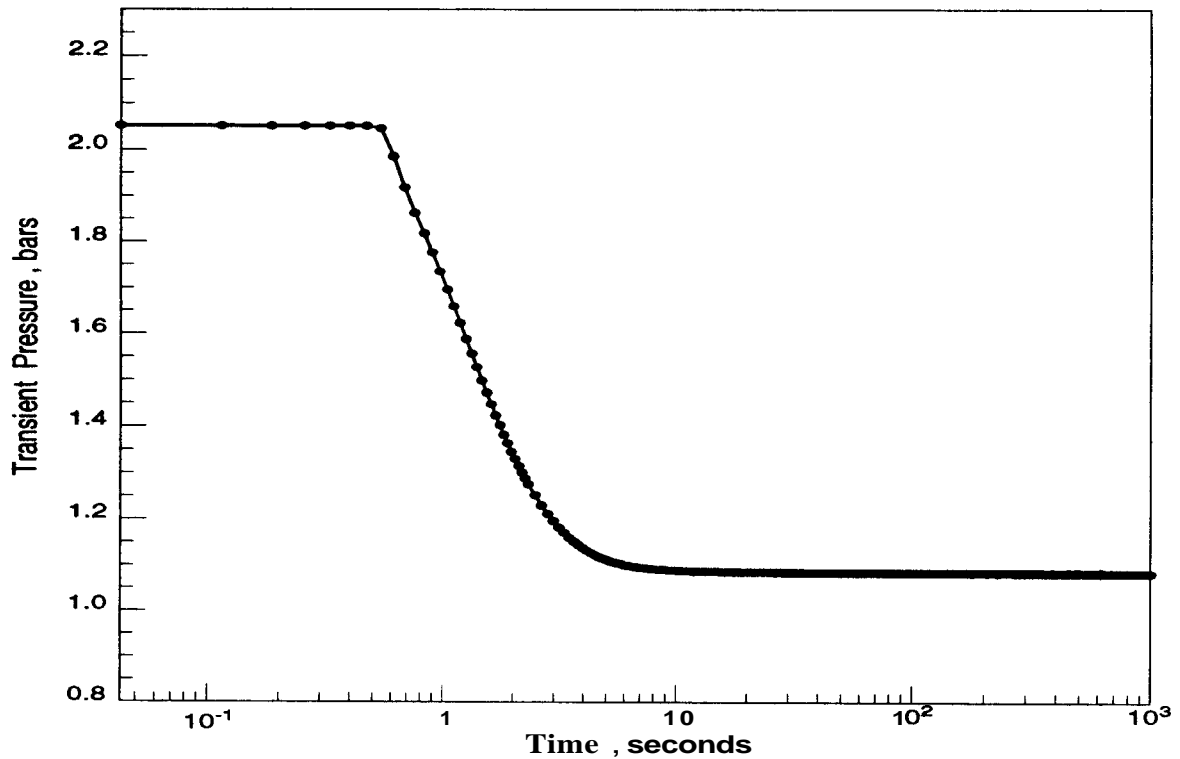
Figure 3.1: Transient Adsorption Experiment with Steam

DATE		April 23, 1993
EXPERIMENTAL RUN	:	No. 1
WELL		Unknown Geysers Well
DEPTH		Shallow Reservoir
MESH		28 - 150 Tyler Standard
CORE HOLDER		30.48 cm X 1.905 cm
STEAM GENERATION	:	Inside the Air Bath
STEAM SAT. PRESSURE	:	2.053 bars
AIR BATH TEMP.		394.21 Kelvin
VACUUM TIME		23.3 hrs
STEAM EXPOS. TIME	:	41 hrs
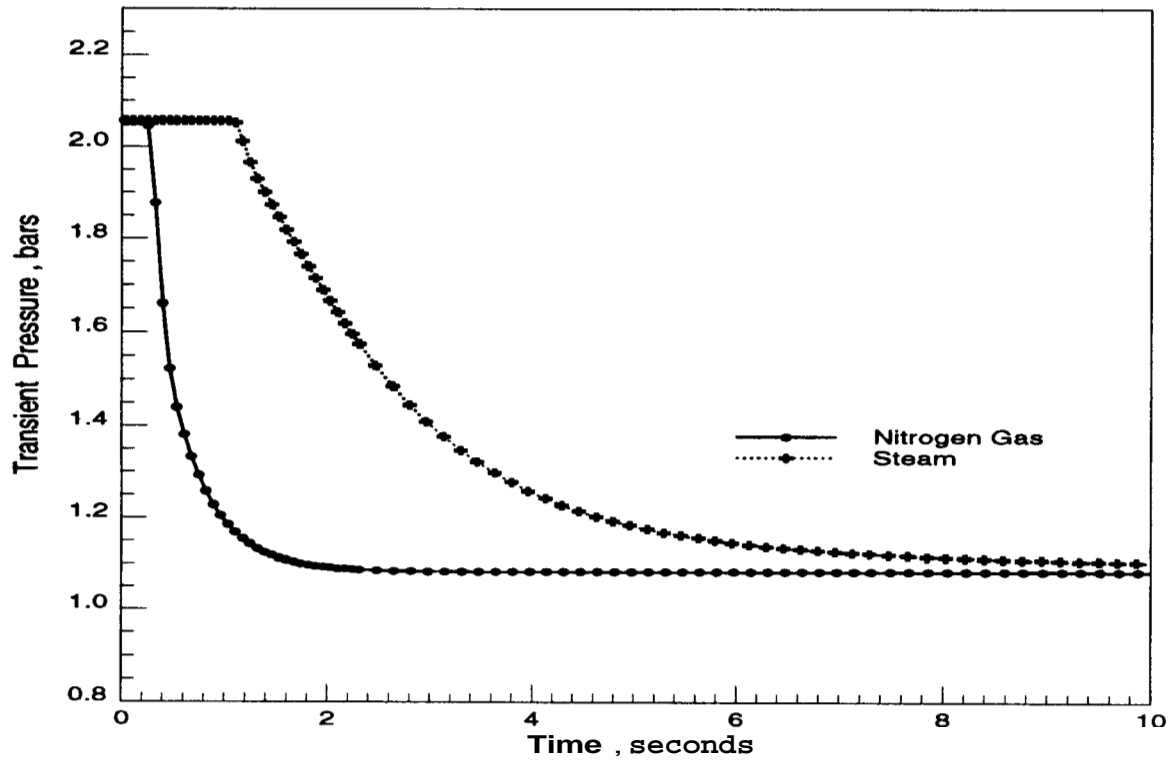
Figure 3.2: Comparison of Steam and Nitrogen

DATE	:	April 30 & May 01, 1993
EXPERIMENTAL RUNS	:	No. 2 and No. 3 respectively
WELL	:	Unknown Geysers Well
DEPTH	:	Shallow Reservoir
MESH	:	28 - 150 Tyler Standard
CORE HOLDER	:	30.48 cm X 1.905 cm
STEAM GENERATION		Inside the Air Bath
VACUUM TIME	:	**24** hrs
STEAM EXPOS. TIME	:	41.5 hrs
N_2 EXPOSURE TIME	:	0.5 hrs
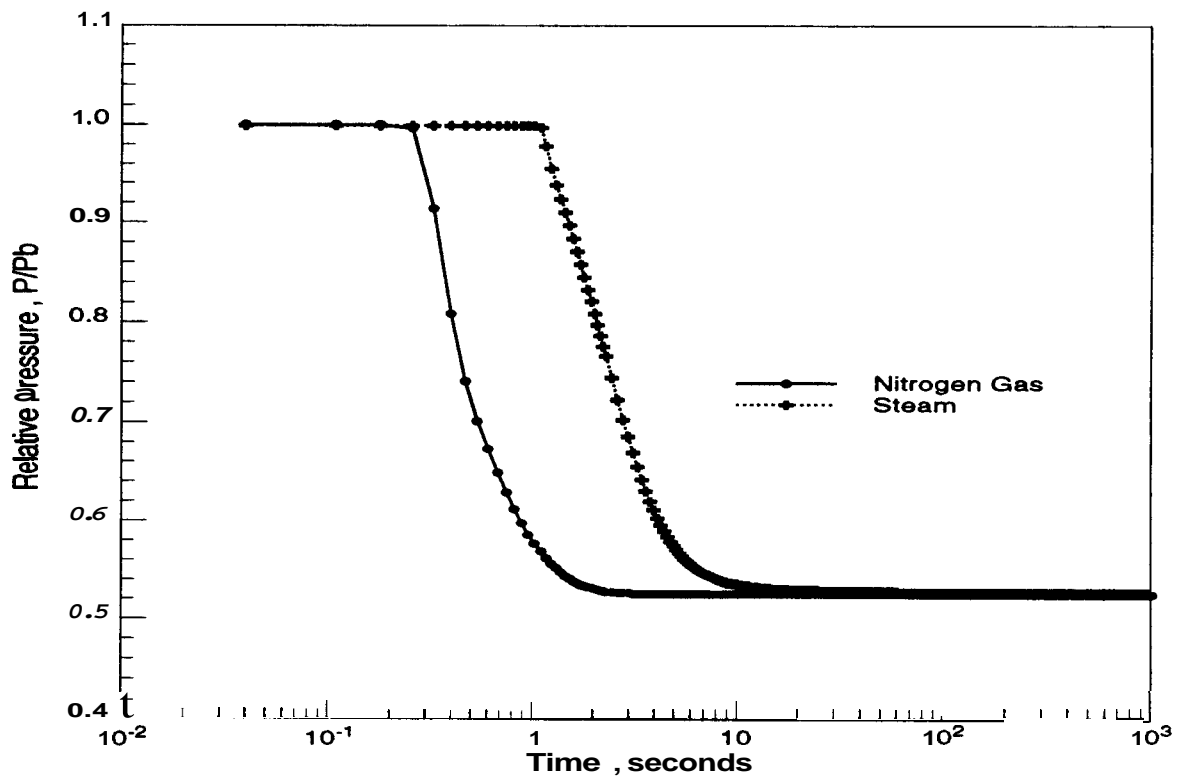
Figure 3.3: Comparison **of** Steam and Nitrogen

DATE	:	April 30 & May 01, 1993
EXPERIMENTAL RUNS	:	No. 2 and No. 3 respectively
WELL	:	Unknown Geysers Well
DEPTH	:	Shallow Reservoir
MESH	:	28 - 150 Tyler Standard
CORE HOLDER	:	**30.48** cm X 1.905 cm
STEAM GENERATION	:	Inside the Air Bath
STEAM SAT. PRES.	:	2.057 bars
AIR BATH TEMP.	:	394.3 Kelvin
VACUUM TIME	:	24 hrs
STEAM EXPOS. TIME	:	41.5 hrs
N_2 EXPOSURE TIME	:	0.5 hrs

The new experiment using a longer core holder, Run **4,** is shown in Figure **3.4.** The dimensions of the new core holder are **58.5** cm in length, **1.905** cm in outer diameter and **0.089** cm in thickness. It was made of stainless steel and could withstand high temperatures, since the experiment was set at about $125°C$.

The whole well cores, which were received in early July **1993,** were from Calpine Corporation's well **MLM-3,** located south of the Geysers field, from a measured depth of **1320** m to **1325** m. One of the cores was broken by a sledge hammer and crushed to rather fine particles, which were then sieved gradually to separate them into more uniform sizes.

The oxide composition of the sample, as obtained by means of x-ray fluorescent test is **as** follows:

Oxide	Concentration in % by weight
SiO_2	**66.70**
TiO_2	**0.58**
Al_2O_3	**12.20**
Fe_2O_3	**11.40**
MnO	**0.10**
MgO	**1.81**
CaO	**1.89**
Na_2O	**3.11**
K_2O	**1.57**
P_2O_5	**0.14**

One of the considerations of the usage of the fine-particle sample instead of whole core was the testing time. Should a whole core be used, the desorption time would be impractically long. Also it would require a new core holder, designed specifically to fit the whole core. **A** study by Shang et al. **(1994)** concluded that well cuttings can be used as substitute for core samples in water adsorption studies.

The sample of uniform size 20-45 Mesh Tyler standard was used to determine the effect of steam adsorption. It was found that the resulting curve of pressure vs. time of Run **4** did not differ greatly from the earlier runs using the shorter core holder, Runs 1 and **2.** This was quite interesting, because the desorption time was initially expected to be longer. One of the explanations was that the particle size (20-45) used was coarser than the previous one (28-150). The coarser the sample particle, the shorter the desorption time, provided that the rock sample is the same. It is noted here also that the two samples are from different rocks.

A replicate run (Run 6), shown in Figure **3.6,** confirmed the same result. It was noticed also that although the curve was similar, there was a perceptible shift of 0.4 seconds. The pressure drop for Runs **4** and 6 started to drop at time below 1 second. The difference might be caused by the presence of remaining air in the water chamber. Air was supposed to be vacuumed out, however some might remained during the first run, immediately following the refill of the water vessel. Subsequent runs did not show this trend.

Run 5 depicted in Figure 3.5 shows the signature of a CO_2-only run. CO_2 was injected into the sample, but the initial pressure was lower than the steam saturation pressure. It was noticed during the course of this experiment that after some time the pressure of either CO_2 or steam inside the sample would decrease with time.

The transient pressure of CO_2 dropped to atmospheric pressure slowly instead of suddenly as in the case of steam.
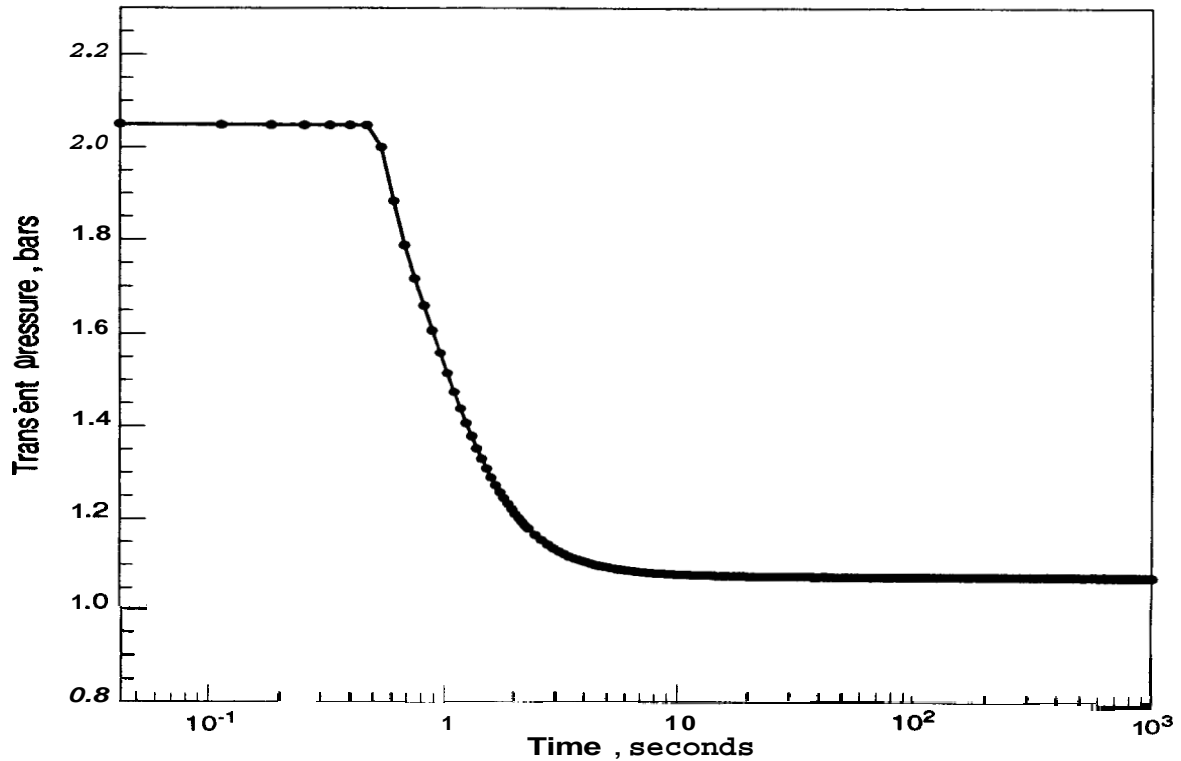
Figure 3.4: **Transient Adsorption Experiment with Steam**

DATE		July 09, 1993
EXPERIMENTAL RUN	:	No. 4
WELL		MLM-3 South Geysers Field
DEPTH		1325 m MD or 1320 m TVD
MESH		20 - 45 Tyler Standard
CORE HOLDER		58.5 cm X 1.905 cm
STEAM GENERATION	:	Inside the Air Bath
STEAM SAT. PRESSURE	:	2.050 bars
AIR BATH TEMP.		394.17 Kelvin
VACUUM TIME		40.0 hrs
STEAM EXPOS. TIME	:	27.6 hrs
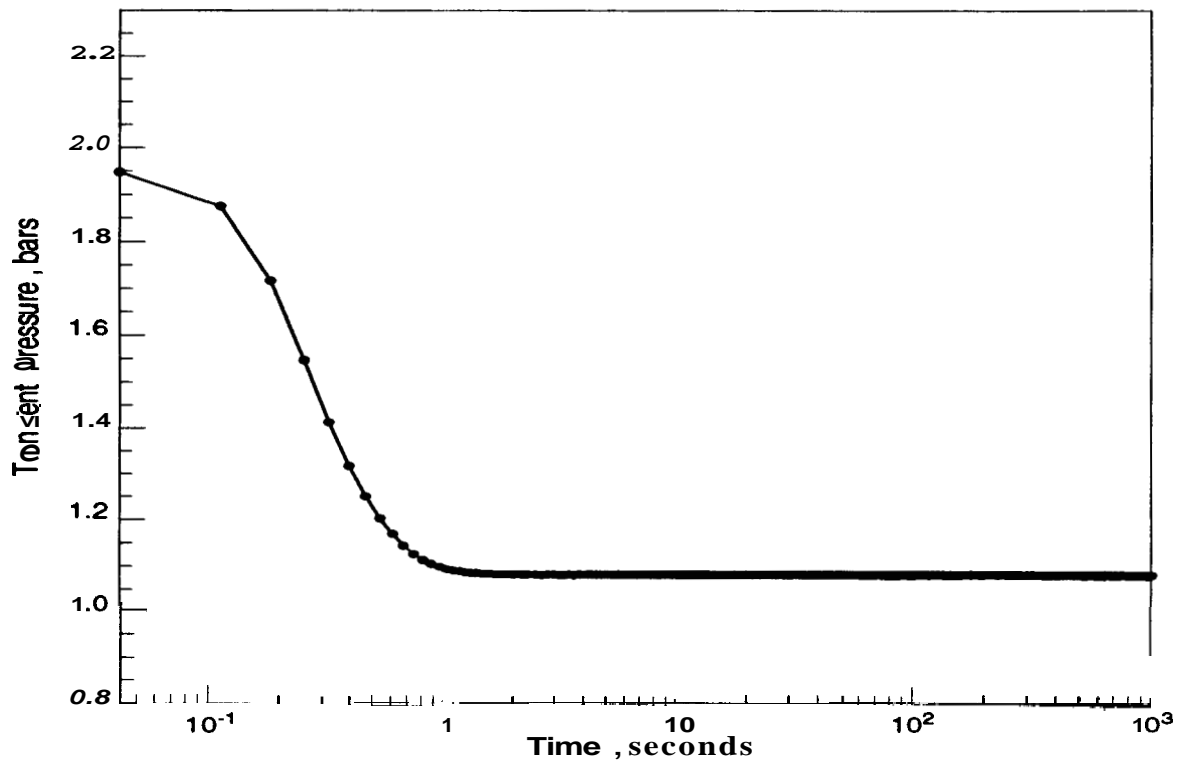
Figure 3.5: Transient Adsorption Experiment with CO_2

DATE	:	July 15, 1993
EXPERIMENTAL RUN	:	No. **5**
WELL	:	MLM-3 South Geysers Field
DEPTH	:	1325 m MD **or** 1320 m TVD
MESH	:	20 - 45 Tyler Standard
CORE HOLDER	:	58.5 cm X 1.905 cm
AIR BATH TEMP.	:	392.66 Kelvin
VACUUM TIME	:	42.6 hrs
CO_2 EXPOSURE TIME	:	23.3 hrs
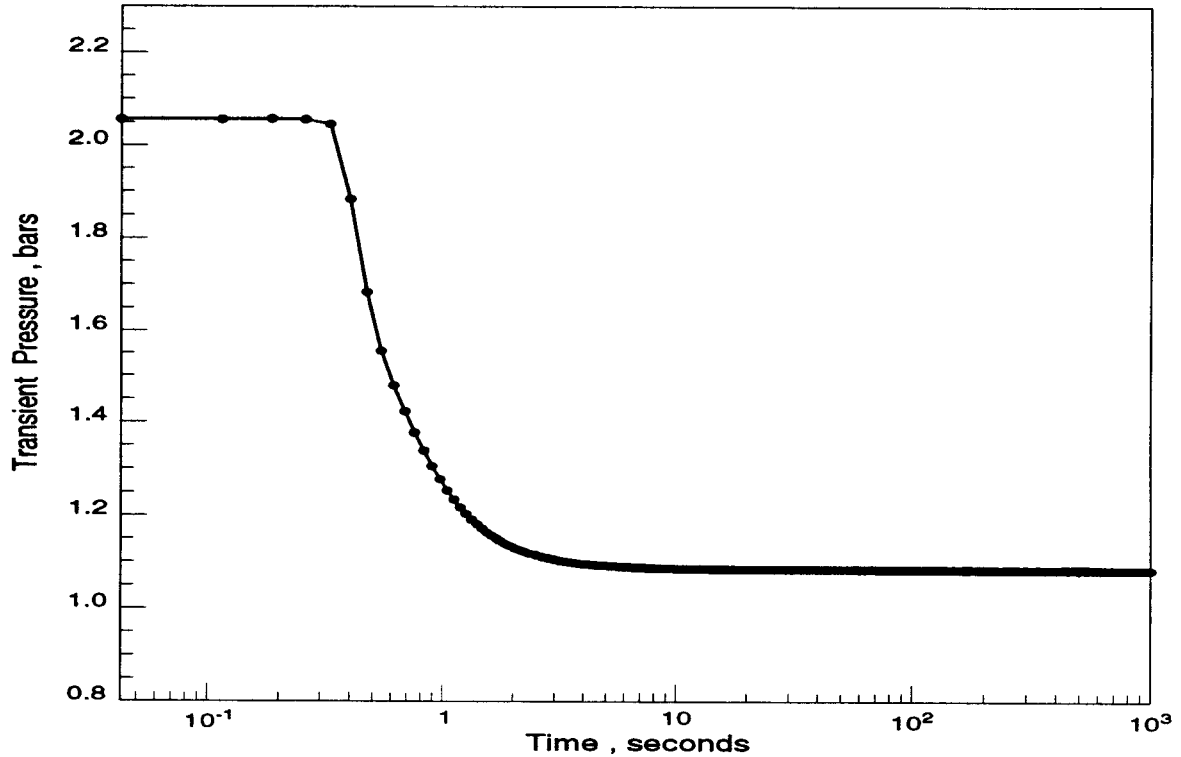
Figure **3.6: Transient Adsorption Experiment with Steam**

DATE		July **23, 1993**
EXPERIMENTAL RUN	:	No. 6
WELL		MLM-3 South Geysers Field
DEPTH		**1325** m MD **or 1320** m TVD
MESH		**20 - 45** Tyler Standard
CORE HOLDER		**58.5** cm X **1.905** cm
STEAM GENERATION	:	Inside the Air Bath
STEAM SAT. PRESSURE	:	**2.056** bars
AIR BATH TEMP.		**394.27** Kelvin
VACUUM TIME		**24.7** hrs
STEAM EXPOS. TIME	:	**43** hrs

So far the steam used in the preceding experiments was generated from the inside of the air bath. **A** comparative run, Run 7, using the outside steam generator was performed and the result is shown in Figure **3.7.**

The resulting curve of Run 7 did not display the steep pressure drop, which was characteristic **of** the previous runs using steam generated inside. It shows a more gradual pressure drop to the atmospheric pressure of 1.1 bars. The initial steam pressure was only about 1.68 bars which was less than the pressure of 2.05 bars that could be achieved using the internal steam vessel. The lower pressure was expected since the outside steam generator temperature was set at 119°C.

The temperature of the pipe connecting the outside steam generator with the air bath was initially set at 121°C. This setting temperature, although initially assumed to be constant, was found later not to be constant. Two days later this setting temperature had decreased to only 115°C, which was below the steam generator temperature, causing condensation in the pipe. This would explain the lower initial pressure of the steam.

Other factors, such as leaking and/or no water in the external steam vessel were ruled out. Pressure testing the system after the run confirmed that no leak took place. Further tests to determine the presence of water in the steam vessel also confirmed that the vessel was not empty **of** water.

This discouraging result coupled with the tedious procedure when using the external steam generator led to the abandonment of this method. Subsequent runs would use only steam generated from the inside of the air bath, which was easier to handle.
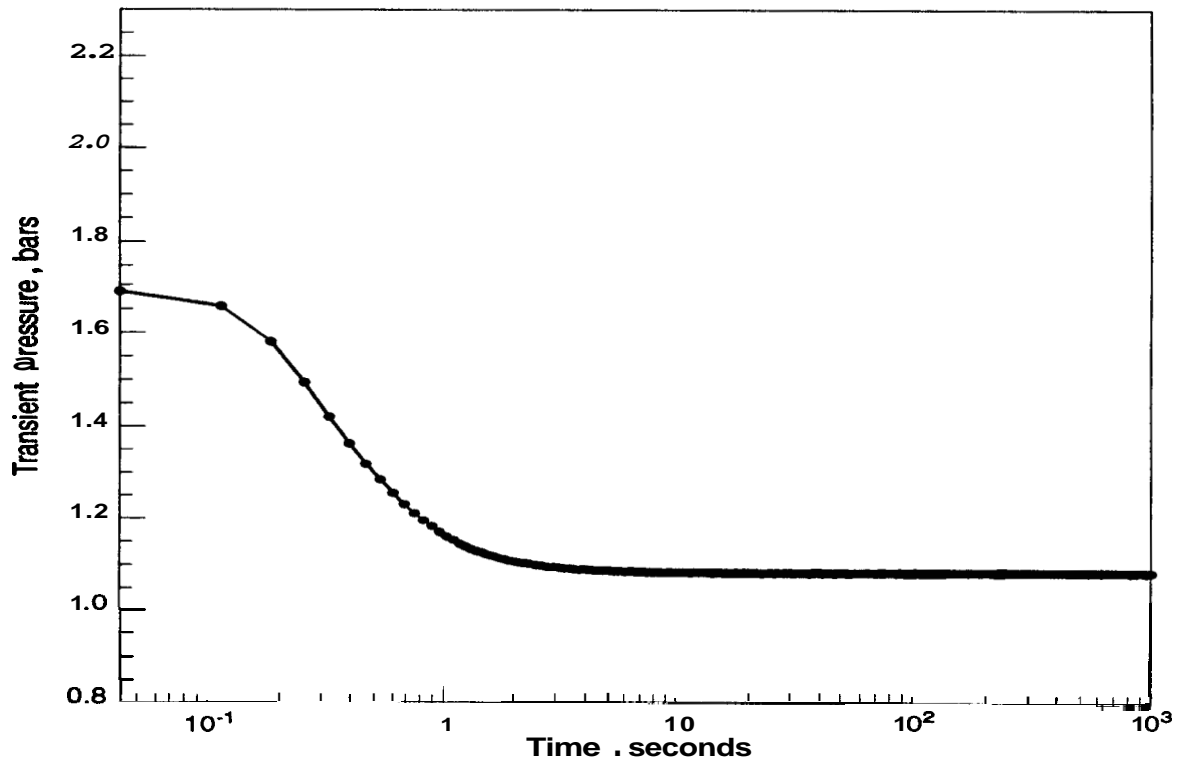
Figure 3.7: Transient Adsorption Experiment with Steam

DATE		July 26, 1993
EXPERIMENTAL RUN	:	No. **7**
WELL		MLM-3 South Geysers Field
DEPTH		1325 m MD or **1320** m TVD
MESH		20 - 45 Tyler Standard
CORE HOLDER		58.5 cm X 1.905 cm
STEAM GENERATION	:	Outside the Air Bath
STEAM SAT. PRESSURE	:	2.056 **bars**
AIR BATH TEMP.		394.26 Kelvin
VACUUM TIME		24.3 hrs
STEAM EXPOS. TIME	:	46.5 hrs

In order to determine the effects of the partial presence of CO_2 on steam adsorption, a run using steam and CO_2, Run 8 was conducted and the result is depicted in Figure **3.8.**

CO_2 was introduced to the air-free sample under vacuum and the pressure was recorded. After some time elapsed for equilibrium, without changing the volume, the steam was added to the system. The resulting pressure was the total combined pressure of both the steam and the CO_2.

The partial pressure of the CO_2 and the steam were calculated to be **0.155** bars and **1.888** bars respectively, giving a total pressure of **2.043** bars. The concentrations of the CO_2 and the steam were therefore **7.6 %** and **92.4 %**,respectively. At this concentration, CO_2 did not show a different pressure transient result compared to Run **6,** using steam only (see Figure **3.6).**

The permeability of the sample used in the last few runs with the new core holder was determined through the method outlined in the Amyx, et al. **(1960)** for permeability measurement.

The data used is as follows:

Area of core		**2.34** cm^2
Length of core		**58.50** cm^2
Downstream pressure	:	1 atm.
Volume of nitrogen		**28,316.85** cm^3.
Viscosity of nitrogen	:	0.018 cp at **83°F**
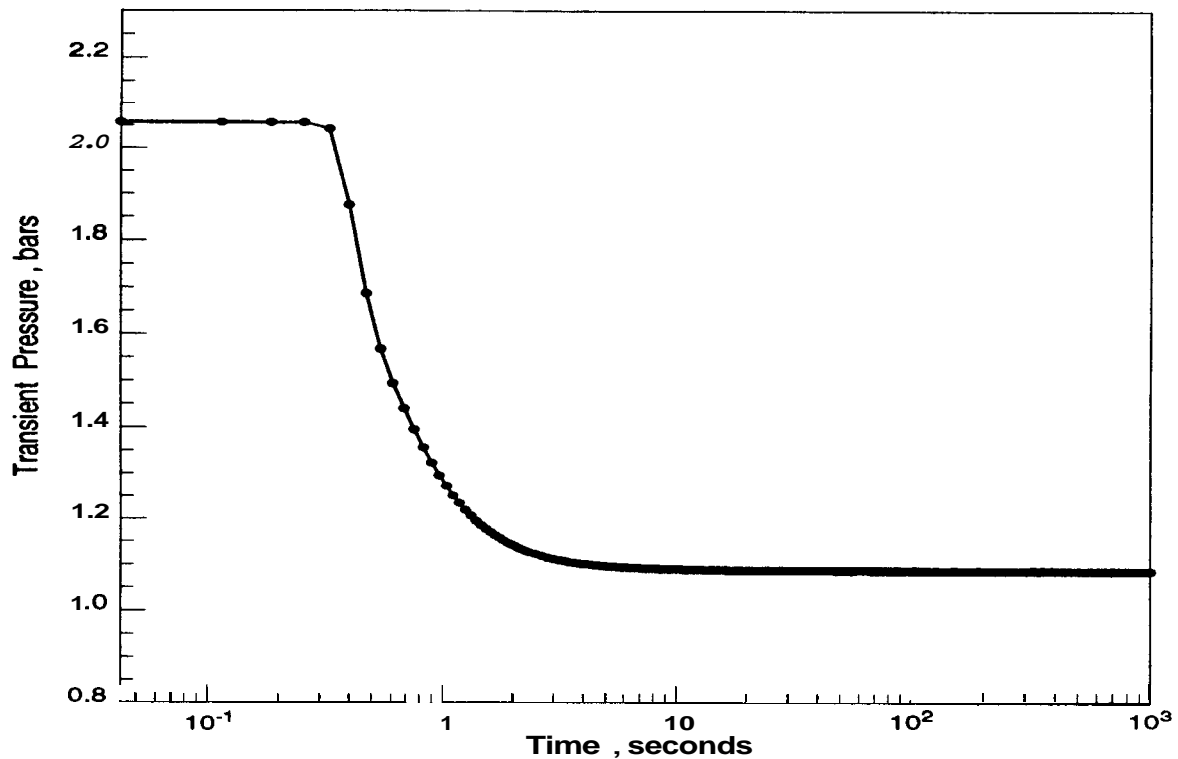
Figure 3.8: **Transient Adsorption Experiment with Steam and CO_2**

DATE		July 29, 1993
EXPERIMENTAL RUN	:	No. 8
WELL		MLM-3 South Geysers Field
DEPTH		1325 m MD or 1320 m TVD
MESH		20 - 45 Tyler Standard
COREHOLDER		58.5 cm X 1.905 cm
STEAM GENERATION	:	Inside the Air Bath
STEAM SAT. PRESSURE	:	2.058 bars
AIR BATH TEMP.		394.30 Kelvin
VACUUM TIME		25.5 hrs
STEAM EXPOS. TIME	:	45.6 hrs
CO_2 PARTIAL PRES.		0.155 bars (7.6 %)
STEAM PARTIAL PRES.	:	1.888 bars (92.4 %)

In order to ensure a correct result, three measurements were performed.

Upstream pressure   :   **9.25, 13.5** and **15.5** psig.

Time   **160, 121** and **103** seconds respectively.

Gas permeability   :   **89.17, 72.90** and **71.31** Darcy respectively.

A graph then was constructed to show the relationship between the reciprocal mean pressure and the observed permeability. The straight line connecting all the repressentative points at an infinite reciprocal mean pressure (at zero mean pressure) is the equivalent liquid permeability after the "Klinkenberg Effect" was removed. The permeability was computed to be **37.5** Darcy.

The weight of the sample was measured to be **195.5** grams. Using the weight, the volume and the density of the sample (**2.7** g/cm^3), the porosity of the **20-45** Mesh size sample was calculated to be **47** %.

The pressure data, obtained from the experiment, was used as input into a computer program together with data of permeability, porosity and dimensions, etc. The non-linear regression program was written by Qi **(1993)**, using the adsorption subroutine developed by Nghiem and Ramey **(1991).** The inferred parameters are **A** and B in the Langmuir isotherm:

$$X = \frac{\frac{P}{psat}}{A + B\frac{P}{psat}}$$

Running time for the optimization computer program depends on the initial estimates of the parameters. Some initial estimate values would not converge and some would converge after an unreasonably long time. It was found that initial estimate values of **A** = **1000** and B = **1** always produced results in just minutes.

Figure **3.28** is the inferred adsorption graph based on the values of **A** and B found from the transient pressure data of the **20-45** Mesh size sample.

The first sample used in the experiment was quite coarse (**20-45** Mesh size); therefore, the desorption times were very brief. In order to prolong the time a finer sample size (**45-150** Mesh size) was used in the same core holder.

Three similar runs, Runs 9, **11** and **12,** were performed and the results are shown in Figures **3.9, 3.11** and **3.12.** The results are not exactly the same although the experiments were conducted under similar conditions. The discrepancies might be due to the difference in the quantity of steam inside the sample prior to the desorption run and or the difference in atmospheric pressure. Some entrapped air or liquid might have been present in the former run. This fluid itself occupied some spaces and as a result the steam did not fully fill all the pore space of the sample as desired.

Using the same technique as in the previous sample, CO_2 gas was introduced to the sample in Runs **10** and **15.** CO_2 concentrations of **20%** and **36%** were used (Figs. **3.10** and **3.15).**

It was found that up to **36%** concentration, CO_2 did not have any effect whatsoever on the steam adsorption. This observation was based on the comparison of the transient pressure curves of steam (Runs 9, **11** and **12)** and of the mixture of steam and CO_2 (Runs **10** and **15).** The similarity between the two curves is very striking.

In order to establish the difference between partial and full CO_2 concentrations, two CO_2-only runs, Runs **13** and **14** were completed. Run **13** had its initial pressure equal to the initial steam pressure, whereas Run **14** had a lower initial pressure. These two runs are shown in Figures **3.13** and **3.14** respectively.

Although the two runs had different initial pressure, their breakthrough times were consistent at around **10** seconds.

Figure 3.9: Transient Adsorption Experiment with Steam

DATE	August 05, 1993
EXPERIMENTAL RUN :	No. 9
WELL	MLM-3 South Geysers Field
DEPTH	1325 m MD or 1320 m TVD
MESH	45 - 150 Tyler Standard
CORE HOLDER	58.5 **cm** X 1.905 cm
STEAM GENERATION :	Inside the Air Bath
STEAM SAT. PRESSURE :	2.061 bars
AIR BATH TEMP.	394.35 Kelvin
VACUUM TIME	23.6 hrs
STEAM EXPOS. TIME :	40.9 hrs
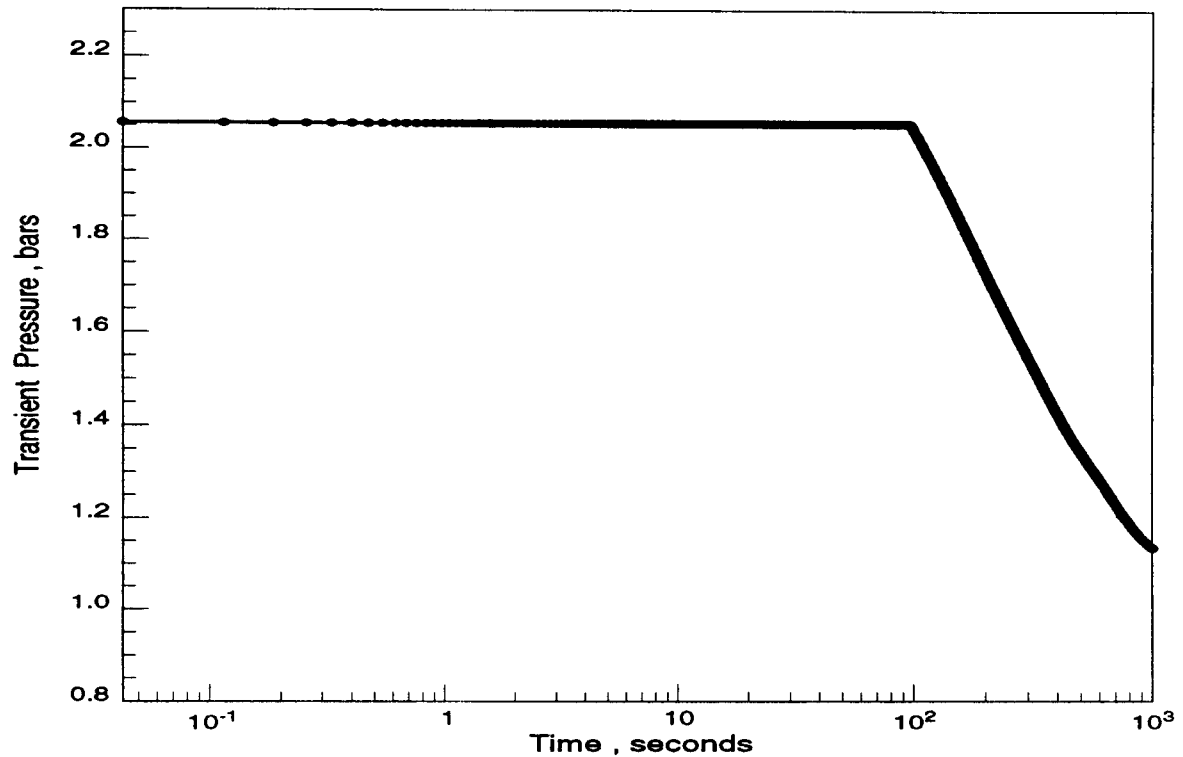
Figure **3.10:** Transient Adsorption Experiment with Steam and CO_2

DATE		August 11, 1993
EXPERIMENTAL RUN	:	No. 10
WELL		MLM-3 South Geysers Field
DEPTH		1325 m MD or 1320 m TVD
MESH		45 - 150 Tyler Standard
CORE HOLDER		58.5 cm X 1.905 cm
STEAM GENERATION	:	Inside the Air Bath
STEAM SAT. PRESSURE	:	2.056 bars
AIR BATH TEMP.		394.27 Kelvin
VACUUM TIME		25.0 hrs
STEAM EXPOS. TIME	:	42.2 hrs
CO_2 PARTIAL PRES.		0.40 bars (19.6 %)
STEAM PARTIAL PRES.	:	1.64 bars (80.4 %)

SECTION **3.** *EXPERIMENTAL RESULTS*

Figure 3.11: Transient Adsorption Experiment with Steam

DATE		December 02, 1993
EXPERIMENTAL RUN	:	No. 11
WELL		MLM-3 South Geysers Field
DEPTH		1325 m MD or 1320 m TVD
MESH		45 - 150 Tyler Standard
CORE HOLDER		58.5 cm X 1.905 cm
STEAM GENERATION	:	Inside the Air Bath
STEAM SAT. PRESSURE	:	2.066 bars
AIR BATH TEMP.		394.42 Kelvin
VACUUM TIME		24.0 hrs
STEAM EXPOS. TIME	:	42.8 hrs

Figure 3.12: Transient Adsorption Experiment with Steam

DATE		December 05, 1993
EXPERIMENTAL RUN	:	No. 12
WELL		MLM-3 South Geysers Field
DEPTH		1325 m MD **or** 1320 m TVD
MESH		45 - 150 Tyler Standard
CORE HOLDER		58.5 cm X 1.905 cm
STEAM GENERATION	:	Inside the Air Bath
STEAM SAT. PRESSURE	:	2.055 bars
AIR BATH TEMP.		394.25 Kelvin
VACUUM TIME		25.0 hrs
STEAM EXPOS. TIME	:	43.5 hrs

Figure 3.13: Transient Adsorption Experiment with CO_2

DATE	:	December 11, 1993
EXPERIMENTAL RUN	:	No. 13
WELL	:	MLM-3 South Geysers Field
DEPTH	:	1325 m MD **or** 1320 m TVD
MESH	:	45 - 150 Tyler Standard
CORE HOLDER	:	58.5 cm X 1.905 cm
AIR BATH TEMP.	:	394.13 Kelvin
VACUUM TIME	:	27.2 hrs
CO_2 EXPOSURE TIME	:	24.5 hrs

Figure **3.14: Transient Adsorption Experiment with** CO_2

DATE	December 16, **1993**
EXPERIMENTAL RUN	No. **14**
WELL	MLM-3 South Geysers Field
DEPTH	**1325** m MD or **1320** m TVD
MESH	**45 - 150** Tyler Standard
CORE HOLDER	**58.5** cm X **1.905** cm
AIR BATH TEMP.	**394.28** Kelvin
VACUUM TIME	**24.0** hrs
CO_2 EXPOSURE TIME	**52.5** hrs

Figure 3.15: Transient Adsorption Experiment with Steam and CO_2

DATE		December 20, 1993
EXPERIMENTAL RUN	:	No. 15
WELL		MLM-3 South Geysers Field
DEPTH		1325 m MD or 1320 m TVD
MESH		45 - 150 Tyler Standard
CORE HOLDER		58.5 cm X 1.905 cm
STEAM SAT. PRESSURE	:	2.059 bars
AIR BATH TEMP.		394.32 Kelvin
VACUUM TIME		24.0 hrs
STEAM EXPOS. TIME	:	25.8 hrs
CO_2 PARTIAL PRES.		0.74 bars (36%)
STEAM PARTIAL PRES.	:	1.32 bars (64%)

In order to measure the permeability of the **45-150** Mesh size sample, nitrogen gas was used to obtain the following data:

Upstream pressure   :   **140, 180, 220** and **260** psig.

Time   **530, 315, 234** and **185** seconds respectively.

Gas permeability   :   **0.411, 0.435, 0.402** and **0.371** Darcy respectively.

After experiments for the **45-150** Mesh size sample had been completed, the permeability of the sample was measured. Similar to the previous method used in obtaining the permeability of the **20-45** Mesh size sample, a graph was constructed to show the relationship between the reciprocal mean pressure and the observed permeability. After the "Klinkenberg Effect" had been removed, the permeability was then extrapolated to be 0.207 Darcy.

After the experiments for the **45-150** Mesh size sample had been finalized, the porosity of the sample was measured accordingly. The porosity was found to be **41%**, by calculating the volume of sample occupied by water. This method of finding porosity by introducing water inside the sample had a drawback in that the sample became more compact, resulting in a lower permeability.

Figure **3.29** is the inferred adsorption mass graph based on the transient pressure data of the **45-150** Mesh size sample. The same nonlinear regression program was used to obtain the parameters of Langmuir isotherm equation and subsequently the adsorbed mass.

At the conclusion of experiment with CO_2, a new series of experiments was initiated using salt. The sample was evacuated and **5%** saline solution was later introduced to the air-free sample inside the sample holder. After drying it in the airbath to evaporate the liquid, the sample was ready for the adsorption test.

It was found that the log progression factor of **1005** was not sufficient in recording the complete transient pressure data. Data recording was cut off at **40** minutes after

the start of the pressure transient measurement. Experimenting with other factors, higher than **1005** and up to 1008, did not produce a close duplication of data. The breakthrough times increased with the log progression factors. Figure **3.16** depicts the selection of log progression factor with respect to pressure and time.

The solution to this problem was to change the sample to a coarser particle size having higher permeability, therefore a **20-45** Mesh size sample **was** used. This was the same size sample as the one used in the previous experiments, Runs **4** to 8. The sequence of the experiment was also the same as before, where the steam-only run preceded any other run in order to establish a base curve.
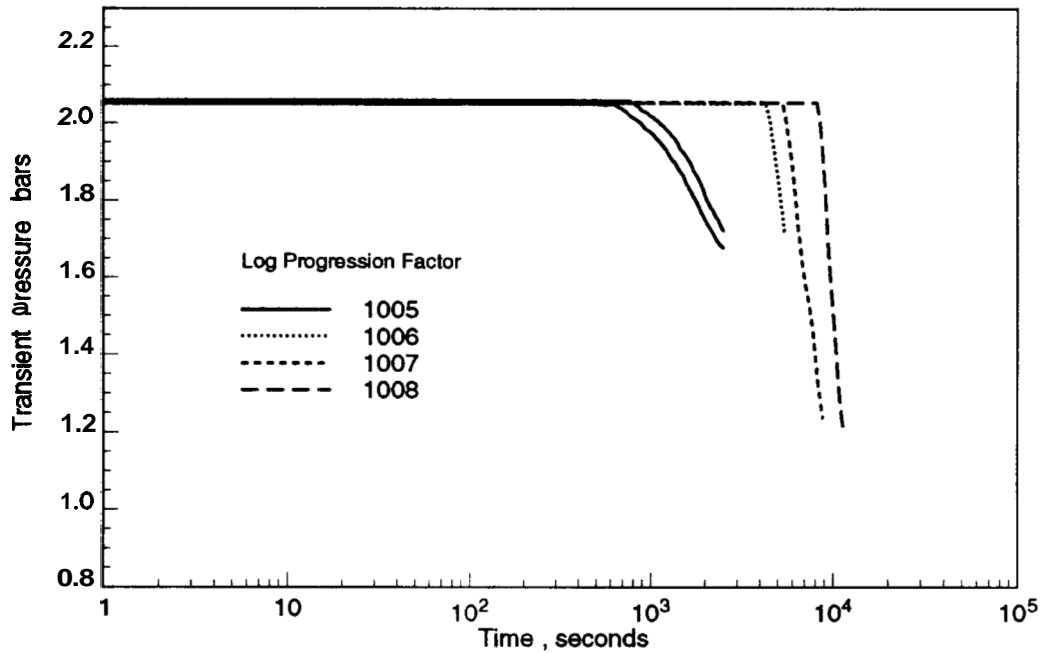
Figure **3.16: Experiment Using 45 ‑ 120 Mesh Size and Salt**

Care was exercised in this experiment using salt due to fear of corrosion of the equipment. **As** much as possible the presence of salt was localized. Salt was added to the sample and dried subsequently, leaving no saline solution in the steel tubing.

The sample of **20-45** Mesh, still the same one obtained from Well MLM-3, was compacted carefully to ensure good packing. The sample was then evacuated to create a vacuum condition. Water was used as a means to gauge the amount of pore space (porosity). Besides that water was used to compact the sample further. The porosity was calculated to be **54.4%.**
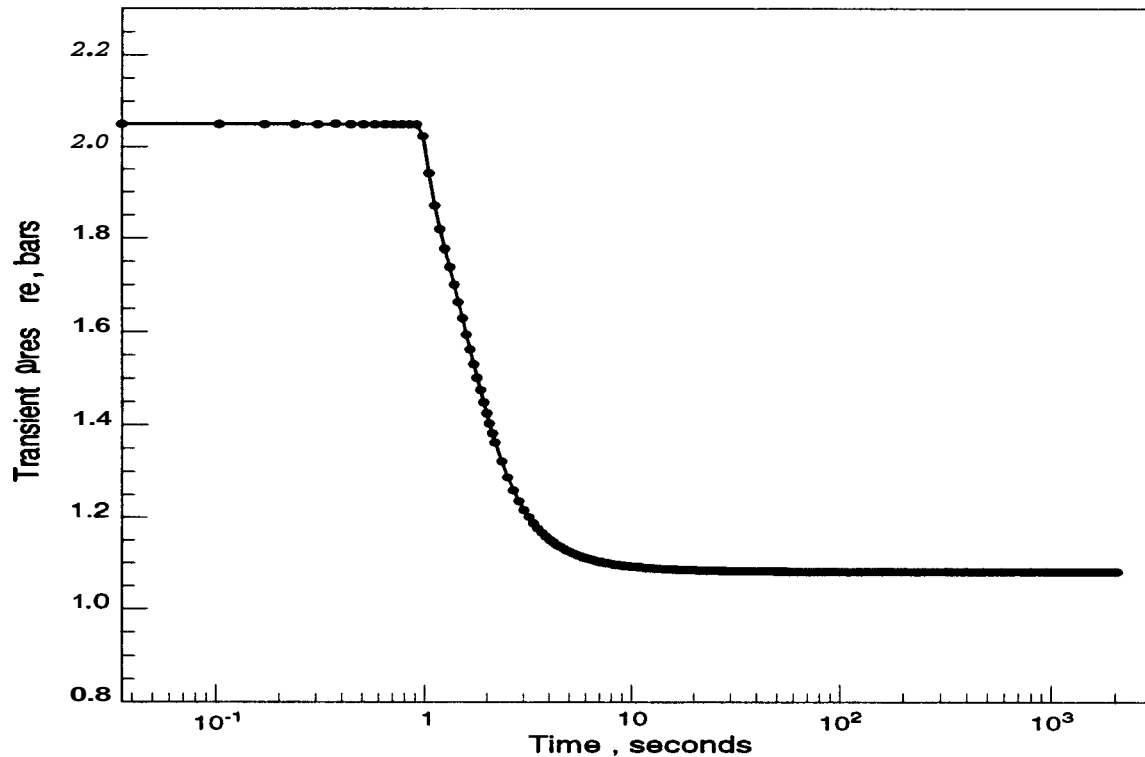
Figure 3.17: **Experiment with 20-45 Mesh Size without Salt**

DATE   April 23, 1994

EXPERIMENTAL RUN   :   No. 16

WELL   **MLM-3** South Geysers Field

DEPTH   1325 m MD or 1320 m TVD

MESH   20 - 45 Tyler Standard

CORE HOLDER   58.5 cm X 1.905 cm

STEAM SAT. PRESSURE :   2.0507 bars

AIR BATH TEMP.   394.19 Kelvin

VACUUM TIME   23.5 hrs

STEAM EXPOS. TIME   :   24.5 hrs

The resulting transient pressure of this new sample is shown **as** Run 16 shown in Fig. 3.17. This is similar to the ones obtained before for the same sample size, 20-45 Mesh. There is a slightly longer breakthrough time detected for the current experiment. This would be expected since the current experiment required the sample to be compacted more than the previous experiment resulting in less permeable sample. Less permeable sample produces longer breakthrough time.

This experiment was replicated using the same sample to confirm the reproducibility of transient pressure curve of steam without any saline effect. Figure 3.18 shows the replicate run, Run 17. It was found that Runs 16 and 17 are in close agreement with each other, in fact they overlap.

The next step was the measurement of permeability. Using the same previous method, the following data was obtained:

Upstream pressure	:	25, 21.4, 18, 14.4, 11 and 9.3 psig.
Time	:	73.5, 80.0, 92.6, 108.8, 141.2
		and 170.0 seconds respectively.
Gas permeability	:	55.09, 63.32, 69.70, 80.25, 87.76
		and 90.01 Darcy respectively.

A graph was constructed to show the relationship between the reciprocal mean pressure and the observed permeability. After the "Klinkenberg Effect" was removed, the permeability was extrapolated to be 31 Darcy. This is in agreement with the permeability value found previously for the 20-45 Mesh size sample, which was 37.5 Darcy. The lower permeability was due to compaction of the sample during introduction of the water.
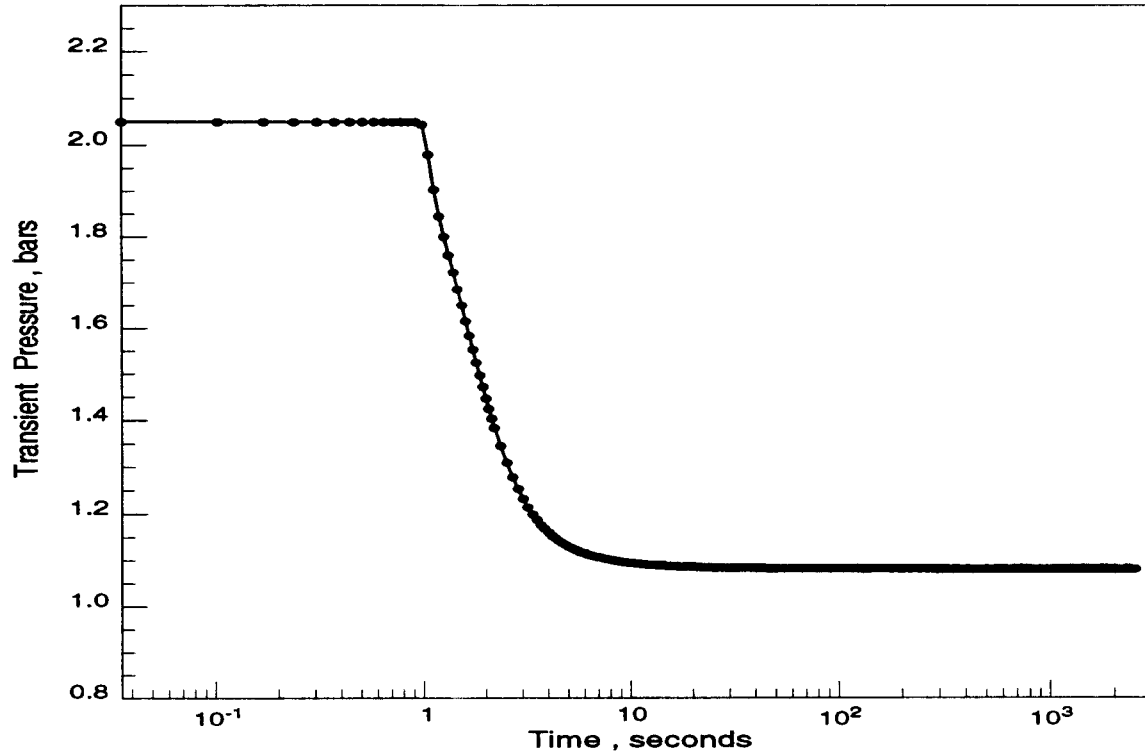
Figure 3.18: Experiment with **20-45** Mesh Size without Salt
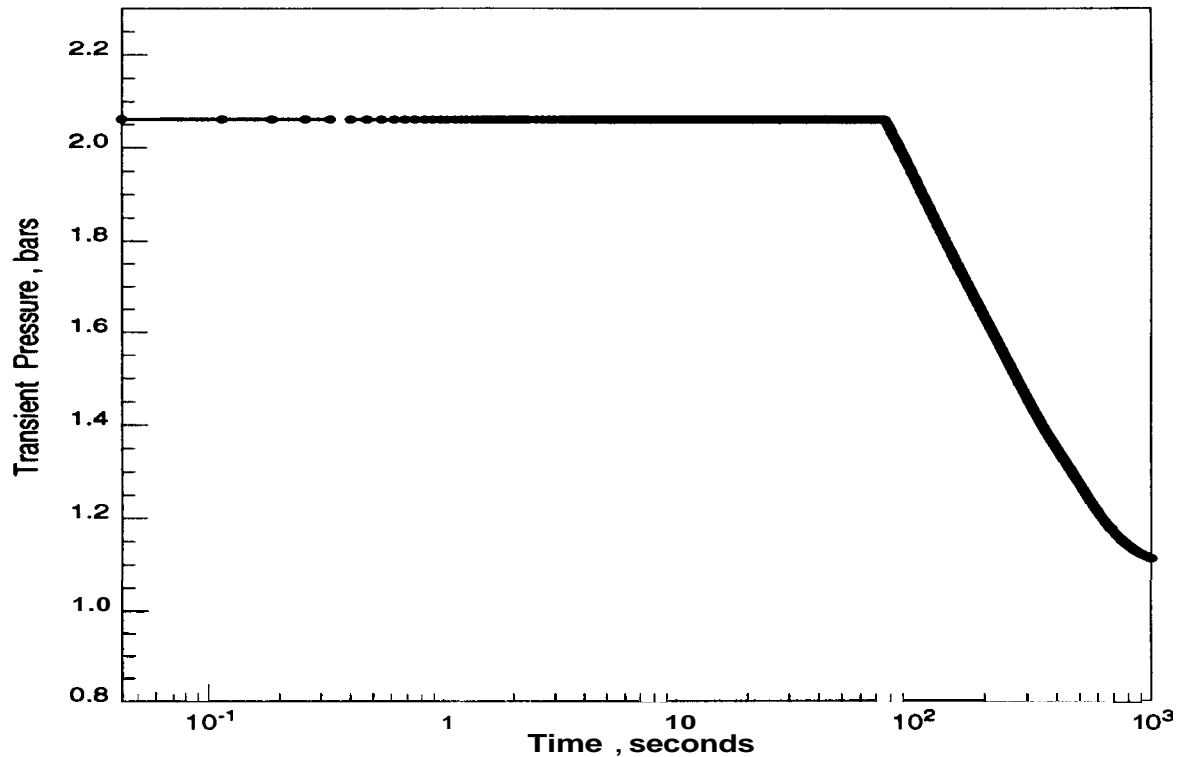
DATE   April 25, 1994
EXPERIMENTAL RUN   :   No. 17
WELL   MLM-3 South Geysers Field
DEPTH   1325 m MD or 1320 m TVD
MESH   20 - 45 Tyler Standard
CORE HOLDER   58.5 cm X 1.905 cm
STEAM SAT. PRESSURE :   2.0490 bars
AIR BATH TEMP.   394.16 Kelvin
VACUUM TIME   22.67 hrs
STEAM EXPOS. TIME   :   23.0 hrs

Runs 18 to 20 in Figures 3.19 to 3.21 respectively show the results of adding salt to the sample prior to a steam adsorption process. It can be seen that the three runs match closely to each other.

It is observed that the initial pressure of these two runs was still the same as the previous two runs using only steam. Should salt have been added directly to the water, the saturation steam pressure would be less. Theoretically the steam pressure inside the sample would be less by the presence of salt, however the pressure reduction could not be measured due to the unfavorable location of the pressure transducers. If the transducer were inside the sample, rather than at the outside of the sample as it is, the variation in pressure could be perhaps be measured.

Another observation here is that the breakthrough time for the run with salt is longer than for the run without salt. Apparently the addition of salt to the sample has the effect of reducing the permeability of the sample. Salt grains, originated from the saline solution, filled some of the pore space of the sample. Hence the flow area was reduced, and the transmissibility of the steam was impaired.

The tail of Run 18 did not show a smooth transition, but rather oscillated before converging to atmospheric pressure. This aberration was present also in the replicate runs (Runs 19 and 20) shown in Figs. 3.20 and 3.21 respectively, but not in the previous runs. It can be said that this aberration was caused by the addition of salt to the sample.
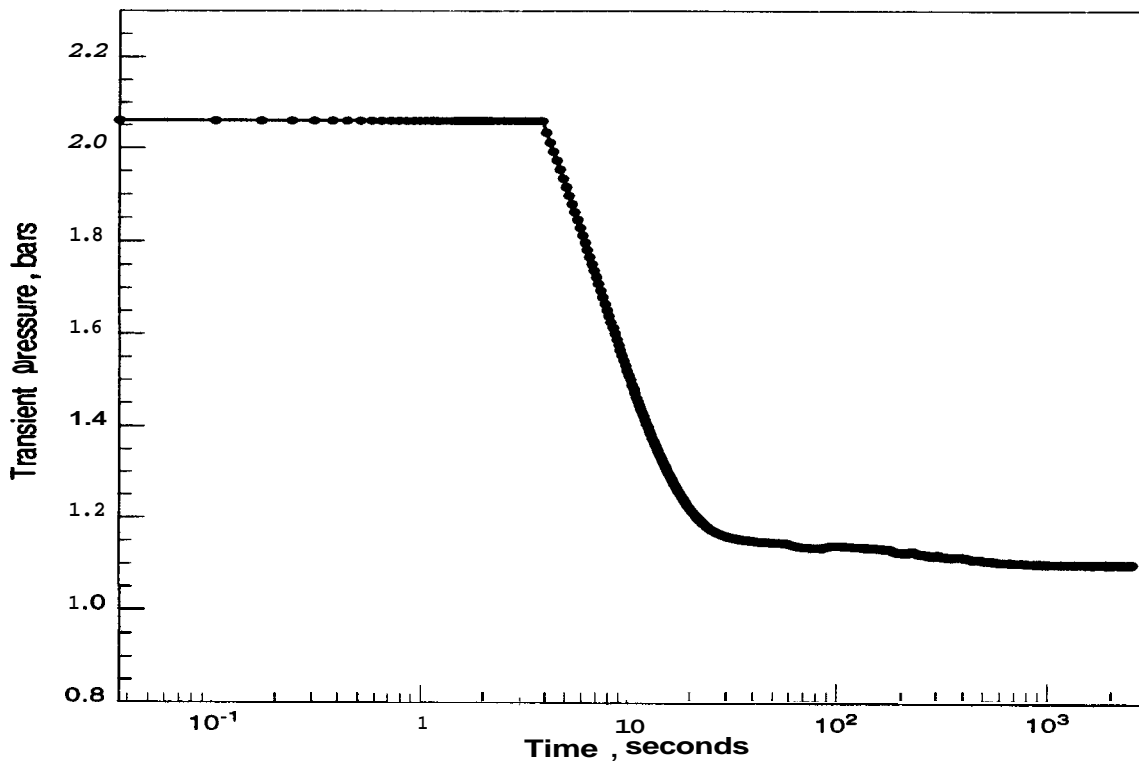
Figure 3.19: Experiment with **20-45** Mesh Size with Salt
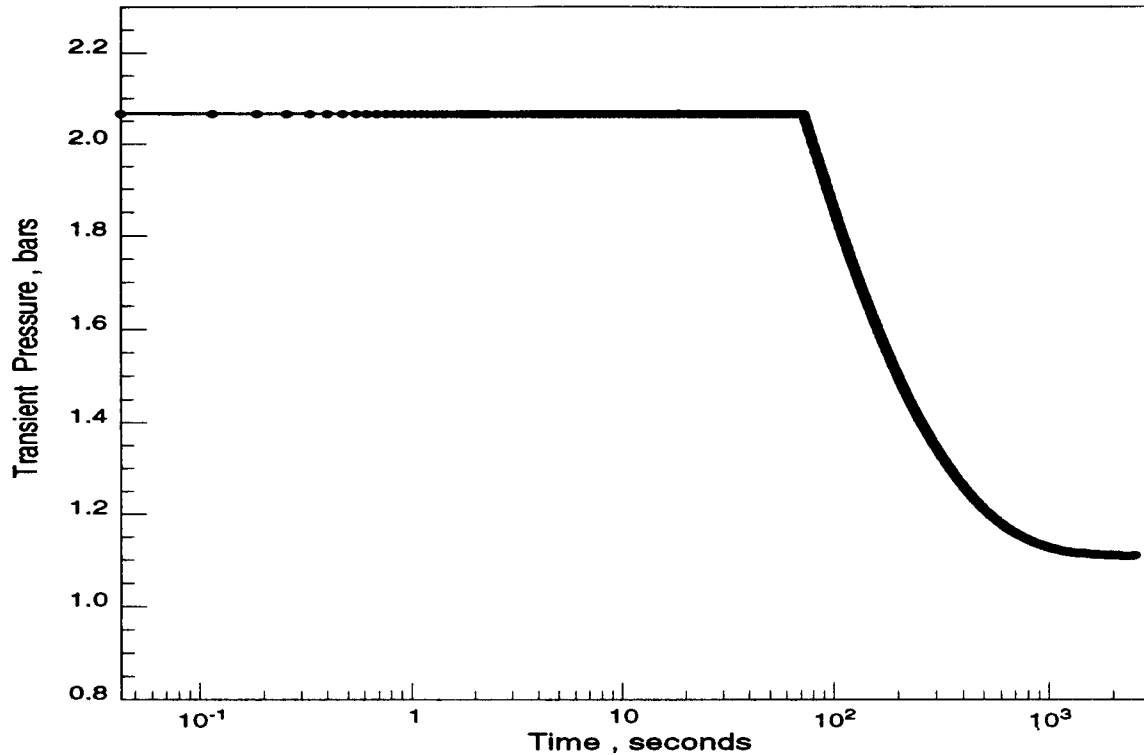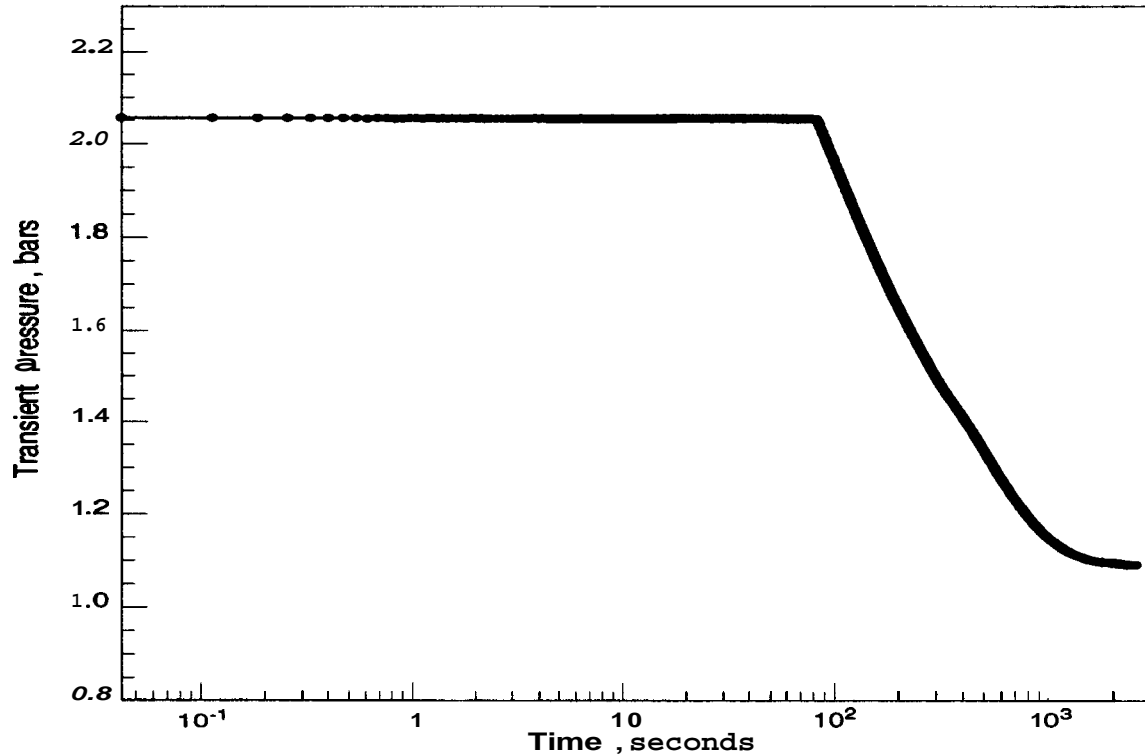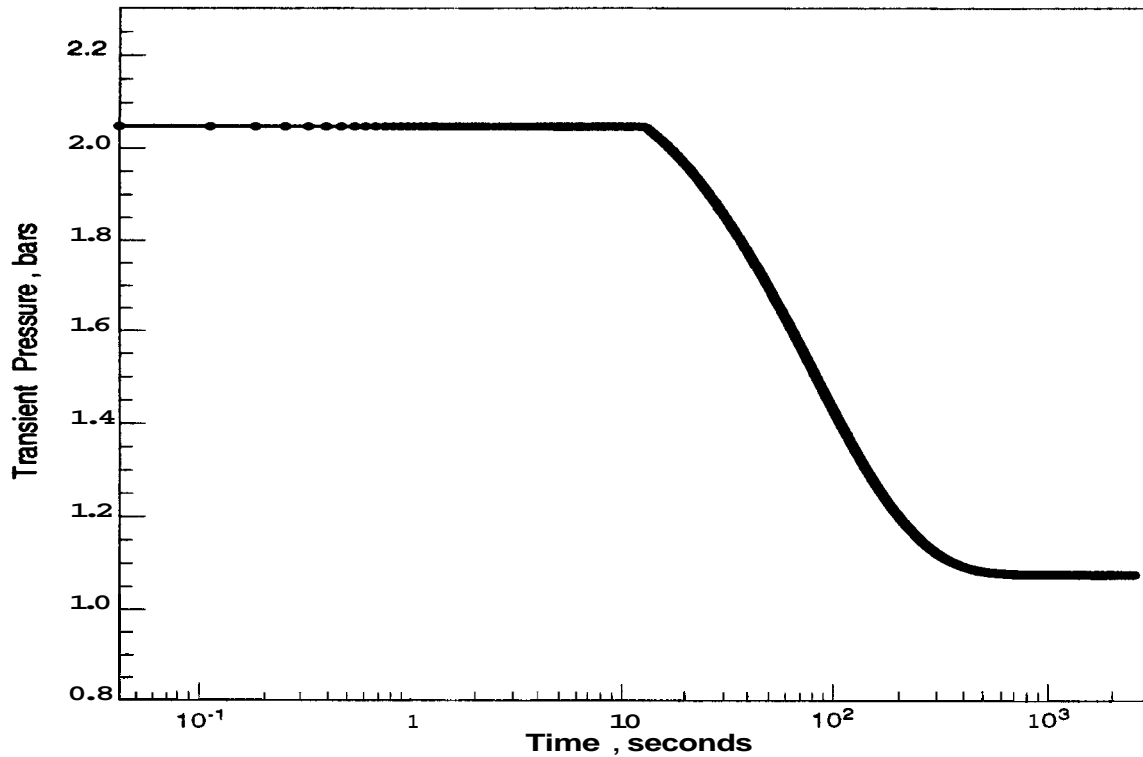
DATE   April 29, 1994
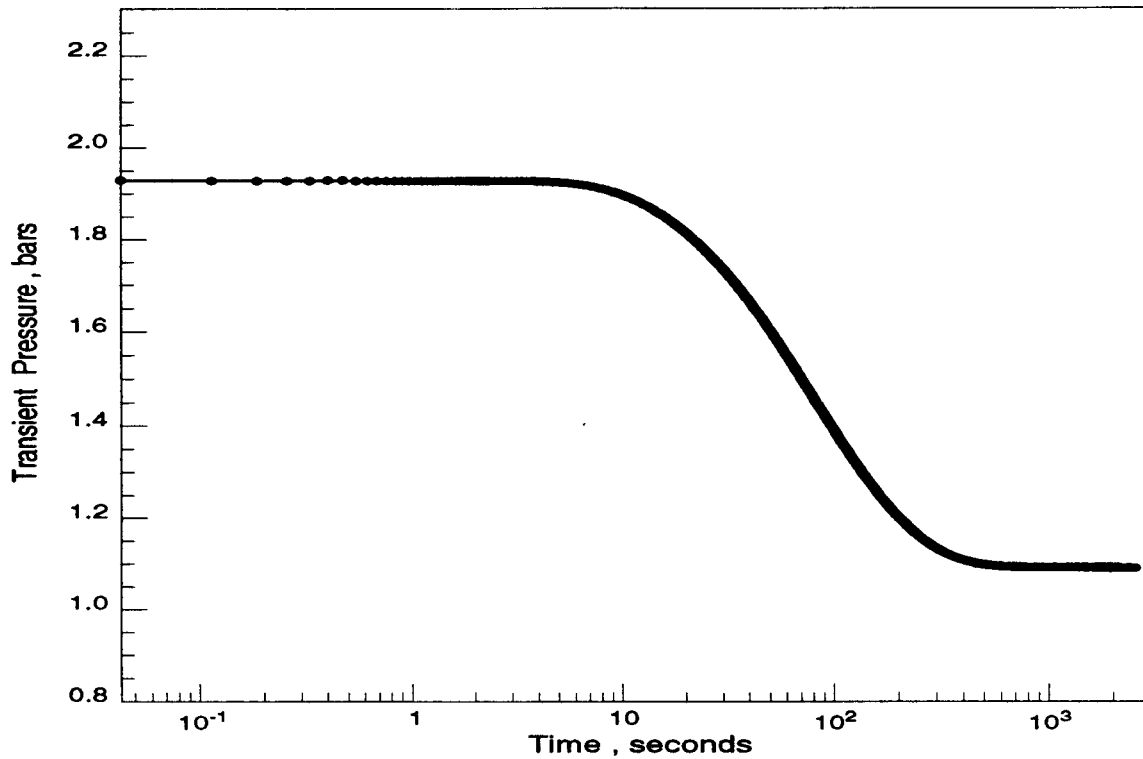
EXPERIMENTAL RUN   :   No. 18

WELL   MLM-3 South Geysers Field

DEPTH   1325 m MD or 1320 m TVD

MESH   20 - 45 Tyler Standard

CORE HOLDER   58.5 cm X 1.905 cm

STEAM SAT. PRESSURE :   2.0602 bars

AIR BATH TEMP.   394.33 Kelvin

VACUUM TIME   23.25 hrs

STEAM EXPOS. TIME   :   23.8 hrs
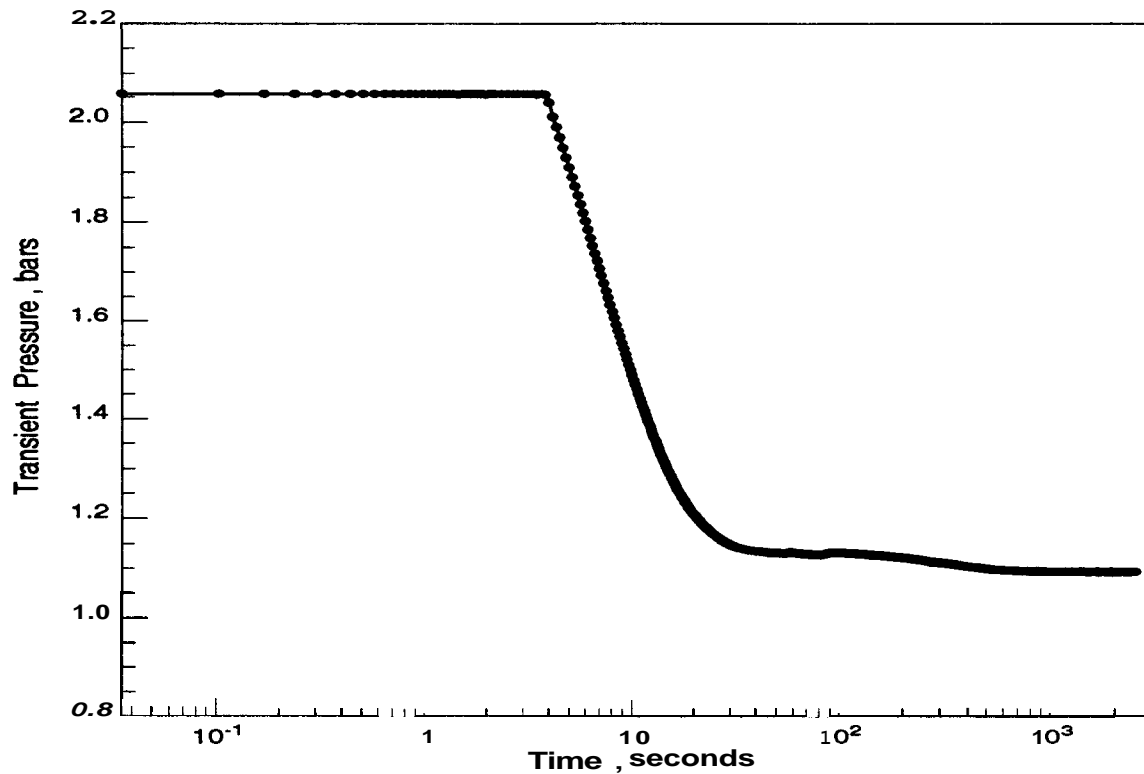
Figure 3.20: Experiment with **20-45** Mesh Size with Salt
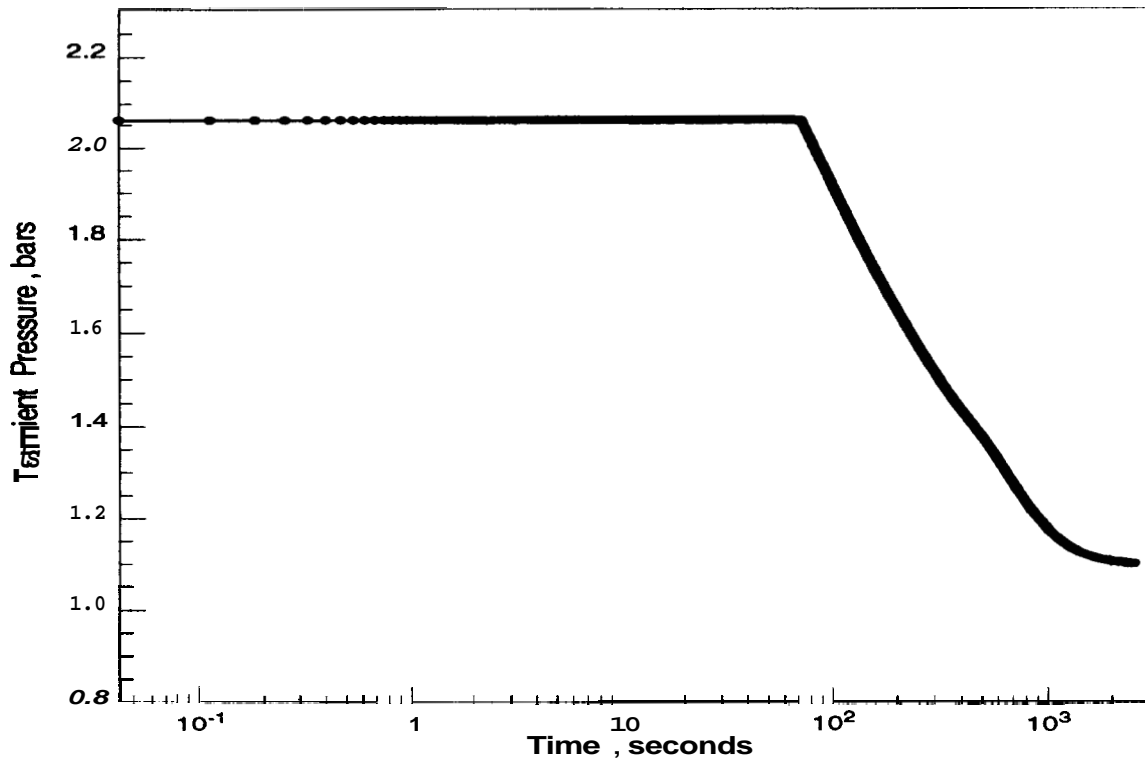
DATE   May 01, 1994

EXPERIMENTAL RUN   :   No. 19

WELL   MLM-3 South Geysers Field

DEPTH   1325 m MD or 1320 m TVD

MESH   20 - 45 Tyler Standard

CORE HOLDER   58.5 cm X 1.905 cm

STEAM SAT. PRESSURE :   2.0570 bars

AIR BATH TEMP.   394.28 Kelvin

VACUUM TIME   23.5 hrs

STEAM EXPOS. TIME   :   27.2 hrs
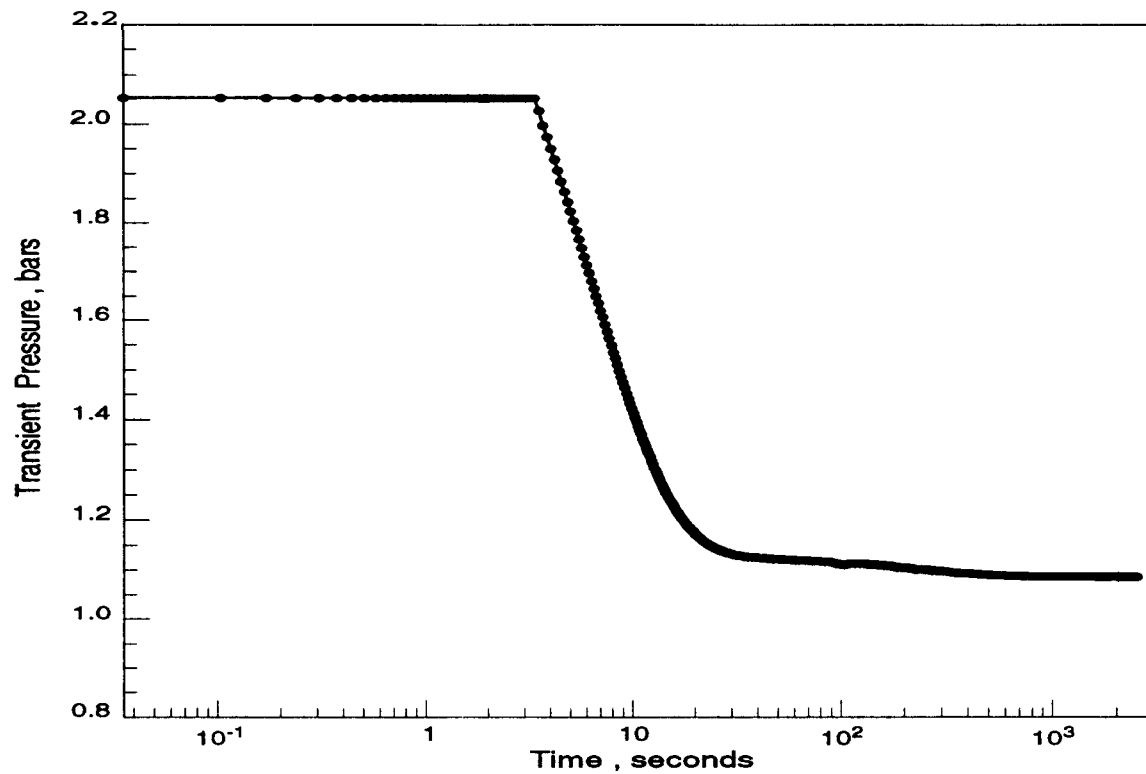
Figure 3.21: Experiment with **20-45** Mesh Size with Salt

DATE	May 04, 1994
EXPERIMENTAL RUN :	No. 20
WELL	MLM-3 South Geysers Field
DEPTH	1325 m MD or 1320 m TVD
MESH	20 - 45 Tyler Standard
CORE HOLDER	58.5 cm X 1.905 cm
STEAM SAT. PRESSURE :	2.0524 bars
AIR BATH TEMP.	394.21 Kelvin
VACUUM TIME	24.4 hrs
STEAM EXPOS. TIME :	24.75 hrs

3.1   Summary of the Results

A summary of the experimental runs is as follows:

Run	Date	Description of Sample	Fluid	Remarks
1	Apr. 23, 1993	Geysers 28-150 Mesh	Steam only	30.48-cm core
2	Apr. 30, 1993	Geysers 28-150 Mesh	Steam only	30.48-cm core
3	May 01, 1993	Geysers 28-150 Mesh	Nitrogen only	30.48-cm core
4	Jul. 09, 1993	Geysers 20-45 Mesh	Steam only	58.5-cm core
5	Jul. 15, 1993	Geysers 20-45 Mesh	CO_2 only	58.5-cm core
6	Jul. 23, 1993	Geysers 20-45 Mesh	Steam only	58.5-cm core
7	Jul. 26, 1993	Geysers 20-45 Mesh	Steam only	external steam
8	Jul. 29, 1993	Geysers 20-45 Mesh	Steam and **7.6%** CO_2	58.5-cm core
9	Aug. 05, 1993	Geysers 45-150 Mesh	Steam only	58.5-cm core
10	Aug. 11, 1993	Geysers 45-150 Mesh	Steam and 19.6% CO_2	58.5-cm core
11	Dec. 02, 1993	Geysers 45-150 Mesh	Steam only	58.5-cm core
12	Dec. 05, 1993	Geysers 45-150 Mesh	Steam only	58.5-cm core
13	Dec. 11, 1993	Geysers 45-150 Mesh	CO_2 only	58.5-cm core
14	Dec. 16, 1993	Geysers 45-150 Mesh	CO_2 only	58.5-cm core
15	Dec. 20, 1993	Geysers 45-150 Mesh	Steam and 36% CO_2	58.5-cm core
16	Apr. 23, 1994	Geysers 20-45 Mesh	Steam only	without salt
17	Apr. 25, 1994	Geysers 20-45 Mesh	Steam only	without salt
18	Apr. 29, 1994	Geysers 20-45 Mesh	Steam only	with salt
19	May 01, 1994	Geysers 20-45 Mesh	Steam only	with salt
20	May 04, 1994	Geysers 20-45 Mesh	Steam only	with salt

3.1.1 The Effects of Sample Size

The graph below compares the different in pressure response with regard to sample size. Larger particle size results in early breakthrough time due to the relatively higher permeability. Only the **1993** steam-only runs (Runs **4, 6, 9, 11** and **12**) were compared. The **1994** steam-only runs (Runs 16 and 17) were excluded from Fig. **3.22,** because of a slightly different method in preparation of the sample. The latter runs were compacted more than the former runs.
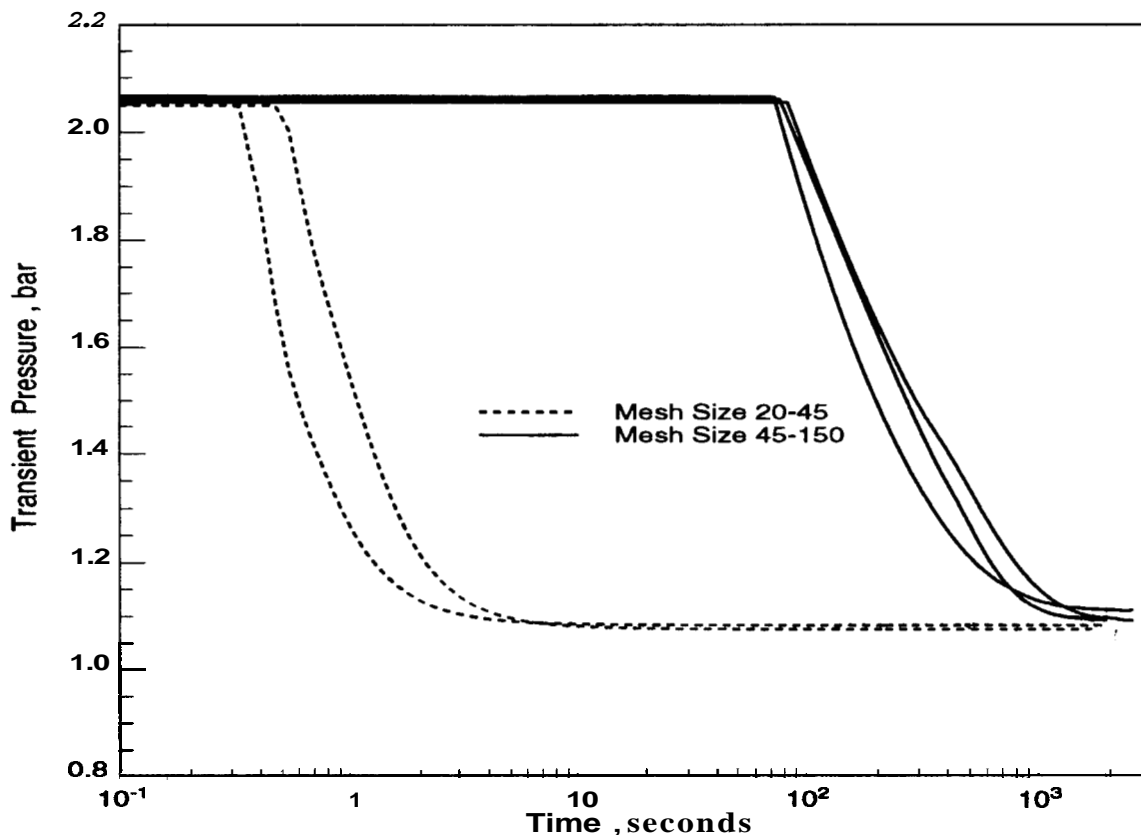
Figure **3.22: Comparison of Mesh Size**
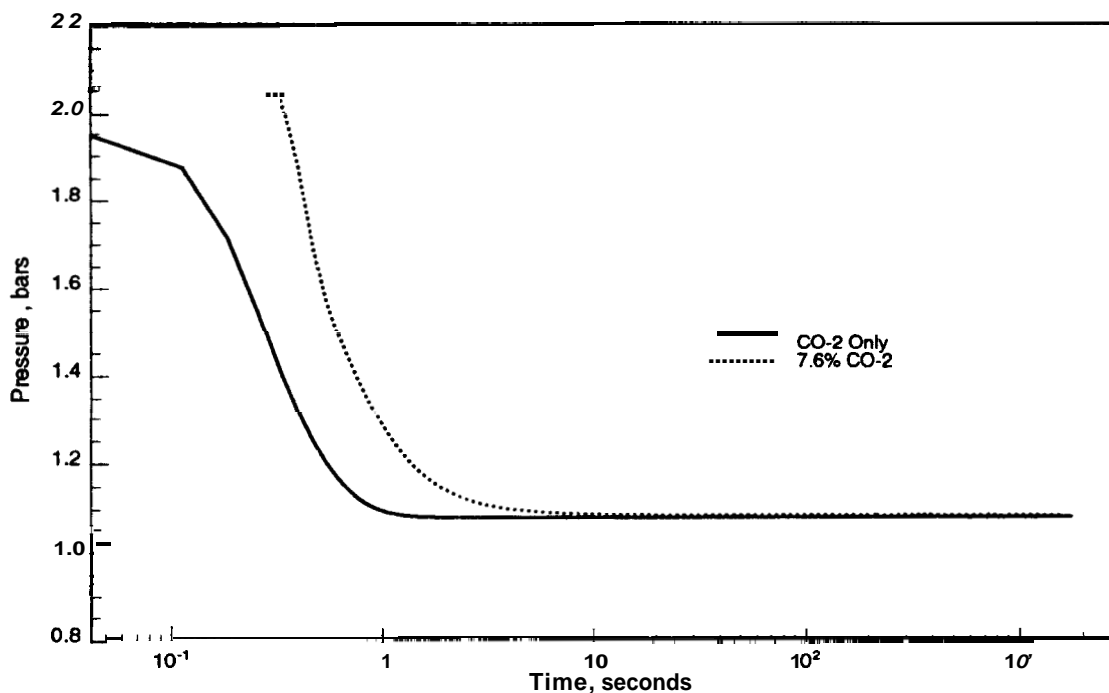
Figure **3.23: The Presence of CO_2 in 20-45 Mesh Size**

3.1.2 The Effects of CO_2 on Adsorption

Figures **3.23** to **3.26** depict the runs with CO_2 in comparison with the steam runs. Figures **3.23** and **3.25** show only the CO_2 runs, either all CO_2 (Runs **5, 13, 14)** or a mixture of CO_2 with steam (Runs 8, 10, **15).** If steam-only data are included, the results are shown in Figures **3.24** and **3.26.**

Pressure transient data from the above runs were fed into the nonlinear regression program and the resulting Langmuir isotherm graphs were shown in bottom pottion of Figs. **3.28** and **3.29** for **20-45** and **45-150** Mesh size respectively. It is noted that the addition of CO_2 to steam did not affect the amount of steam adsorbed per unit mass of sample.
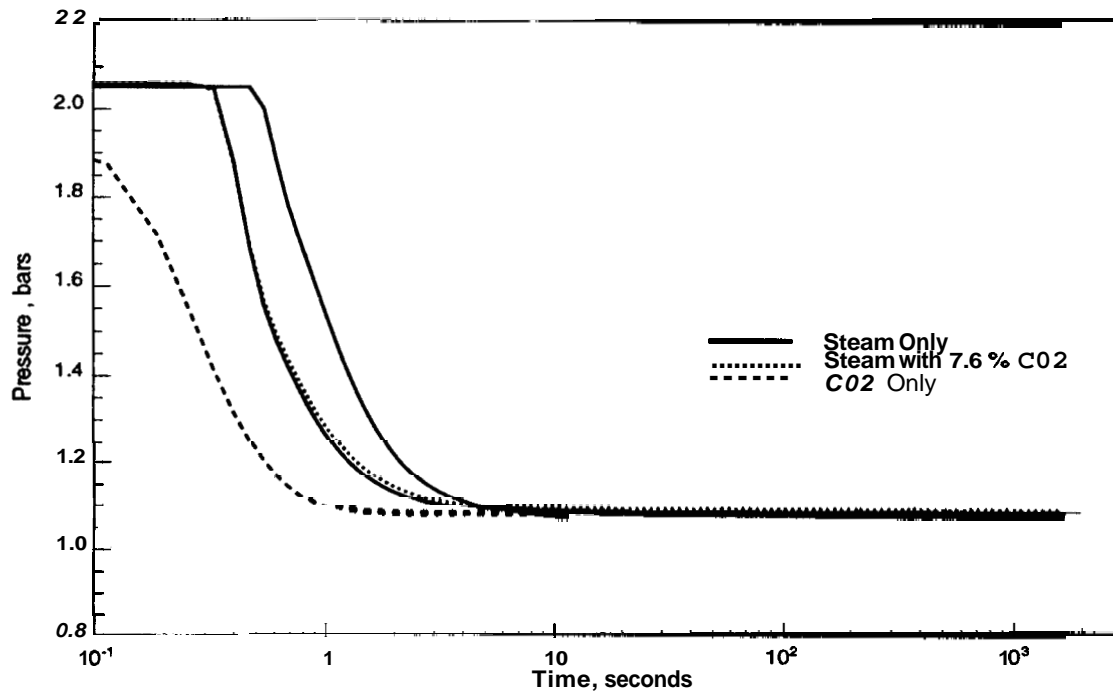
Figure **3.24: Comparison of Steam and CO$_2$ Using 20-45 Mesh Size**

3.1.3 The Effects of Salt on Adsorption

The graph in Fig. **3.27** summarizes the effect of salt addition to the **20-45** Mesh size sample. Two runs without salt (Runs 16, **17**) and three runs with salt (Runs 18, **19, 20**) are juxtaposed here. It can be seen that the breakthrough time for the run with salt is longer than the one without salt.

It is noted that the "salt" runs are also slow at returning back to atmospheric pressure at the end of the run. This characteristic was not detected in the "non-salt" runs.

Figure **3.30** inferred that the addition of salt generated more adsorption mass per unit mass of sample. The Langmuir isotherm for "salt" runs is more concave upward compared to "non-salt" runs. Hence, for a particular relative pressure the adsorbed mass is higher in the case of "salt" runs.
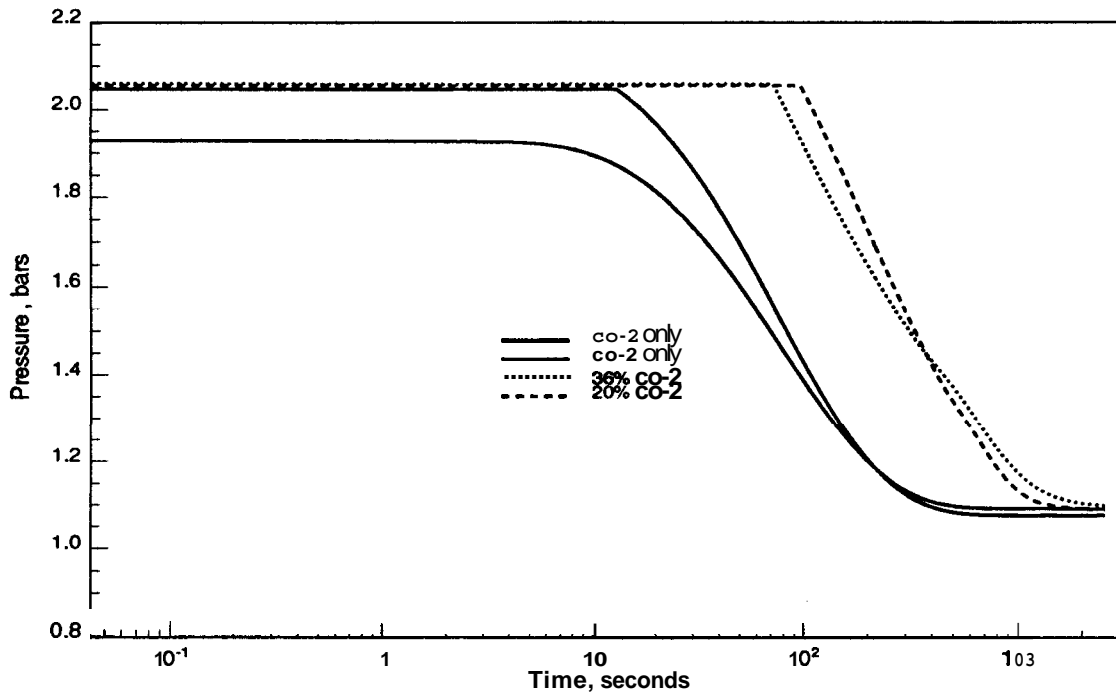
Figure **3.25: The Presence of CO$_2$ in 45 - 120 Mesh Size**
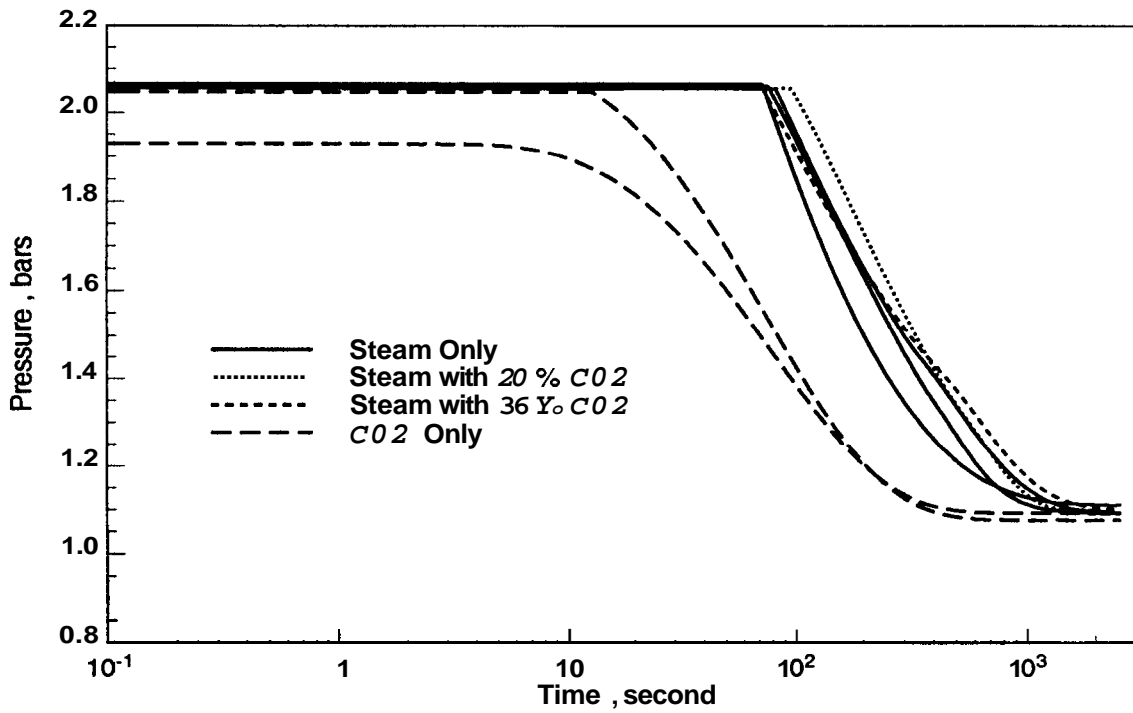
Figure **3.26: Comparison of Steam and CO$_2$ Using 45-150 Mesh Size**

3.1.4   The Langmuir Isotherms

The transient pressure data, as well as porosity, permeability and the sample dimensions, was fed into a nonlinear regression program (Qi, 1993). This computer program, using a one-dimensional geothermal adsorption simulator (Nghiem and Ramey, 1991), generated the two parameters of the Langmuir isotherm equation.

A summary of the parameters generated by the program is as follows:

For 20-45 Mesh size sample

Experiment Date	Run	A	B	Remarks
09-Jul-93	4	6385	-5296	Steam only
23-Jul-93	6	32027	-29433	Steam only
29-Jul-93	8	22931	-20538	Steam & CO_2

For 45-150 Mesh size sample

Experiment Date	Run	A	B	Remarks
05-Aug-93	9	7567	-6449	Steam only
11-Aug-93	10	3340	-2619	Steam & CO_2
02-Dec-93	11	4842	-3729	Steam only
05-Dec-93	12	2518	-1778	Steam only
20-Dec-93	15	1821	-1122	Steam & CO_2

Figures 3.28 and 3.29 are based on the experiments done in 1993. Subsequent experiments in 1994 to investigate the effect of salinity on adsorption generated the following parameters:
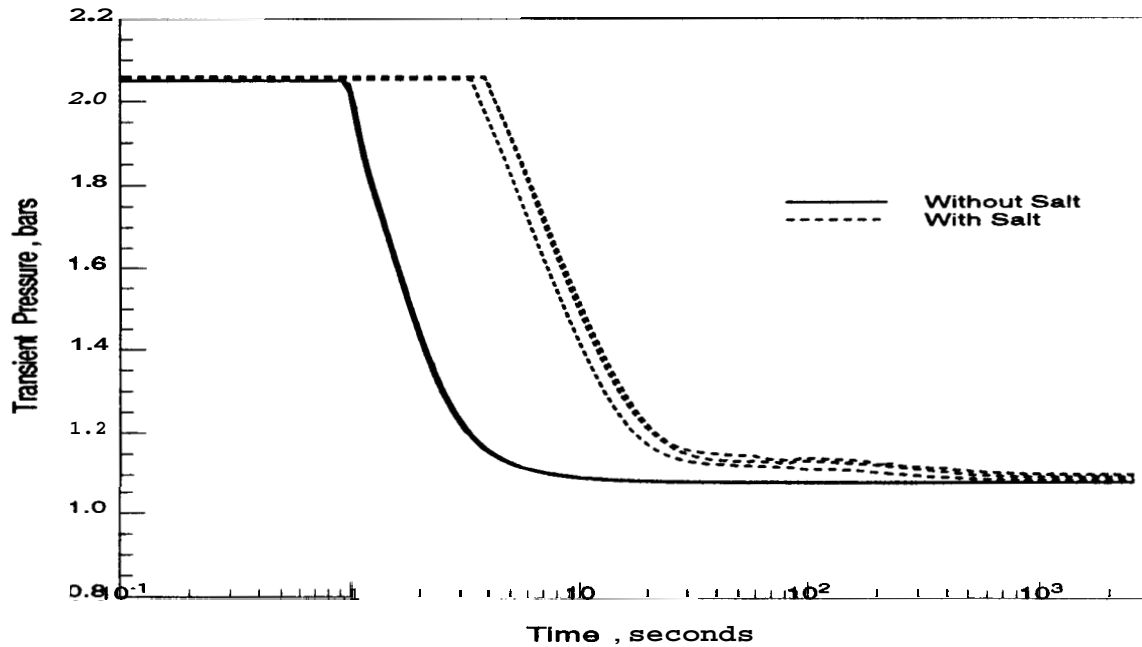
Figure 3.27: **The Presence of Salt in 20-45 Mesh Size**

For 20-45 Mesh size sample

Experiment Date	Run	A	B	Remarks
23-Apr-94	16	6446	-5725	No salt
25-Apr-94	17	5976	-5285	No salt
29-Apr-94	18	360	-267	with salt
01-May-94	19	394	-297	with salt
04-May-94	20	450	-338	with salt

The shape of all the isotherms was concave upward. It can be deduced from the shape that the amount of adsorbed mass varies substantially in the pressure ratio range of 0.6 to 1.0.
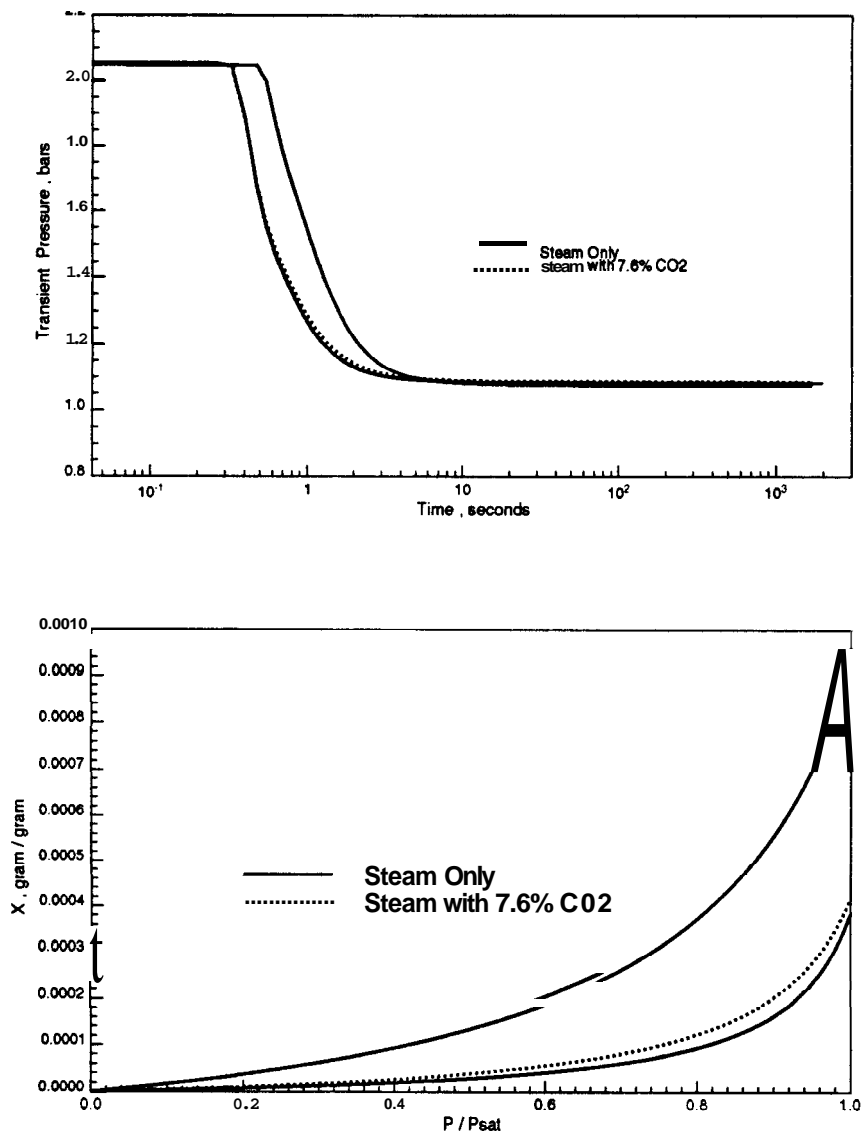
Figure 3.28: Langmuir Isotherms for 20-45 Mesh Size
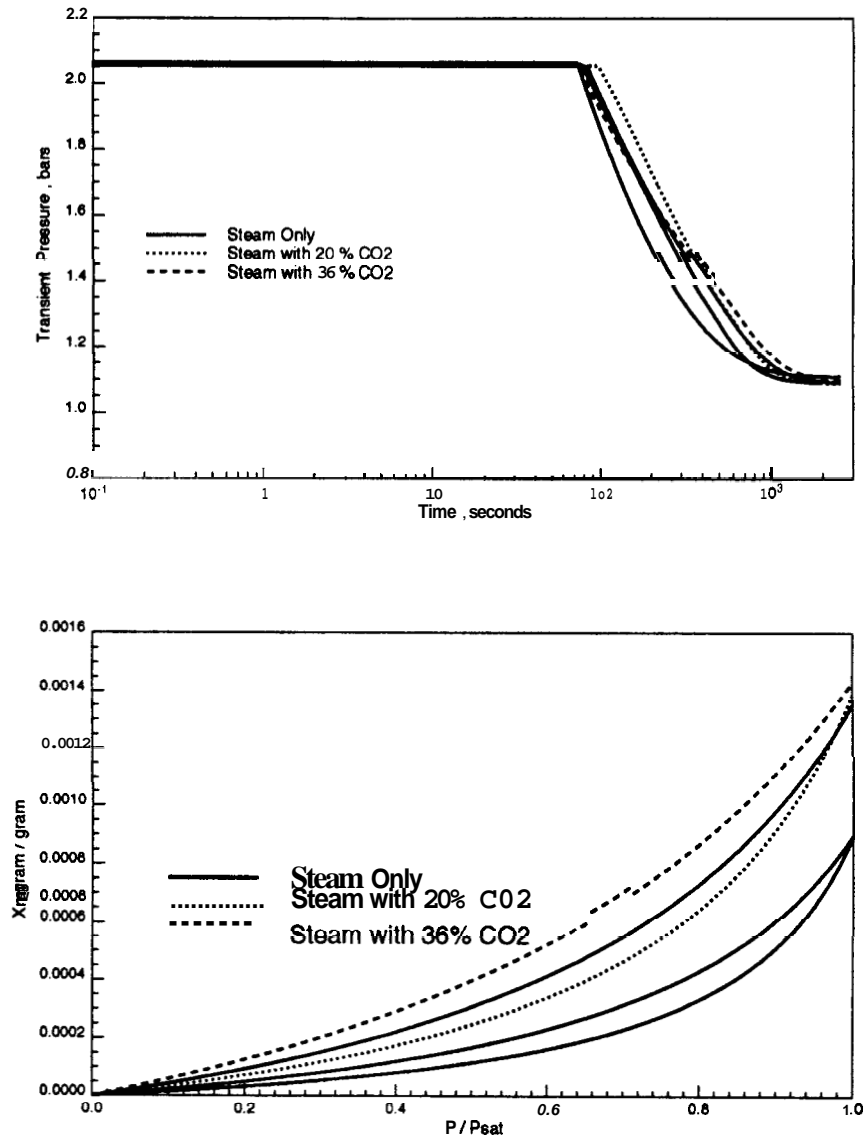
Figure 3.29: Langmuir Isotherms for 45-150 Mesh Size
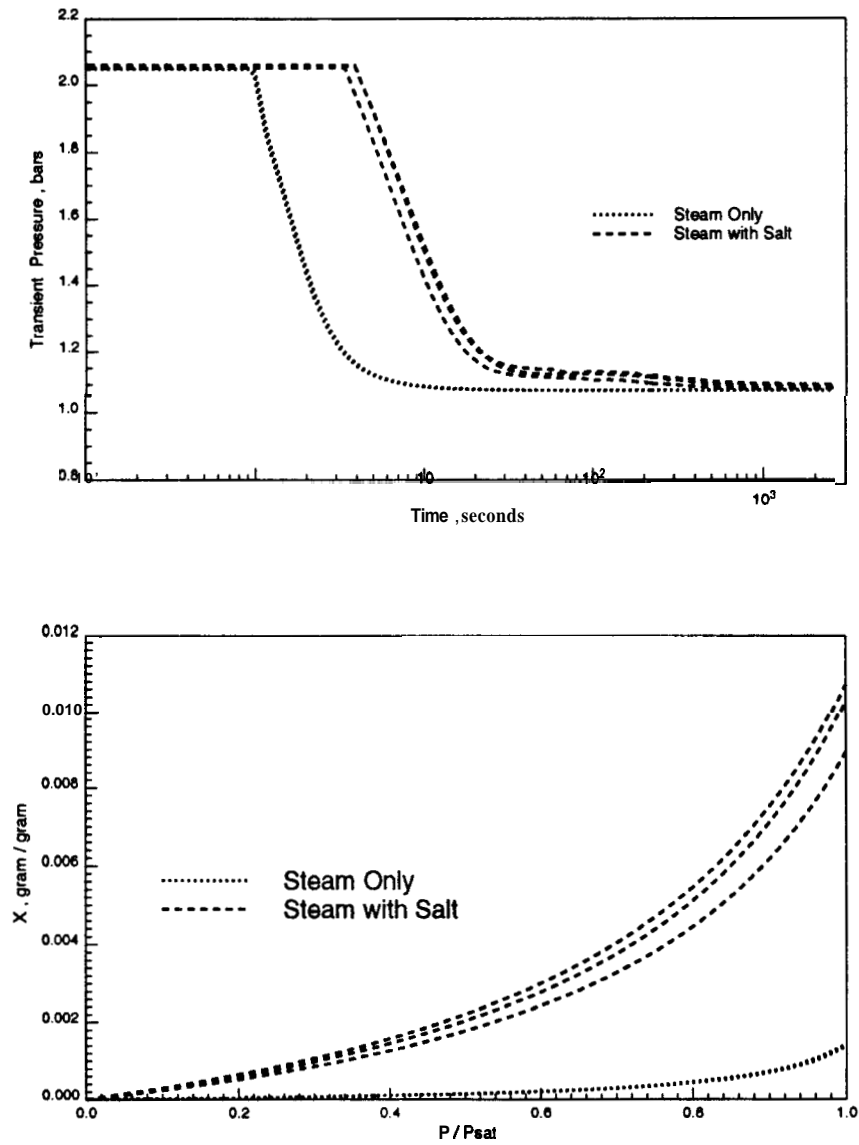
Figure 3.30: Langmuir Isotherms for 20-45 Mesh Size

Section 4

CONCLUSIONS

Based on the observations and results obtained during the course of this series of experiment, several conclusions can be made.

o Higher permeability sample produces a smaller amount of steam adsorption mass per unit mass than a lower permeability sample of the same rock.

o Addition of a partial concentration of CO_2, at least up to **36%** by volume, to the steam used did not affect steam adsorption on the Geysers rock samples.

• Addition of a small concentration of salt to the sample extended the break-through time of a pure steam transient pressure curve and increased the amount of steam adsorbed.

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Appendix A

Experimental Data

The following is an example listing of data acquired during an experimental run. All of the data files are available on floppy disk, however just a single example is shown here because of the space limitation. Should all the 20 runs be listed, it would take additional 600 pages.

WELL MLM3 S. Geysers 1320 m 45-150 Mesh Steam August 5, 1993

	Bottom	Top
The steam charge (volts):	0.924500	0.902500
The steam charge (bars):	2.51208	2.06130
The steam charge (P/Pz):	1.02438	1.00000
The calibration (volts):	0.756350	0.899820
The pressure of the atmosphere (volts):	0.376700	0.477000,
The pressure of the atmosphere (bars):	1.02358	1.08946
The vacuum reading (volts) after the run:	0.437000E-01	0.227000E-01
The saturated vapor pressure of water (volts):		0.902500
The saturated vapor pressure of water (bars):		2.06130
The temperature (degrees kelvin) is:		394.349
The calibration pressure (bars):		2.055180
The geometric progression factor:		1005.0000

The # of samples per displayed point: **40**

	Time(sec)	Bottom(bars)	Top(bars)
1	0.4300E-01	1.0394	2.0609
2	0.1147	1.0417	2.0610
3	0.1862	1.0357	2.0611
4	0.2577	1.0323	2.0610
5	0.3292	1.0318	2.0611
6	0.4006	1.0320	2.0610
7	0.4721	1.0320	2.0612
8	0.5436	1.0328	2.0611
9	0.6151	1.0333	2.0611
10	0.6866	1.0330	2.0612
11	0.7581	1.0335	2.0611
12	0.8296	1.0332	2.0611
13	0.9011	1.0331	2.0612
14	0.9726	1.0333	2.0611
15	1.044	1.0333	2.0611
16	1.116	1.0336	2.0610
17	1.187	1.0334	2.0611
18	1.259	1.0331	2.0611
19	1.330	1.0333	2.0611
20	1.402	1.0329	2.0611
21	1.473	1.0332	2.0612
22	1.545	1.0332	2.0612
23	1.616	1.0331	2.0611
24	1.688	1.0335	2.0612
25	1.760	1.0330	2.0613
26	1.831	1.0330	2.0613
27	1.903	1.0329	2.0613
28	1.974	1.0332	2.0613
29	2.046	1.0332	2.0612

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30	2.117	1.0333	2.0612
31	2.189	1.0336	2.0612
32	2.260	1.0333	2.0614
33	2.332	1.0334	2.0612
34	2.504	1.0334	2.0612
35	2.671	1.0337	2.0612
36	2.838	1.0334	2.0612
37	3.004	1.0335	2.0612
38	3.171	1.0336	2.0612
39	3.337	1.0334	2.0612
40	3.504	1.0337	2.0611
41	3.671	1.0338	2.0612
42	3.837	I.0339	2.0611
43	4.004	1.0339	2.0612
44	4.171	1.0337	2.0613
45	4.337	1.0338	2.0612
46	4.504	1.0340	2.0613
47	4.671	1.0338	2.0612
48	4.837	1.0337	2.0612
49	5.004	1.0338	2.0613
50	5.171	1.0338	2.0613
51	5.337	1.0337	2.0613
52	5.504	1.0338	2.0611
53	5.671	1.0338	2.0612
54	5.837	1.0338	2.0612
55	6.004	1.0336	2.0613
56	6.170	1.0337	2.0613
57	6.337	1.0338	2.0613
58	6.504	1.0337	2.0613
59	6.670	1.0338	2.0612
60	6.837	1.0337	2.0612

61	7.004	1.0337	2.0613
62	7.170	1.0338	2.0613
63	7.337	1.0336	2.0613
64	7.520	1.0340	2.0613
65	7.704	1.0336	2.0613
66	7.887	1.0338	2.0613
67	8.070	1.0334	2.0614
68	8.253	1.0336	2.0613
69	8.437	1.0335	2.0614
70	8.620	1.0336	2.0613
71	8.803	1.0337	2.0614
72	8.987	1.0336	2.0612
73	9.170	1.0336	2.0613
74	9.353	1.0337	2.0613
75	9.537	1.0335	2.0613
76	9.720	1.0333	2.0614
77	9.903	1.0334	2.0613
78	10.09	1.0334	2.0612
79	10.27	1.0335	2.0613
80	10.45	1.0335	2.0613
81	10.64	1.0334	2.0613
82	10.82	1.0334	2.0614
83	11.00	1.0338	2.0613
84	11.19	1.0336	2.0614
85	11.37	1.0336	2.0614
86	11.55	1.0332	2.0614
87	11.74	1.0335	2.0614
88	11.92	1.0335	2.0614
89	12.10	1.0335	2.0613
90	12.29	1.0336	2.0614
91	12.49	1.0335	2.0613

92	12.69	1.0334	2.0613
93	12.89	1.0334	2.0613
94	13.09	1.0333	2.0613
95	13.29	1.0335	2.0613
96	13.49	1.0335	2.0613
97	13.69	1.0335	2.0613
98	13.89	1.0333	2.0614
99	14.09	1.0334	2.0613
100	14.29	1.0332	2.0614
101	14.49	1.0334	2.0613
102	14.69	1.0333	2.0613
103	14.89	1.0329	2.0613
104	15.09	1.0331	2.0613
105	15.29	1.0330	2.0613
106	15.49	1.0332	2.0613
107	15.69	I.0331	2.0613
108	15.89	1.0332	2.0612
109	16.09	1.0331	2.0613
110	16.29	1.0331	2.0613
111	16.49	1.0330	2.0613
112	16.69	1.0331	2.0612
113	16.89	1.0332	2.0613
114	17.09	1.0332	2.0612
115	17.30	1.0332	2.0613
116	17.52	1.0333	2.0612
117	17.74	1.0334	2.0613
118	17.95	1.0333	2.0613
119	18.17	1.0332	2.0613
120	18.39	1.0332	2.0613
121	18.60	1.0330	2.0613
122	18.82	1.0330	2.0613

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123	19.04	1.0332	2.0612
124	19.25	1.0333	2.0612
125	19.47	1.0332	2.0612
126	19.69	1.0332	2.0612
127	19.90	1.0332	2.0612
128	20.12	1.0332	2.0612
129	20.34	1.0331	2.0613
130	20.55	1.0333	2.0612
131	20.77	1.0333	2.0613
132	20.99	1.0336	2.0612
133	21.20	1.0333	2.0612
134	21.42	1.0334	2.0612
135	21.64	1.0334	2.0612
136	21.87	1.0334	2.0613
137	22.10	1.0334	2.0612
138	22.34	1.0335	2.0612
139	22.57	1.0335	2.0613
140	22.80	1.0334	2.0612
141	23.04	1.0334	2.0612
142	23.27	1.0336	2.0613
143	23.50	1.0334	2.0613
144	23.74	1.0337	2.0613
145	23.97	1.0336	2.0611
146	24.20	1.0336	2.0612
147	24.44	I.0335	2.0613
148	24.67	1.0335	2.0612
149	24.90	1.0335	2.0613
150	25.14	1.0336	2.0613
151	25.37	1.0335	2.0614
152	25.60	1.0335	2.0614
153	25.84	1.0333	2.0613

154	26.07	1.0336	2.0613
155	26.32	1.0336	2.0613
156	26.57	1.0336	2.0613
157	26.82	1.0337	2.0613
158	27.07	1.0335	2.0613
159	27.32	1.0333	2.0614
160	27.57	1.0334	2.0613
161	27.82	1.0334	2.0613
162	28.07	1.0334	2.0613
163	28.32	1.0331	2.0613
164	28.57	1.0335	2.0613
165	28.82	1.0335	2.0613
166	29.07	1.0335	2.0614
167	29.32	1.0332	2.0614
168	29.57	1.0333	2.0614
169	29.82	1.0334	2.0614
170	30.07	1.0333	2.0613
171	30.32	1.0332	2.0612
172	30.58	1.0332	2.0614
173	30.85	1.0334	2.0611
174	31.12	1.0332	2.0613
175	31.38	1.0333	2.0613
176	31.65	1.0331	2,0613
177	31.92	1.0329	2.0613
178	32.18	1.0332	2.0613
179	32.45	1.0331	2.0614
180	32.72	1.0329	2.0615
181	32.98	1.0330	2.0614
182	33.25	1.0332	2.0613
183	33.52	1.0330	2.0612
184	33.78	1.0330	2.0613

185	34.05	1.0328	2.0613
186	34.32	1.0329	2.0613
187	34.58	1.0329	2.0613
188	34.85	1.0331	2.0614
189	35.13	1.0332	2.0613
190	35.42	1.0331	2.0612
191	35.70	1.0332	2.0613
192	35.98	1.0333	2.0613
193	36.27	1.0333	2.0613
194	36.55	1.0335	2.0612
195	36.83	1.0332	2.0613
196	37.12	1.0333	2.0612
197	37.40	1.0334	2.0612
198	37.68	I.0333	2.0613
199	37.97	1.0332	2.0613
200	38.25	1.0333	2.0614
201	38.53	1.0334	2.0614
202	38.82	1.0332	2.0613
203	39.12	1.0333	2.0613
204	39.42	1.0332	2.0612
205	39.72	1.0333	2.0612
206	40.02	1.0334	2.0612
207	40.32	1.0335	2.0612
208	40.62	1.0333	2.0613
209	40.92	1.0334	2.0613
210	41.22	1.0335	2.0613
211	41.52	1.0336	2.0613
212	41.82	1.0334	2.0613
213	42.12	1.0336	2.0612
214	42.42	1.0336	2.0612
215	42.72	I.0338	2.0612

216	43.02	1.0338	2.0612
217	43.33	1.0337	2.0613
218	43.65	1.0338	2.0613
219	43.97	1.0339	2.0613
220	44.28	1.0338	2.0613
221	44.60	1.0340	2.0613
222	44.92	1.0341	2.0612
223	45.23	1.0338	2.0612
224	45.55	1.0338	2.0612
225	45.87	1.0341	2.0613
226	46.18	1.0339	2.0612
227	46.50	1.0338	2.0611
228	46.82	1.0341	2.0611
229	47.13	1.0339	2.0612
230	47.47	1.0342	2.0612
231	47.80	1.0342	2.0611
232	48.13	1.0338	2.0611
233	48.47	1.0339	2.0612
234	48.80	1.0340	2.0611
235	49.13	1.0344	2.0611
236	49.47	1.0342	2.0611
237	49.80	1.0341	2.0611
238	50.13	1.0343	2.0611
239	50.47	1.0343	2.0610
240	50.80	1.0344	2.0611
241	51.13	1.0345	2.0610
242	51.48	1.0345	2.0611
243	51.83	1.0344	2.0611
244	52.18	1.0344	2.0611
245	52.53	1.0347	2.0611
246	52.88	1.0349	2.0611

247	53.23	1.0347	2.0611
248	53.58	1.0347	2.0611
249	53.93	1.0347	2.0611
250	54.28	1.0349	2.0611
251	54.63	1.0348	2.0611
252	54.98	1.0349	2.0611
253	55.33	1.0349	2.0611
254	55.70	1.0352	2.0610
255	56.07	1.0349	2.0609
256	56.43	1.0348	2.0611
257	56.80	1.0349	2.0610
258	57.17	1.0350	2.0610
259	57.53	1.0348	2.0611
260	57.90	1.0349	2.0611
261	58.27	1.0351	2.0611
262	58.63	1.0349	2.0612
263	59.00	1.0353	2.0611
264	59.37	1.0355	2.0612
265	59.75	1.0354	2.0611
266	60.13	1.0356	2.0611
267	60.52	1.0352	2.0612
268	60.90	1.0352	2.0612
269	61.28	1.0351	2.0612
270	61.67	1.0352	2.0612
271	62.05	1.0354	2.0611
272	62.43	1.0353	2.0611
273	62.82	1.0352	2.0612
274	63.20	1.0352	2.0613
275	63.60	1.0355	2.0613
276	64.00	1.0354	2.0612
277	64.40	1.0353	2.0612

278	64.80	1.0352	2.0612
279	65.20	1.0353	2.0612
280	65.60	1.0353	2.0613
281	66.00	1.0351	2.0612
282	66.40	1.0353	2.0612
283	66.80	1.0357	2.0612
284	67.20	1.0352	2.0613
285	67.62	1.0354	2.0612
286	68.03	1.0356	2.0613
287	68.45	1.0352	2.0613
288	68.87	1.0345	2.0613
289	69.28	1.0347	2.0614
290	69.70	1.0358	2.0610
291	70.12	1.0355	2.0611
292	70.53	1.0359	2.0610
293	70.95	1.0347	2.0612
294	71.38	1.0359	2.0611
295	71.82	1.0362	2.0609
296	72.25	1.0356	2.0610
297	72.68	1.0371	2.0608
298	73.12	1.0364	2.0609
299	73.55	1.0364	2.0607
300	73.98	1.0360	2.0607
301	74.42	1.0348	2.0612
302	74.85	1.0387	2.0606
303	75.30	1.0352	2.0609
304	75.75	1.0347	2.0607
305	76.20	1.0360	2.0604
306	76.65	1.0357	2.0602
307	77.10	1.0350	2.0574
308	77.55	1.0347	2.0549

309	78.00	1.0352	2.0523
310	78.45	1.0356	2.0500
311	78.91	1.0335	2.0473
312	79.38	1.0357	2.0453
313	79.85	1.0335	2.0422
314	80.31	1.0356	2.0401
315	80.78	1.0370	2.0373
316	81.25	1.0367	2.0348
317	81.71	1.0371	2.0326
318	82.18	1.0344	2.0299
319	82.65	1.0348	2.0274
320	83.13	1.0361	2.0251
321	83.61	1.0347	2.0222
322	84.10	1.0356	2.0199
323	84.58	1.0351	2.0174
324	85.06	1.0359	2.0152
325	85.55	1.0354	2.0125
326	86.03	1.0347	2.0101
327	86.53	1.0350	2.0074
328	87.03	1.0345	2.0049
329	87.53	1.0348	2.0024
330	88.03	1.0355	2.0000
331	88.53	1.0348	1.9975
332	89.03	1.0359	1.9951
333	89.53	1.0352	1.9927
334	90.03	1.0353	1.9902
335	90.55	1.0352	1.9878
336	91.06	1.0355	1.9851
337	91.58	1.0352	1.9826
338	92.10	1.0348	1.9801
339	92.61	1.0350	1.9777

340	93.13	1.0351	1.9751
341	93.65	1.0348	1.9729
342	94.18	1.0348	1.9702
343	94.71	1.0352	1.9677
344	95.25	1.0351	1.9652
345	95.78	1.0347	1.9627
346	96.31	1.0349	1.9603
347	96.84	1.0351	1.9579
348	97.38	1.0350	1.9553
349	97.93	1.0359	1.9528
350	98.48	1.0353	1.9503
351	99.03	1.0350	1.9478
352	99.58	1.0353	1.9454
353	100.1	1.0351	1.9430
354	100.7	1.0342	1.9404
355	101.2	1.0347	1.9381
356	101.8	1.0350	1.9356
357	102.4	1.0350	1.9331
358	102.9	1.0354	1.9306
359	103.5	1.0343	1.9281
360	104.1	1.0352	1.9260
361	104.6	1.0350	1.9233
362	105.2	1.0340	1.9208
363	105.8	1.0348	1.9183
364	106.4	1.0348	1.9158
365	106.9	1.0345	1.9133
366	107.5	1.0353	1.9111
367	108.1	1.0349	1.9086
368	108.7	1.0349	1.9062
369	109.3	1.0345	1.9036
370	109.9	1.0348	1.9012

371	110.5	1.0349	1.8987
372	111.1	1.0339	1.8961
373	111.7	1.0348	1.8938
374	112.3	1.0345	1.8913
375	112.9	1.0344	1.8888
376	113.5	1.0345	1.8864
377	114.1	1.0348	1.8840
378	114.8	1.0346	1.8814
379	115.4	1.0354	1.8793
380	116.0	1.0357	1.8767
381	116.6	1.0346	1.8741
382	117.3	1.0344	1.8717
383	117.9	1.0345	1.8692
384	118.5	1.0348	1.8667
385	119.2	1.0343	1.8644
386	119.8	1.0339	1.8618
387	120.4	1.0336	1.8595
388	121.1	I.0338	1.8569
389	121.7	1.0344	1.8548
390	122.4	1.0345	1.8521
391	123.0	1.0345	1.8499
392	123.7	1.0343	1.8473
393	124.4	1.0339	1.8446
394	125.0	1.0352	1.8425
395	125.7	1.0352	1.8400
396	126.4	1.0349	1.8375
397	127.0	1.0344	1.8351
398	127.7	1.0342	1.8324
399	128.4	1.0347	1.8302
400	129.1	1.0361	1.8280
401	129.8	1.0351	1.8253

402	130.4	1.0352	1.8231
403	131.1	1.0356	1.8209
404	131.8	1.0351	1.8183
405	132.5	1.0357	1.8160
406	133.2	1.0351	1.8133
407	133.9	1.0344	1.8108
408	134.6	1.0347	1.8084
409	135.3	1.0342	1,8057
410	136.1	1.0347	1.8036
411	136.8	1.0350	1.8013
412	137.5	1.0356	1.7989
413	138.2	1.0337	1.7964
414	138.9	1.0336	1.7940
415	139.7	1.0341	1.7915
416	140.4	1.0347	1.7893
417	141.1	1.0346	1.7868
418	141.9	1.0349	1.7846
419	142.6	1.0358	1.7823
420	143.4	1.0362	1.7801
421	144.1	1.0345	1.7774
422	144.9	1.0347	1.7750
423	145.6	1.0365	1.7730
424	146.4	1.0345	1.7702
425	147.2	1.0347	1.7680
426	147.9	1.0340	1.7655
427	148.7	1.0347	1.7633
428	149.5	1.0336	1.7606
429	150.3	1.0357	1.7586
430	151.0	1.0340	1.7559
431	151.8	1.0356	1.7539
432	152.6	1.0344	1.7513

433	153.4	1.0328	1.7491
434	154.2	1.0346	1.7466
435	155.0	1.0334	1.7443
436	155.8	1.0357	1.7422
437	156.6	1.0344	1.7397
438	157.4	1.0349	1.7375
439	158.3	1.0347	1.7352
440	159.1	1.0343	1.7328
441	159.9	1.0350	1.7305
442	160.7	1.0339	1.7281
443	161.6	1.0336	1.7256
444	162.4	1.0344	1.7233
445	163.2	1.0346	1.7210
446	164.1	1.0334	1.7186
447	164.9	1.0347	1.7165
448	165.8	1.0341	1.7142
449	166.6	1.0345	1.7119
450	167.5	1.0365	1.7098
451	168.4	1.0337	1.7073
452	169.2	1.0334	1.7049
453	170.1	1.0341	1.7029
454	171.0	1,0335	1.7003
455	171.8	1.0365	1.6983
456	172.7	1.0339	1.6959
457	173.6	1.0357	1.6937
458	174.5	1.0358	1.6917
459	175.4	1.0348	1.6890
460	176.3	1.0351	1.6869
461	177.2	1.0353	1.6846
462	178.1	1.0343	1.6825
463	179.0	1.0341	1.6799

464	179.9	1.0328	1.6776
465	180.8	I.0364	1.6759
466	181.8	1.0336	1.6731
467	182.7	1.0345	1.6710
468	183.6	1.0338	1.6686
469	184.6	1.0361	1.6668
470	185.5	1.0337	1.6645
471	186.5	I.0344	1.6622
472	187.4	1.0356	1.6599
473	188.4	1.0342	1.6576
474	189.3	1.0337	1.6553
475	190.3	1.0345	1.6534
476	191.3	1.0361	1.6513
477	192.2	1.0355	1.6488
478	193.2	1.0335	1.6466
479	194.2	1.0346	1.6443
480	195.2	1.0339	1.6423
481	196.2	1.0346	1.6399
482	197.2	1.0327	1.6373
483	198.2	1.0352	1.6353
484	199.2	1.0329	1.6328
485	200.2	1.0359	1.6312
486	201.2	1.0351	1.6290
487	202.2	1.0338	1.6262
488	203.3	1.0345	1.6245
489	204.3	1.0349	1.6220
490	205.3	1.0340	1.6201
491	206.4	1.0350	1.6179
492	207.4	1.0351	1.6154
493	208.5	1.0344	1.6135
494	209.5	1.0360	1.6113

495	210.6	1.0333	1.6089
496	211.6	1.0343	1.6068
497	212.7	1.0360	1.6045
498	213.8	1.0349	1.6024
499	214.9	1.0344	1.6000
500	216.0	1.0338	1.5981
501	217.0	1.0346	1.5957
502	218.1	1.0341	1.5934
503	219.2	1.0350	1.5913
504	220.3	1.0341	1.5893
505	221.5	1.0328	1.5870
506	222.6	1.0342	1.5850
507	223.7	1.0352	1.5830
508	224.8	1.0352	1.5804
509	226.0	1.0354	1.5786
510	227.1	1.0346	1.5762
511	228.2	1.0335	1.5738
512	229.4	1.0334	1.5719
513	230.5	1.0365	1.5694
514	231.7	1.0354	1.5676
515	232.9	1.0358	1.5653
516	234.0	1.0353	1.5631
517	235.2	1.0352	1.5610
518	236.4	1.0332	1.5592
519	237.6	1.0335	1.5566
520	238.8	1.0354	1.5545
521	240.0	1.0340	1.5526
522	241.2	1.0366	1.5503
523	242.4	1.0374	1.5478
524	243.6	1.0348	1.5459
525	244.8	1.0335	1.5437

526	246.1	1.0331	1.5423
527	247.3	1.0359	1.5392
528	248.5	1.0324	1.5373
529	249.8	1.0327	1.5354
530	251.0	1.0342	1.5331
531	252.3	1.0361	1.5306
532	253.6	1.0344	1.5288
533	254.8	1.0338	1.5266
534	256.1	1.0346	1.5245
535	257.4	1.0340	1.5224
536	258.7	1.0352	1.5199
537	260.0	1.0330	1.5181
538	261.3	1.0353	1.5154
539	262.6	1.0347	1.5139
540	263.9	1.0338	1.5117
541	265.2	1.0343	1.5093
542	266.5	1.0345	1.5073
543	267.9	1.0332	1.5054
544	269.2	1.0350	1.5032
545	270.5	1.0356	1.5011
546	271.9	1.0346	1.4989
547	273.2	1.0329	1.4973
548	274.6	1.0372	1.4943
549	276.0	1.0358	1.4923
550	277.4	1.0367	1.4903
551	278.7	1.0366	1.4881
552	280.1	1.0354	1.4861
553	281.5	1.0361	1.4840
554	282.9	1.0363	1.4817
555	284.3	1.0364	1.4801
556	285.8	1.0368	1.4777

557	287.2	1.0354	1.4758
558	288.6	1.0333	1.4742
559	290.0	1.0362	1.4716
560	291.5	1.0367	1.4695
561	292.9	1.0339	1.4678
562	294.4	1.0377	1.4652
563	295.9	1.0361	I.4635
564	297.3	1.0334	1.4616
565	298.8	1.0350	1.4593
566	300.3	1.0361	1.4570
567	301.8	1.0345	1.4554
568	303.3	1.0347	1.4529
569	304.8	1.0347	1.4513
570	306.3	1.0349	1.4492
571	307.8	1.0345	1.4473
572	309.4	1.0357	1.4453
573	310.9	1.0363	1.4428
574	312.4	1.0359	1.4410
575	314.0	1.0358	1.4389
576	315.6	1.0369	1.4367
577	317.1	1.0349	1.4353
578	318.7	1.0331	1.4335
579	320.3	1.0352	1.4313
580	321.9	1.0345	1.4294
581	323.5	1.0347	1.4272
582	325.1	1.0364	1.4249
583	326.7	1.0345	1.4234
584	328.3	1.0339	1.4213
585	329.9	1.0338	1.4195
586	331.6	1.0350	1.4176
587	333.2	1.0368	1.4153

588	334.9	1.0353	1.4135
589	336.5	1.0366	1.4114
590	338.2	1.0350	1.4097
591	339.9	1.0360	1.4077
592	341.6	1.0362	1.4057
593	343.3	1.0359	1.4038
594	345.0	1.0350	1.4020
595	346.7	1.0346	1.4004
596	348.4	1.0359	1.3982
597	350.1	1.0368	1.3963
598	351.8	1.0360	1.3944
599	353.6	1.0354	1.3927
600	355.3	1.0360	1.3906
601	357.1	1.0358	1.3888
602	358.8	1.0364	1.3871
603	360.6	1.0351	1.3853
604	362.4	1.0357	1.3832
605	364.2	1.0353	1.3816
606	366.0	1.0357	1.3797
607	367.8	1.0349	1.3781
608	369.6	1.0346	1.3764
609	371.4	1.0354	1.3745
610	373.3	1.0339	1.3729
611	375.1	1.0350	1.3711
612	377.0	1,0349	1.3693
613	378.8	1.0353	1.3675
614	380.7	1.0350	1.3658
615	382.6	1.0356	1.3641
616	384.5	1.0349	1.3624
617	386.4	1.0355	1.3607
618	388.3	1.0338	1.3590

619	390.2	1.0347	1.3572
620	392.1	1.0348	1.3555
621	394.1	1.0345	1.3542
622	396.0	1.0345	1.3523
623	398.0	1.0350	1.3505
624	399.9	1.0351	1.3489
625	401.9	1.0347	1.3474
626	403.9	1.0344	1.3456
627	405.9	1.0349	1.3439
628	407.9	1.0340	1.3423
629	409.9	1.0337	1.3406
630	411.9	1.0338	1.3389
631	413.9	1.0338	1.3373
632	416.0	1.0334	1.3356
633	418.0	1.0342	1.3340
634	420.1	1.0340	1.3325
635	422.2	1.0340	1.3306
636	424.3	1.0339	1.3291
637	426.4	1.0336	1.3274
638	428.5	1.0341	1.3256
639	430.6	1.0338	1.3241
640	432.7	1.0335	1.3225
641	434.8	1.0343	1.3206
642	437.0	1.0340	1.3190
643	439.1	1.0343	1.3174
644	441.3	1.0342	1.3157
645	443.5	1.0339	1.3139
646	445.6	1.0343	1.3122
647	447.8	1.0339	1.3105
648	450.0	1.0342	1.3089
649	452.3	1.0338	1.3073

650	454.5	1.0343	1.3055
651	456.7	1.0338	1.3040
652	459.0	1.0332,	1.3023
653	461.2	1.0342	1.3004
654	463.5	1.0340	1.2988
655	465.8	1.0339	1.2970
656	468.1	1.0341	1.2952
657	470.4	1.0340	▋2935
658	472.7	1.0341	1.2918
659	475.0	1.0346	1.2901
660	477.4	1.0343	1.2885
661	479.7	1.0343	1.2867
662	482.1	1.0343	1.2850
663	484.5	1.0344	1.2832
664	486.8	1.0340	1.2815
665	489.2	1.0344	1.2797
666	491.7	1.0338	1.2779
667	494.1	1.0339	1.2762
668	496.5	1.0345	1.2744
669	499.0	1.0337	1.2729
670	501.4	1.0336	1.2709
671	503.9	1.0340	1.2691
672	506.4	1.0342	1.2677
673	508.9	1.0351	1.2657
674	511.4	1.0344	1.2640
675	513.9	1.0348	1.2623
676	516.4	1.0347	1.2606
677	518.9	1.0348	1.2586
678	521.5	1.0325	1.2570
679	524.1	1.0330	1.2552
680	526.6	1.0331	1.2535

681	529.2	1.0326	1.2517
682	531.8	I.0323	1.2499
683	534.4	1.0322	1.2485
684	537.1	1.0329	1.2467
685	539.7	1.0326	1.2450
686	542.4	1.0324	1.2434
687	545.0	1.0323	1.2416
688	547.7	1.0321	1.2398
689	550.4	1.0328	1.2380
690	553.1	1.0326	1.2365
691	555.8	1.0326	1.2349
692	558.6	1.0327	1.2332
693	561.3	1.0323	I.2315
694	564.1	1.0322	1.2300
695	566.9	1.0319	1.2284
696	569.6	1.0315	1.2265
697	572.4	1.0319	1.2250
698	575.3	1.0317	1.2234
699	578.1	1.0319	1.2216
700	580.9	I.0318	1.2202
701	583.8	1.0317	1.2187
702	586.7	1.0324	1.2169
703	589.5	1.0317	1.2152
704	592.4	1.0323	1.2135
705	595.4	1.0316	1.2122
706	598.3	1.0316	1.2105
707	601.2	1.0316	1.2088
708	604.2	1.0317	1.2074
709	607.2	1.0314	I.2059
710	610.1	1.0316	1.2043
711	613.1	1.0311	1.2029

712	616.2	1.0303	1.2019
713	619.2	1.0304	1.2004
714	622.2	1.0302	1.1989
715	625.3	1.0307	1.1975
716	628.4	1.0305	1.1960
717	631.5	1.0306	1.1946
718	634.6	1.0303	1.1930
719	637.7	1.0301	1.1916
720	640.8	1.0298	1.1904
721	644.0	1.0302	1.1889
722	647.1	1.0301	1.1877
723	650.3	1.0302	1.1862
724	653.5	1.0307	1.1848
725	656.7	1.0311	1.1834
726	660.0	1.0306	1.1821
727	663.2	1.0302	1.1807
728	666.5	1.0310	1.1794
729	669.8	1.0306	1.1780
730	673.1	1.0309	1.1770
731	676.4	1.0309	1.1756
732	679.7	1.0310	1.1744
733	683.0	1.0307	1.1730
734	686.4	1.0311	1.1717
735	689.8	1.0305	1.1707
736	693.1	1.0310	1.1695
737	696.5	1.0308	1.1683
738	700.0	1.0307	1.1673
739	703.4	1.0299	1.1661
740	706.8	1.0295	1.1648
741	710.3	1.0298	1.1635
742	713.8	1.0301	1.1626

743	717.3	1.0298	1.1615
744	720.9	1.0301	1.1604
745	724.4	1.0296	1.1596
746	728.0	1.0297	1.1584
747	731.6	1.0301	I.1573
748	735.2	1.0301	I.1563
749	738.8	1.0298	1.1553
750	742.4	1.0291	1.1542
751	746.1	1.0295	1.1532
752	749.7	1.0299	1.1522
753	753.4	1.0296	1.1509
754	757.1	1.0292	1.1501
755	760.8	1.0296	1.1491
756	764.6	1.0295	1.1482
757	768.3	1.0294	1.1472
758	772.1	1.0297	1.1464
759	775.9	1.0293	1.1455
760	779.7	1.0296	1.1446
761	783.6	1.0302	I.1438
762	787.4	1.0300	1.1429
763	791.3	1.0297	I.1419
764	795.2	1.0298	I.1410
765	799.1	1.0296	1.1403
766	803.0	1.0295	1.1395
767	807.0	1.0298	1.1385
768	810.9	1.0298	1.1378
769	814.9	1.0293	1.1370
770	818.9	I.0300	1.1362
771	822.9	1.0294	1.1356
772	827.0	1.0300	1.1348
773	831.1	1.0291	1.1340

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774	835.1	1.0300	1.1331
775	839.2	1.0296	1.1324
776	843.4	1.0292	1.1320
777	847.5	1.0292	1.1311
778	851.7	1.0290	1.1304
779	855.9	1.0296	1.1296
780	860.1	1.0300	1.1291
781	864.3	1.0297	1.1284
782	868.6	1.0293	1.1276
783	872.8	1.0286	1.1271
784	877.1	1.0293	1.1265
785	881.5	1.0284	1.1257
786	885.8	1.0298	1.1251
787	890.1	1.0293	1.1244
788	894.5	1.0294	1.1240
789	898.9	1.0299	1.1234
790	903.3	1.0296	1.1228
791	907.8	1.0297	1.1223
792	912.3	1.0301	1.1216
793	916.7	1.0292	1.1211
794	921.3	1.0291	1.1205
795	925.8	1.0297	1.1198
796	930.3	1.0297	1.1195
797	934.9	1.0297	1.1190
798	939.5	1.0295	1.1184
799	944.1	1.0294	1.1178
800	948.8	1.0290	1.1175
801	953.5	1,0290	1.1171
802	958.1	1.0292	1.1165
803	962.9	1.0292	1.1162
804	967.6	1.0292	1.1156

805	972.4	1.0295	1.1152
806	977.1	1.0295	1.1148
807	981.9	1.0296	1.1144
808	986.8	1.0294	1.1140
809	991.6	1.0294	1.1136
810	996.5	1.0300	1.1131
811	1001.	1.0297	1.1127
812	1006.	1.0304	1.1123
813	1011.	1.0302	1.1118
814	1016.	1.0291.	1.1116
815	1021.	1.0298	1.1111
816	1026.	1.0299	1.1107
817	1031.	1.0298	1.1104
818	1036.	1.0293	1.1099
819	1042.	1.0296	1.1095
820	1047.	1.0300	1.1090
821	1052.	1.0290	1.1087
822	1057.	1.0297	1.1083
823	1062.	1.0292	1.1080
824	1067.	1.0291	1.1075
825	1073.	1.0291	1.1073
826	1078.	1.0288	1.1067
827	1083.	1.0294	1.1063
828	1089.	1.0292	1.1061
829	1094.	1.0290	1.1057
830	1099.	1.0291	1.1053
831	1105.	1.0288	1.1052
832	1110.	1.0289	1.1049
833	1116.	1.0289	1.1045
834	1121.	1.0290	1.1042
835	1127.	1.0291	1.1039

836	1132.	1.0296	1.1035
837	1138.	1.0292	1.1031
838	1143.	1.0290	1.1030
839	1149.	1.0286	1.1026
840	1155.	1.0292	1.1024
841	1160.	1.0291	1.1021
842	1166.	1.0295	1.1020
843	1172.	1.0294	1.1017
844	1178.	1.0288	1.1014
845	1183.	1.0290	1.1013
846	1189.	1.0290	1.1012
847	1195.	1.0284	1.1010
848	1201.	1.0284	1.1008
849	1207.	1.0284	1.1007
850	1213.	1.0283	1.1007
851	1219.	1.0283	1.1003
852	1225.	1.0281	1.1003
853	1231.	1.0278	1.1001
854	1237.	1.0282	1.0998
855	1243.	1.0287	1.0998
856	1249.	1.0280	1.0994
857	1255.	1.0284	1.0994
858	1261.	1.0278	1.0991
859	1268.	1.0280	1.0989
860	1274.	1.0286	1.0986
861	1280.	1.0280	1.0983
862	1286.	1.0278	1.0982
863	1293.	1.0280	1.0981
864	1299.	1.0287	1.0979
865	1305.	1.0284	1.0979
866	1312.	1.0283	1.0977

867	1318.	1.0277	1.0975
868	1325.	1.0286	1.0972
869	1331.	1.0276	1.0969
870	1338.	1.0281	1.0971
871	1345.	1.0298	1.0969
872	1351.	1.0278	1.0971
873	1358.	1.0275	1.0971
874	1365.	1.0287	1.0971
875	1371.	1.0268	1.0969
876	1378.	1.0274	1.0966
877	1385.	1.0269	1.0965
878	1392.	1.0293	1.0966
879	1398.	1.0287	1.0966
880	1405.	1.0275	1.0964
881	1412.	1.0284	1.0966
882	1419.	1.0282	1.0964
883	1426.	1.0282	1.0964
884	1433.	1.027'6	1.0958
885	1440.	1.0293	1.0965
886	1447.	1.0283	1.0958
887	1455.	1.0294	1.0957
888	1462.	1.0278	1.0963
889	1469.	1.0275	1.0960
890	1476.	1.0262	1.0963
891	1483.	1.0281	1.0958
892	1491.	1.0250	1.0961
893	1498.	1.0273	1.0954
894	1506.	1.0273	1.0950
895	1513.	1.0262	1.0957
896	1520.	1.0262	1.0949
897	1528.	1.0261	1.0953

898	1535.	1.0270	1.0952
899	1543.	1.0280	1.0949
900	1551.	1.0268	1.0950
901	1558.	1.0268	1.0949
902	1566.	1.0277	1.0945
903	1574.	1.0269	1.0949
904	1581.	1.0272	1.0946
905	1589.	▮0260	1.0945
906	1597.	1.0270	1.0944
907	1605.	1.0262	1.0942
908	1613.	1.0278	▮0944
909	1621.	1.0272	1.0943
910	1629.	1.0286	1.0936
911	1637.	1.0256	1.0941
912	1645.	1.0285	1.0937
913	1653.	1.0254	1.0945
914	1661.	1.0253	1.0940
915	1669.	1.0266	1.0928
916	1678.	1.0249	1.0938
917	1686.	1.0283	1.0927
918	1694.	1.0218	1.0941
919	1703.	1.0298	1.0931
920	1711.	1.0216	1.0944
921	1719.	1.0243	1.0938
922	1728.	1.0243	1.0939
923	1736.	1.0235	1.0935
924	1745.	1.0278	1.0930
925	1754.	1.0252	1.0932
926	1762.	1.0252	1.0934
927	1771.	1.0261	1.0930
928	1780.	▮0258	1.0935

929	1788.	1.0271	1.0930
930	1797.	1.0274	1.0927
931	1806.	1.0251	1.0930
932	1815.	1.0261	1.0927
933	1824.	1.0263	1.0925
934	1833.	1.0256	1.0926
935	1842.	1.0242	1.0929
936	1851.	1.0271	1.0925
937	1860.	1.0248	1.0924
938	1870.	1.0267	1.0927
939	1879.	1.0264	1.0921
940	1888.	1.0269	1.0925
941	1897.	1.0265	1.0922
942	1907.	1.0264	1.0924
943	1916.	1.0257	1.0928
944	1926.	1.0273	1.0923
945	1935.	1.0267	1.0924
946	1945.	1.0253	1.0924