BENCH-SCALE EXPERIMENTS IN THE STANFORD GEOTHERMAL PROJECT

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The Stanford Geothermal Project bench-scale experiments are designed to improve the understanding of geothermal reservoir physics. Three sets of experiments are discussed in the following sections: (1) vapor pressure lowering in porous media due to capillarity and adsorption, (2) the effect of temperature on absolute permeability, and (3) the determination of steam-water relative permeability for drainage processes.

Vapor Pressure Lowering

Vapor pressure lowering in porous media may be important to both reserve evaluation and geothermal reservoir performance prediction. Vapor pressure lowering is a lowering of the vapor pressure curve. As shown schematically in Fig. 1, it occurs at low water saturations. The lowering may be caused by (1) capillarity, i.e., curved liquid-vapor interfaces in porous media and/or by (2) surface adsorption of fluid molecules at the solid-fluid interface. It is believed that capillary effects occur at low water saturations, but that vapor pressure lowering is minor until saturations are so low that adsorption phenomena dominate (Hsieh et al., 1978).

The importance of vapor pressure lowering is further demonstrated by the following hypothetical situation. If the temperature and pressure of a geothermal reservoir are determined to be that of point A in Fig. 1, a reservoir engineer may use the flat surface vapor pressure curve and assume the reservoir is 100% dry steam and contains no liquid water. In actual practice, further lowering of reservoir pressure may allow capillary or adsorbed water to vaporize. Thus, both the reserves and the rate of production are increased beyond that predicted with the assumption of no vapor pressure lowering (and no liquid water saturation).

The following calculation demonstrates the possible importance of surface adsorption. A reservoir rock of 1 m^2/gm surface area, 25% porosity, and 10.6 $Å^2$ surface area per H_2O molecule will have 7.9.5 m^2 surface area per cc pore volume and 2.24×10^{-3} gm H_2O per cc pore volume.

At the arbitrary condition of 200°C and 15 bars, saturated steam density (should use superheated) is .00786 gm H_2O/cc. Using the above unconfirmed assumptions, one layer of adsorbed H_2O will increase reservoir water content by 29%. Ten layers of adsorbed H_2O will further increase reservoir water content. One unanswered question remains: "How much of the adsorbed H_2O can be produced?"

The experimental apparatus required for this study is now assembled. Vapor pressure lowering will be determined as a function of pressure, temperature, and amount of H_2O, using the apparatus shown in Fig. 2. However, it is expected that at each temperature level studied, results will demonstrate multilayer adsorption "plateaus" as shown in Fig. 3. To better understand the adsorption phenomena and to try to estimate the number of adsorption layers, the BET cell shown in Fig. 4 has already been used to determine nitrogen surface areas of consolidated sandstones (Berea) and unconsolidated sand packs. These studies may be extended to include natural gas adsorption phenomena as they occur in natural gas reservoirs.

Effect of Temperature on Absolute Permeability

Experimental results of Weinbrandt (1972), Cassé (1974), Aruna (1976), and others suggest the absolute permeability of sandstones and unconsolidated sands to water is reduced up to 65% at elevated temperatures and confining pressures. Permeability reductions with increased temperature were not observed for: nitrogen, oil, or octonol. In addition, permeability reduction was not: observed for water flowing through limestone. Recently, Dr. A. Danesh, visiting professor from Abadan Institute of Technology, Iran, performed additional experiments flowing water and oil through unconsolidated sand and unconsolidated stainless steel. His results were similar to those of Cassé and hruna, but similar reductions in permeability also occurred for unconsolidated stainless steel (Danesh et al., 1978).

Subsequent experiments were recently completed using water and either unconsolidated sand or limestone ground and sieved to a similar mesh size. These experiments did not reproduce the temperature level effects. The reason the results were different may be due to a different experimental procedure. In particular, water was pumped through the care during the entire experiment. In the earlier experiments, water may not have flowed through the core during heating and cooling between measurements at different temperatures. The solid-liquid boundary layer, intermolecular force mechanism, as suggested by Danesh to explain the permeability reductions, may indicate that such procedural differences are important. Future experiments will attempt to verify Danesh's conclusions.

Stean-Water Relative Permeability

Steam and liquid relative permeabilities, expressed as a function of liquid saturation, are required in the numerical models used to calculate mass and energy recovery from two-phase geothermal reservoirs. Currently, modified Corey-type equations are used because adequate techniques for determining proper steam-water relative permeabilities are still under development. Relative permeabilities are often expressed as equations for convenience.

Sufficient data can be obtained from steady, two-phase, non-isothermal flow experiments to allow the construction of steam-water relative permeability curves for a drainage process. Water saturation can be measured with a capacitance probe (Chen et al., 1978). A preliminary relative permeability curve is shown in Fig. 5. The data has not been corrected for temperature or Klinkenberg slip effects, and the core has not yet been analyzed for nonhomogeneity caused by possible hydrothermal alteration.

In addition, isothermal nitrogen-displacing-water experiments were performed to provide gas-water drainage relative permeabilities at a variety of temperatures. These gas-water relative permeabilities provide an interesting comparison to the steam-water relative permeabilities. One example is shown in Fig. 6. Data analysis is not yet complete, and differences between the two curves have not yet been explained. Stewart et al. (1953) has stated that gas-expansion and gas drive drainage relative permeabilities are identical for hydrocarbons in homogeneous sandstone cores. For this reason, the steam-water and the nitrogen-water experiments are expected to yield similar, and possibly identical, results. Future effort will focus on refining the quality of data obtained from these two types of experiments.

References

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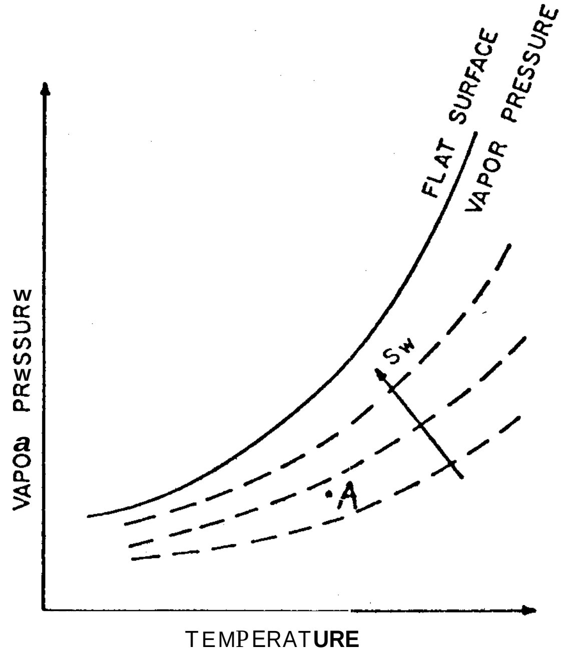

FIGURE 1. HYPOTHETICAL VAPOR PRESSURE CURVE DEPENDENCE ON WATER SATURATION (S_w)

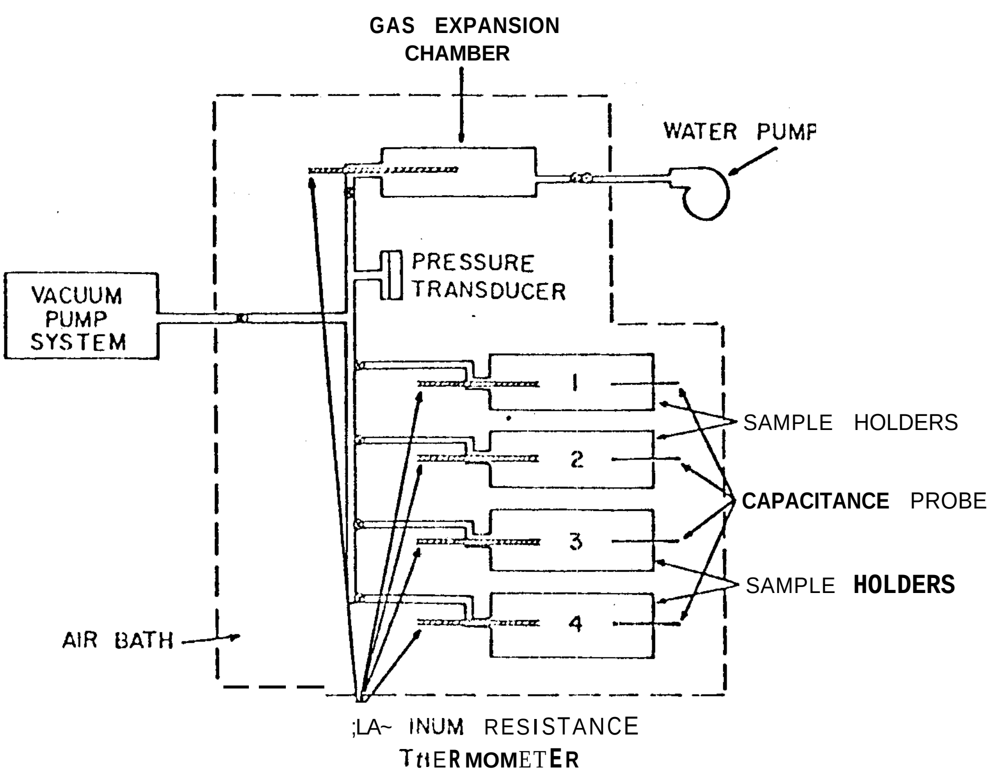

FIGURE 2. APPARATUS USED TO DETERMINE WATER ADSORPTION AND VAPOR PRESSURE LOWERING

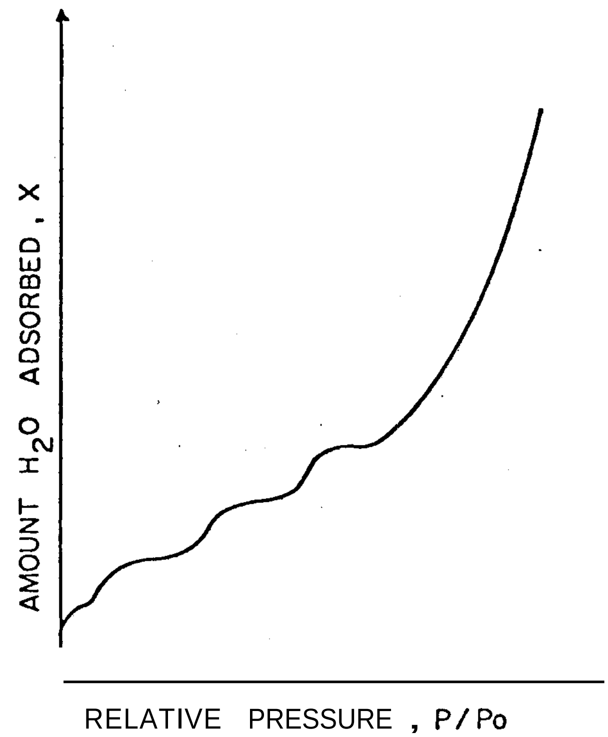

FIGURE 3. SCHEMATIC FIGURE SHOKING AN ADSORPTION ISOTHERM FOR $H_2O - S_iO_2$

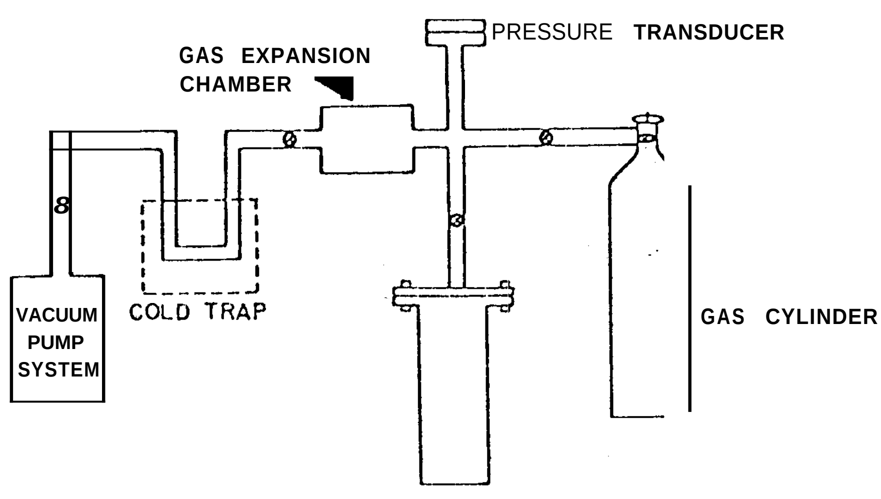

FIGURE 4. BET CELL USED TO DETERMINE ROCK SURFACE AREA

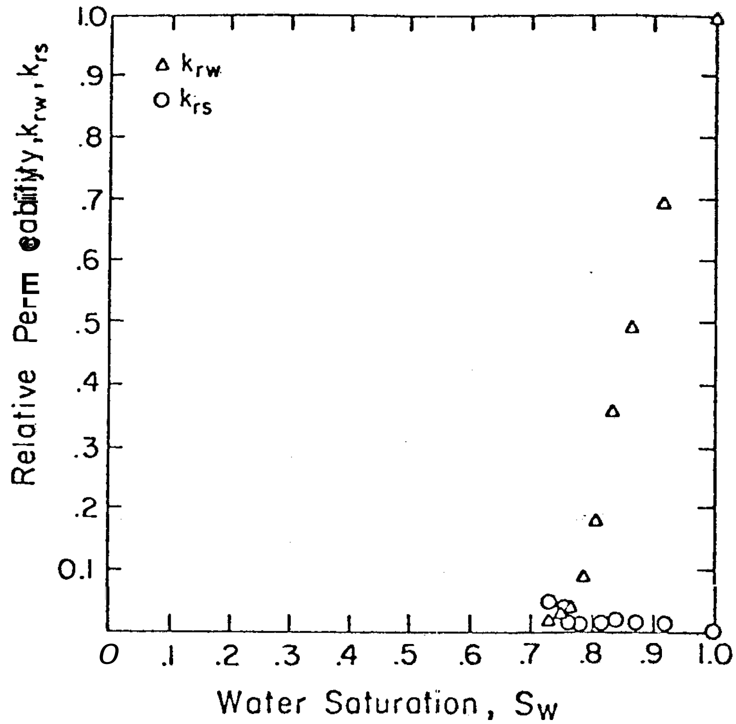

FIGURE 5. STEAM-WATER RELATIVE PERMEABILITY DETERMINED FROM NONISOTHERMAL, BOILING FLOH EXPERIMENT (330-280°F)

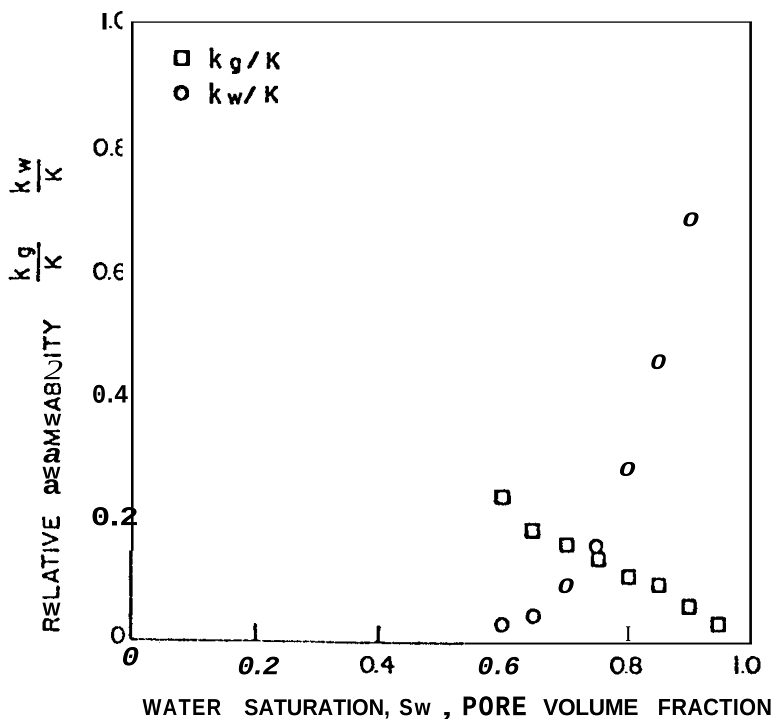

FIGURE 6. KITROGEN-WATER RELATIVE PERMEABILITY DETERMINED FROM ISOTHERMAL GAS-DRIVE EXPERIMENT (300°F)