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ADSORPTION IN VAPOR-DOMINATED SYSTEMS

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ABSTRACT

Vapor-dominated geothermal systems have been produced for almost 90 years. But the storage mechanism is still in doubt. The fluid must be stored as a liquid, yet the pressure at reservoir temperature is well into the superheated steam region for flat-surface thermodynamics. One popular mechanism is that the liquid phase is a brine. Another possibility is that the liquid phase is adsorbed. A study of the Big Geysers shallow steam production indicates that adsorption is a reasonable mechanism.

INTRODUCTION

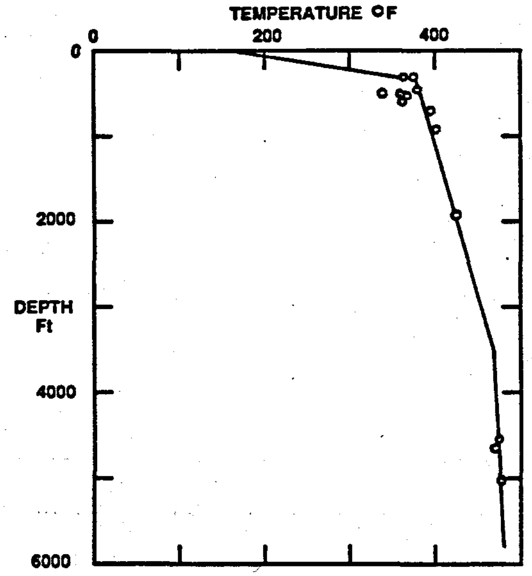
The existence of humankind is tied to the fruits of the earth. Some have been beneficial and others sometimes catastrophic. Eruption of volcanoes is an example. The earliest writings record events tied to hot fluids issuing from the earth. Thus geothermal systems have been studied for centuries. One of the oldest books on mining, de re Metallica, Agricola (1565), cites study of juices which issue boiling from the earth. There are references to biblical events involving hot earth fluids. Thus scientists have studied geothermal systems from recorded history. Geothermal fluids were used for space heating and cooking before recorded history without doubt.

Early geothermal theory was that geothermal fluids were magmatic. But geochemical studies proved that geothermal fluids were mainly meteoric. Surface water migrated to depths in the earth and were heated. Hot fluid then rose toward the surface because of low density. Thus geothermal systems were believed to be active hydrothermal systems subject to recharge. If a geothermal system were produced at the natural recharge rate, the system would produce at steady state and would last forever.

The first geothermal reservoir model, Whiting and Ramey(1969), coupled heat and mass balances and permitted recharge fluid to enter from a variety of aquifer geometries. This -model was applied to Wairakei, New Zealand data yielding the surprising result that recharge was not significant. We thought at the time this resulted because the model had measured the reservoir and aquifer together.

Shortly afterwards, another reservoir study was made of the original producing area of the Geysers: The Big Geysers, Ramey(1968). This steamfield was drilled in the 1920's, and a few wells were allowed to blow to the atmosphere until the Thermal Power Company began the modern development of the Geysers in the late 1950's. A piece of a casing from one of the original wells was displayed in the Thermal Power Company offices in San Francisco. It appeared like new casing and the Thermal Power Company personnel cited this as proof of the non-corrosive nature of the steam. In 1967, a thorough effort was made to determine the initial state of this reservoir and to collect data and perform a reservoir engineering analysis. The reason was preparation of material for a tax trial to be held in 1968, Ramey (1968).

Although more than 20 wells had been drilled in the Big Geysers and the adjacent Sulphur Bank-Happy Jack area of the Geysers Steam Field, Wells were mainly idle and venting to the atmosphere. However a group of wells producing from shallow depths had supplied Units 1 and 2 (25 MWe total) since 1957. Data collected from this group of wells is given in Table 1. Temperature-depth data is shown in Fig. 1. The cluster of points between depths of 500 to 1000 ft represent wells producing the shallow steam zone. Data on steam pressure-temperature from the shallow zone indicated that the steam ranged from saturated to superheated. See Fig. 2.



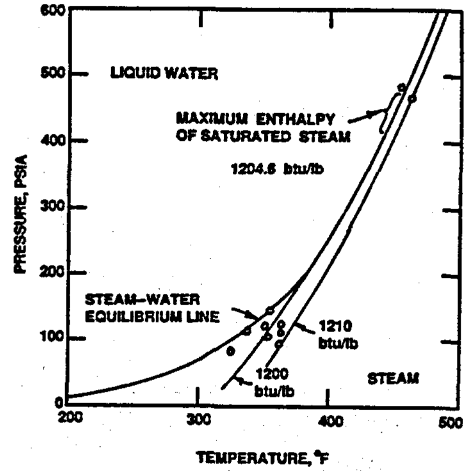


Fig.1 Temp. vs. Depth-Wells in Big Geysers Area(Ramey, 1968)

Fig.2 Pres. vs. Temp. for Big Geysers Area Well Tests Oct. 1967-Jan. 1968 (Ramey, 1968)

An attempt was made to model the data in Table 1 using the Whiting-Ramey (1969) model. This attempt failed because the pressure decline per unit mass produced exceeded that permitted by the model. In view of the high enthalpy shown on Fig. 2, the data in Table 1 was modelled by the well-known dry gas p/z vs mass produced method. Figure 3 displays the result. This information was presented to the tax court and eventually aided extablishing the tax depletion allowance for geothermal steam production.

In the months following the 1968 trial, it became apparent that the mass of steam indicated by Fig. 3, 240 billion pounds at a p/z of zero, was too great for the steam to be stored as vapor. At 400F, the density of steam is 0.5367 lb/cu ft and the density of hot water is 53.65 lb/cu ft--100 times greater than that of vapor. The paradox was that steam was stored as liquid--but liquid could not exist at the reservoir temperature and pressure, and no liquid had ever been produced. This is a simplification. Either salt in solution or a curved liquid-vapor interface may reduce the vapor pressure of water.

Two theories were proposed at that time: (1) liquid water might exist as perched liquid, or as a deep boiling interface, and (2) liquid might exist as adsorbed liquid in micropores, White(1973).

VAPOR PRESSURE LOWERING

The Whiting-Ramey study of Wairakei, New Zealand was performed in 1964-66. Results indicated that the initial state had been compressed liquid and that boiling in the reservoir would start in 1966. Future performance forecast depended on unknown factors: would liquid and vapor segregate by gravity, and would vapor pressure be less in the reservoir than for flat surfaces above ground?

These questions were studied by Cady in a doctoral dissertation at Stanford, Cady (1969). He used unconsolidated sand to experimentally study performance of geothermal systems. He found that an isothermal single-phase steam zone could exist within a few inches of a two-phase zone undergoing pressure and temperature drop. He also found no vapor pressure lowering with unconsolidated sand. Bilhartz (1971) extended this study, but found similar results for unconsolidated sand. Strobel (1973) studied an artificially-consolidated porous medium (cement and sand) and did find measurable vapor pressure lowering, but of a

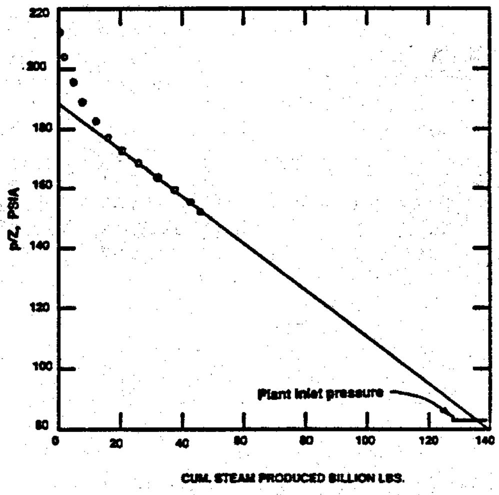


Fig.3 P/Z vs. Cum. Steam Prod. Big Geysers Area Shallow Zone (Ramey, 1968)

magnitude less than would be expected from the work of Calhoun, et al.(1949).

Calhoun et al. and the other previously mentioned studies considered vapor pressure lowering to result from curved liquid interfaces. But Hsieh (1980) observed that the Calhoun et al data could be explained better by adsorption than by curved surface vapor pressure. Hsieh (1980, 1983) found small adsorption with unconsolidated sand, but large adsorption with consolidated sands. He attributed the difference to adsorption in micropores and observed that the mass adsorbed as liquid could be ten times greater than the mass of vapor for even high porosity sandstones.

Herkelrath et al.(1982, 1983) also studied adsorption of steam. They found that steam transmitted pressure pulses more slowly than uncondensible gases in a porous medium. They measured steam adsorption in a soil and found results consistent with transient flow experiments. The Hsieh and Herkelrath et al. adsorption results are given in Figs.4 and 5. The adsorption shown on Fig. 4 is about 0.001 lb/lb rock, and on Fig. 5 about 0.01 lb/lb rock.

Economides (1983, 1985) studied the effect of adsorption on vapor-dominated geothermal systems. He used results of the Hsieh and Herkelrath et al. adsorption measurements and made the reasonable assumption that the mass adsorbed was essentially a linear function of pressure to the flat surface vapor pressure (see Figs. 4 and 5). This led him to conclude that pressure, not p/z, should be a linear function of the mass produced for field data. He regraphed the data from Table 1 and presented Fig. 6. The results for either p or p/z vs mass produced are similar. The match in Fig. 6 appears better than it actually is because the first two pressure points in Table 1 are not shown. Figure 7 presents the Table 1 results completely. Neither model matches the early drop in pressure.

DISCUSSION AND CONCLUSIONS

Consider that a vapor-dominated steam reservoir contains vapor and must contain liquid by virtue of convection and condensation as heat is transfer-

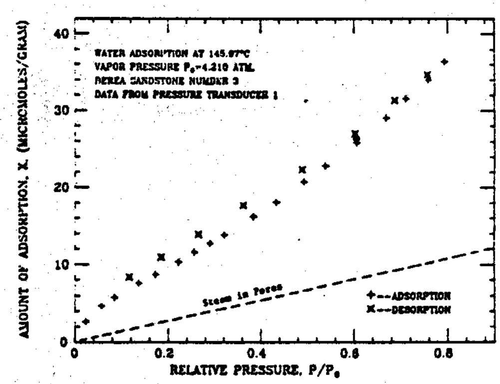


Fig.4 Water adsorption isotherm at 145.97C (Hsieh, 1980)

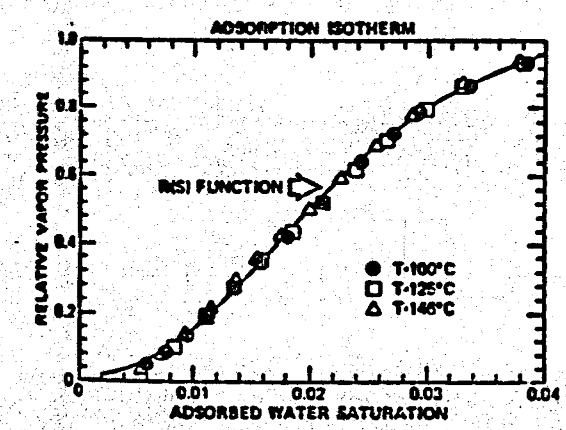


Fig.5 Adsorption Isotherm for water and silty sand (Herkelrath, et al., 1982,1983)

red to the overburden, Truesdell and White (1973), White (1973). Then:

lbs vapor + lbs liquid =

$$V\phi(1-S_w)\rho_v + V\phi S_w \rho_l$$

where V is the reservoir bulk volume, cu ft, ϕ is the fractional porosity, Sw is the fractional water saturation, ρ is density, lb/cu ft, and the subscripts v represents vapor and l is liquid.

The shallow Big Geysers steam reservoir was about 400F in temperature. The density of vapor is 0.5367 lb/cu ft and the density of hot liquid is 53.65 lb/cu ft. Thus:

lbs vapor + lbs liquid =

$$V\phi[(1-S_w)0.5367 + S_w 53.65]$$

Inspection of the right-hand side indicates the larger density of liquid controls the expression, and the vapor term may be neglected. It appears the term "vapor-dominated" is ironic.

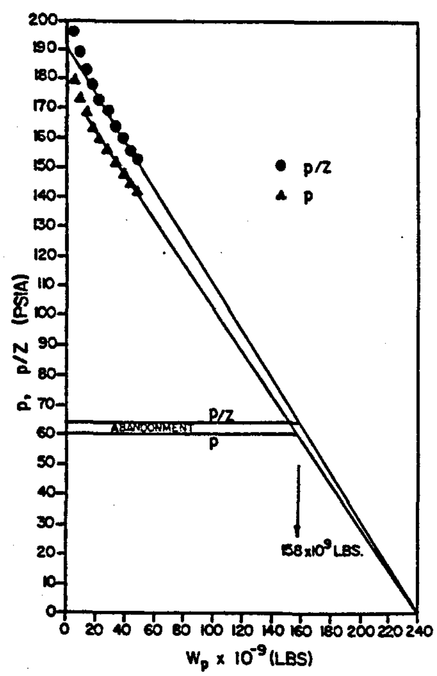


Fig.6 p and p/Z vs cum. prod. for Big Geysers Shallow zone (Economides and Miller, 1985)

If it is assumed that the only mechanism for storage of liquid in the shallow zone is adsorption, then Fig. 7 presents the desorption curve for the entire shallow zone. This is an important and new observation. If this is true, some other conclusions are that the desorption curve for Geysers greywacke is not linear with pressure, and that desorption behaves as though the system has a large variation in compressibility. However, the storage mechanism is not compression. Inspection of Fig. 7 shows a large drop in pressure for a small unit of production at the start, then a gradual drop in pressure with mass produced which is nearly linear. The linear extrapolation of pressure vs mass produced assumes a linear relationship. It is not known just what the relationship is.

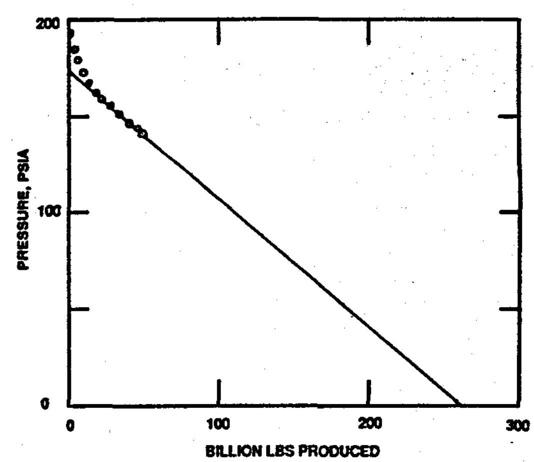


Fig.7 p vs cum.prod. for the Big Geysers shallow zone

There is additional information which indicates that storage of liquid as micropore fluid is reasonable. The shallow zone has a limited thickness of a few thousand feet at most. This zone was developed on a very close well spacing (0.5 acres per well) but liquid was never encountered in the steam interval. Studies of changes in the gravitational field indicate that the center of gravity of the mass produced from the field should be not more than 5,000 feet below the surface, Isherwood (1977).

The rapid drop in pressure on start of production appears common to most vapor-dominated systems. Italian reservoirs typically behave this way. New areas at The Geysers typically have a high rate of pressure drop which moderates after a time. Perhaps the desorption model offers an explanation for this behavior. A key remaining problem is measurement of adsorption for geothermal system rocks to determine whether adsorption does resemble Fig. 7, and if so, what shape is proper for the extrapolation.

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TABLE 1--BIG GEYSERS FIELD SHALLOW ZONE CUMULATIVE PRODUCTION AND RESERVOIR PRESSURE* (Ramey, 1968)

year	No. Wells	Steam Produced MMlb/yr	Mlb/hr	Cum. MMMlbs	** p, psia	Z= pv/nRT	p/Z, psia
1957	0	0	0	0	194	0.913	212
1957	5	1109.8	126.7	1.1	187	0.915	204
1958	5	3224.4	368.1	4.3	180	0.917	196
1959	10	3426.7	391.2	7.8	174	0.919	189
1960	10	4698.2	536.3	12.5	169	0.921	183
1961	10	4246.5	484.7	16.7	164	0.922	178
1962	10	4377.6	497.7	21.1	160	0.923	173
1963	13	5299.7	605.0	26.4	156	0.924	169
1964	12	6197.5	707.4	32.6	152	0.925	164
1965	9	5509.9	629.0	38.1	148	0.927	160
1966	7	4941.4	564.0	43.0	145	0.928	156
1967	7	3847.3	439.0	46.9	142	0.929	153

* Excludes prod. from original wells drilled in 1920's and prod. from wells T-8, T-13, and T-14 after deepening.

** Measured at the wellhead.