INTERPRETATION OF DOWNHOLE MEASUREMENTS AT BACA

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ABSTRACT

Downhole measurements in geothermal wells cannot be literally interpreted as reservoir profiles: the well profile is partly or wholly determined by fluid motion in the well. Careful interpretation is needed, and more care in two-phase systems.

Two idealised conceptional models are described, to give a background idea of expected reservoir fluid state. A full set of measurements on Baca field, New Mexico, has been released (1). These measurements (2 - 5) are used to illustrate interpretation, and construct a conceptual model of Baca reservoir.

Baca is a liquid-dominated reservoir, with a two-phase region containing the best producers. No abnormally pressured zone has yet been penetrated by drilling.

INTRODUCTION - TWO CONCEPTUAL MODELS

Geothermal reservoirs are distinguished from petroleum by their natural discharge. The undisturbed state is a dynamic state, not a static one. The natural upflow of fluid produces a fluid distribution in the reservoir rock. Exploitation aims at removing this fluid at far greater rate, depleting the storage in the system. However, the initial fluid state is best understood by reference to idealised models:

UNIFORM VERTICAL UPFLUX MODEL. This model has been used successfully to describe fields in New Zealand: Wairakei, Broadlands and Kawerau. There is a source of fluid at some greater depth. This fluid rises vertically, uniformly spread across the field. Lateral conduction and mixing is negligible. At sufficient depth, the fluid is liquid. Rising and depressurising, it reaches a depth at which it boils (Wairakei, 400m; Broadlands, 1500m; Kawerau, 1000m). Above this depth two phases flow to surface, the steam flux increasing as pressure falls. At all depths the vertical pressure gradient is near, but above, hydrostatic. The reservoir is called "liquid-dominated" as the pressure profile resembles that of liquid water. The superhydrostatic gradient is needed to drive both phases upwards. At the three New Zealand fields the pressure gradient was 110% of hydrostatic, and a similar result is found below for Baca. Within the two-phase zone, where both steam and water flow to surface, the reservoir contains both phases, with saturation adjusted to give the correct balance of vertical heat and mass flux. Drilling into this reservoir finds a two-phase mixture in place: the two phases are intimately mixed, not vertically segregated.

This conceptual model applies well to fields where the natural flow is primarily vertical. The three fields instanced are all in level terrain, with the water table close to ground surface. Fluid does rise more or less vertically, to discharge at surface.

HYBRID RESERVOIR: HORIZONTAL OUTFLOW AND PARASITIC VAPOR. This system too is driven by an upflow of fluid from greater depth. However, the terrain is mountainous. At exploitable depths, the upflow is two-phase. From this upflow region, liquid flows away horizontally, to ultimate discharge as chloride springs; and steam rises vertically, to give a parasitic vapor zone and steam-heated surface discharge above the upflow. Figure 1 sketches this model. Except for the vapor zone, pressures are liquid-dominated and controlled by the elevation of the chloride springs. This is much the picture outlined for Baca by Dondanville (quoted in (4)). Tongonan field in The Philippines (7) is an example where both upflow and outflow regions have been drilled. In the upflow zone the pressure gradient is again about 10% above hydrostatic, and there is a measured horizontal pressure difference along the outflow.

There may of course be graduations between these two extremes. Thus, even at Broadlands the upflow apparently originates on the east of the field. Both east and west halves of the field are two-phase, but enthalpies are higher in the east, reflecting partial steam separation. Broadlands field (6) shows a number of similarities to Baca: both are gassy two-phase fields with permeability problems (J.W.Pritchett, pers. comm.). These similarities were exploited in examining Baca data.

INTERPRETATION OF DOWNHOLE MEASUREMENTS

Measurements in geothermal wells should never be believed. Not, that is, as a gauge of the reservoir properties. Two properties of geothermal reservoirs cause this: the fractured permeability, and the non-static reservoir fluid state.

Most geothermal fields consist of fractured rock. A well draws its fluid from one or at most a few fractures. Most often, one dominates. *Only* at this depth does the well contact the reservoir. Only here does a stable-shut well reflect reservoir pressures. Pressures elsewhere in the well reflect the weight of the fluid (water, steam, two-phase) column in the well; seldom is this the same as the reservoir pressure gradient. The discharge enters the well at this point, and the fluid quality is determined here. Bottomhole pressures and temperatures, for example, are little guide to reservoir pressures and fluid quality.

Apart from its major feed, a well will have some other permeability. Some wells intersect more than one major feed. Measurements in such wells can be very difficult to interpret (8), as in petroleum wells intersecting multi-layer systems (9).

The natural state of the reservoir corresponds to an upflux of fluid, and correspondingly the pressure gradient exceeds hydrostatic. No well can duplicate a superhydrostatic pressure profile. In addition, if the reservoir contains two phases, the fluid in the well cannot duplicate the reservoir fluid profile. The fluid in the well cannot be equilibrium with the reservoir except at one or two points. If there are any secondary feeds, and there usually are, fluid will move in the well; entering at one point and leaving at another. This fluid motion governs the temperature and pressure profiles measured. Detailed interpretation consists of deducing the implied fluid motion, and what that in turn implies about the reservoir. An interpretation manual (10) consists of no more than a catalogue of combinations of feed points and reservoir fluid. The physical examples are similar, and the inferences identical, to those resulting from drilling at Yellowstone (11).

Four types of profiles appear in geothermal wells in unexploited liquid-dominated fields: (a) impermeable, (b) isothermal, (c) boiling point, (d) internal discharge. Another, (e) steam cap, appears when subhydrostatic conditions are penetrated; usually after exploitation.

The *impermeable* profile occurs in wells where permeability is so poor there is little flow in the well. A temperature profile is measured with so much zigzag detail that conduction must dominate over fluid convection in the well.

An *isothermal* profile appears when liquid water is flowing in the well, upwards or downwards, between two feeds. The temperature is correspondingly nearly constant. Baca-10 (Figure 2) shows this, with water at 500°F flowing between 3700' ASL and perforations at 5700'. This flow identifies some permeability at both its endpoints. Wells Y-3 and Y-4 at Yellowstone are further examples.

A *boiling-point* profile is seen when a well apparently contains a column of water, all at boiling-point. It corresponds to a small *two-phase* upflow in the well. Water and some steam enter the well, and flow up, to be injected higher up. The steam flow is small enough that steam rises as bubbles through the water column, and a hydrostatic pressure gradient is preserved in the well. Steam usually rises in the well above the upper injection point, now with a slow counterflow of water, and so the boiling-point profile can persist into the casing or even to wellhead. This steam, on condensation, provides the gas that enables some wells to build up a gas column in the casing very rapidly. Baca-4 seems to show a boiling-point profile.

Combinations are possible. A common one is an isothermal topped by a boiling-point profile. Liquid water enters the well and boils on its way up.

If a two-phase upflow is more vigorous, the fluid in the well becomes mixed, and an *internal discharge* profile results. Baca-15 shows a nice example. A feed lower down the well is discharging - hence the characteristic discharging pressure profile - but into a higher feed, not to surface. Like a boiling-point profile, this one usually continues to wellhead. Because the well is discharging, the measured pressure profile is no guide to reservoir pressures. At Baca-15 the major permeability is perhaps at 6000', near the casing shoe, with only minor permeability below supplying the discharge. If so, the pressure measured at 6000' will be somewhat above the reservoir. Deeper in the well there is a large discrepancy. An internal discharge profile was found, and recognised, at Yellowstone in hole Y-2. They are common at Broadlands. On occasion pressure changes due to exploitation have altered the vertical gradient around a well, causing it to switch between these last three profiles. The pressure and temperature changes in the well are spectacular. Internal or crossflows such as described here do also occur in petroleum (S.K. Sanyal, H.J. Ramey Jr, W.E. Brigham, pers. comms.). However, in the geothermal context they are exaggerated by the coupling to thermal effects. And the short-circuit established by the well is between two parts of the same reservoir, not distinct reservoirs.

The boiling-point and internal discharge profiles identify the reservoir as two-phase at the depth where fluid enters the well. They also disguise other reservoir detail. If there were a temperature inversion, it could be completely disguised. The dotted line for Baca-4, Figure 2, illustrates this. If that were the reservoir temperature, no measurements in Baca-4 would show it. At both Broadlands and Wairakei this has happened, the cold zone later revealing itself when pressure gradients initiate a downflow in the well of this cold liquid. The presence of an upflow, as the stable-shut well state, also identifies the reservoir pressure gradient as superhydrostatic. Otherwise the well would not always initiate an upflow.

If there is a subhydrostatic pressure profile in the reservoir, a well stands shut with a liquid downflow, or more commonly with a *steam cap* profile. The well stands with a water column beneath a steam column. One subhydrostatic case is when the reservoir contains a steam cap - a vapor-dominated zone over a liquid-dominated one. A well penetrating this stands with a steam cap profile; and in addition exhibits a distinctive behavior on discharge. At low flow (high WHP) it discharges only steam, and at higher flow a steam-water mixture. The well is unstable over intermediate pressures (8). No well at Baca shows this behavior, which is discussed in greater detail elsewhere (10, pp.41-45).

DISCHARGE. The definitive measurement of two-phase conditions is given by the measurement of discharge enthalpy. A well drawing from single-phase liquid ("water-fed" well) produces at the enthalpy of liquid water at the temperature of the well's major feed (not bottomhole). A two-phase well has a higher enthalpy. Two-phase wells usually have enthalpies which increase with flow rate (Figure 3) and vary with time. Fake two-phase wells (those with separate single-phase steam and water entries) are recognised by the decrease of enthalpy with flow rate. Baca-11 and 15 are normal two-phase wells. Sometimes wells discharge at enthalpies very near liquid water, and for these the best diagnosis of two-phase conditions is by the well profile. Baca-4, with its boiling-point profile and enthalpy of liquid water within the range of downhole temperatures, is an example. There are wells at Wairakei which have for years produced at the enthalpy of liquid water at the temperature of their feed point; and that temperature has dutifully followed the falling pressure along the saturation line. Wells like this are normally near the liquid/two-phase boundary.

INFLUENCE OF GAS. Non-condensible gas can significantly distort the saturation curve. Baca-4 and 13 have about 0.8% carbon dioxide content, suggesting that this is the gas content of unboiled liquid phase. The solubility of carbon dioxide (12) at 500-600°F means this will exert a partial pressure of 260-190 psi, and so a difference this large may occur, in two-phase conditions, between pressure and SVP. Once boiling occurs, gas partitions preferentially into the steam phase, and gas partial pressure falls. If measured pressure and temperature are near saturation, this implies not only is the well in two-phase, but that a significant steam fraction has formed. Because of the gas partial pressure variations caused by variable steam fraction, temperature may vary considerably at the same depth (and pressure). At Broadlands, with up to 800 psi gas pressure, at the 1230 psia datum (about 3000' deep), the temperature in two-phase may be anywhere between 480°F and 560°F. Higher temperatures, higher steam fractions, and higher enthalpies will be found in the centre of the two-phase zone.

BACA SECTIONS

Figures 4 and 5 show two plots of data from Baca. Figure 4 is a plot of the reservoir pressure vs depth. For each well, an estimate or guess was made of its primary feed, the depth where pressure is controlled. This depth is best found from downhole surveys as the well is warming up after drilling (10), and from injection surveys. As this data was not available, less reliable estimates were made from the stable profiles and drilling records. For Baca-12 no guess could be made, and for Baca-13 it was not possible to choose between two values. The points do fall on a single line, including one of the two for Baca-13. The slope of the line is 0.34 psi/ft, corresponding to water at 500°F. Compared to the reservoir temperature of 500-600°F, this confirms the superhydrostatic gradient. The apparent pressure differences between the wells are explained by the differing feed depths, at which they contact the reservoir.

Figure 5 is a cross-section along a line joining Baca-14 and 16. Temperatures influenced by wellbore motion were ignored, and smooth contours drawn. Using the reservoir pressure, the boiling point for water with 0.8% CO_2 is plotted. This defines the two-phase zone. Baca-11 and 15 are near the centre. As the plan isotherms (4) indicate, there is a strong gradient at right angles to this section. Temperatures increase to the northwest, as will the size of the two-phase zone and fluid enthalpies in it. Baca-4 must be near the southeast end of the two-phase. A vapor zone is expected, from the conceptual model. However, no well is open to such a zone, which must lie closer to surface.

FIELD TEST

A field scale interference test was performed. Among the monitor wells, Baca-10 responded, and this was used to obtain kh = 6000 md-ft, ϕh = 90 ft in a confined aquifer of liquid water, no boundaries of which had been found. Baca-4, 15 and 16 gave no response. Baca-16 might be ignored as it is unproductive. After the test the field recovered to within measurement error of its original pressure.

The nonresponse of Baca-4 and 15, and the total field recovery, are explained by the presence of two-phase, which is some orders of magnitude more compressible than liquid water (13). For a volumetric heat capacity of 2.5 x 10^6 J/m^3 °C (37 Btu/ft^3 °F), the two-phase compressibility for water-steam, at a pressure P psi, is:

$$\phi c_t = 280\ P^{-1.66}\ \text{psi}^{-1}\ .$$

Non-condensible gas decreases this, and this effect is here ignored. At 750 psi, ϕc_t = 0.0047 psi^{-1}. With such a large compressibility, no interference is expected. Consider Baca-15 responding to the discharge of Baca-11. Both feed at around 6000', so 750 psi is a representative pressure. If ϕ = 10%, k = 66 md. Baca-11 discharged at 720 Btu/lb, which at 510°F is 33% steam. Assuming the fracture-flow relative permeabilities (14), $k_{rw} + k_{rs} = 1$, the viscosity of the steam-water mixture is 40.5 Pa.s = 0.04 cp. This gives a diffusivity of 0.026 ft^2/s, and to travel the 1600' between Baca-11 and Baca-15 takes three years. There would probably be faster transmission along preferred paths, but no field response is expected.

The high compressibility of the two-phase also explains the final field pressure recovery. The compressibility of the total system - liquid and two-phase - is dominated by its two-phase component. The two-phase zone in Figure 5 is 6000' wide and 3000' deep. Ignoring the northwest extension, and taking it as a cone, the volume is 3.6 x 10^{10} ft^3. At an average 1000 psi, the compressibility is ϕc_t = 0.003 psi^{-1}. Baca-11's discharge, of 1320 Mlb at 720 Btu/lb, referred back to 510^{o}F, is 440 Mlb steam and 880 Mlb water, occupying 9.4 x 10^7 ft^3, 80% of which was steam. The production of Baca-6 and Baca-13, less the injected fluid, is 500 Mlb, occupying 10^7 ft^3. The total volume loss to the reservoir is 10^8 ft^3, causing a pressure drop

$$\Delta P = \Delta V/V\phi c_t = 0.9 \text{ psi}$$

which is not observable. This calculation, using the two-phase compressibility, is equivalent to a heat and mass balance on the two-phase zone.

SUMMARY

Baca contains a liquid-dominated reservoir, with no zones of abnormal pressure. There is a two-phase zone penetrated by wells 4, 11 and 15, this zone being surrounded by cooler liquid, except to the northwest. The two-phase wells are identified by: stable-shut profiles, discharge enthalpy, and lack of interference.

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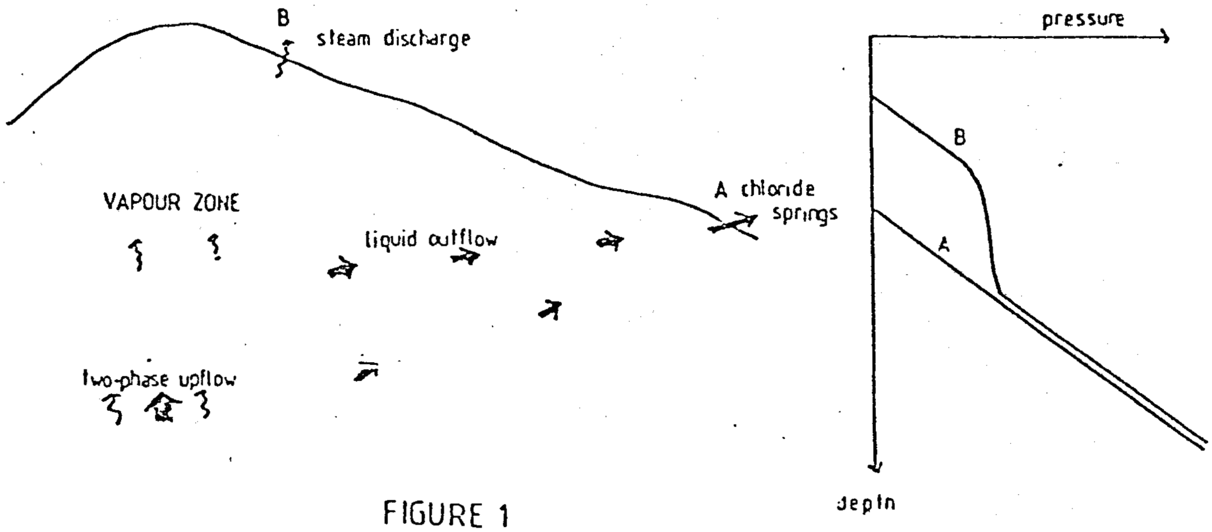

FIGURE 1

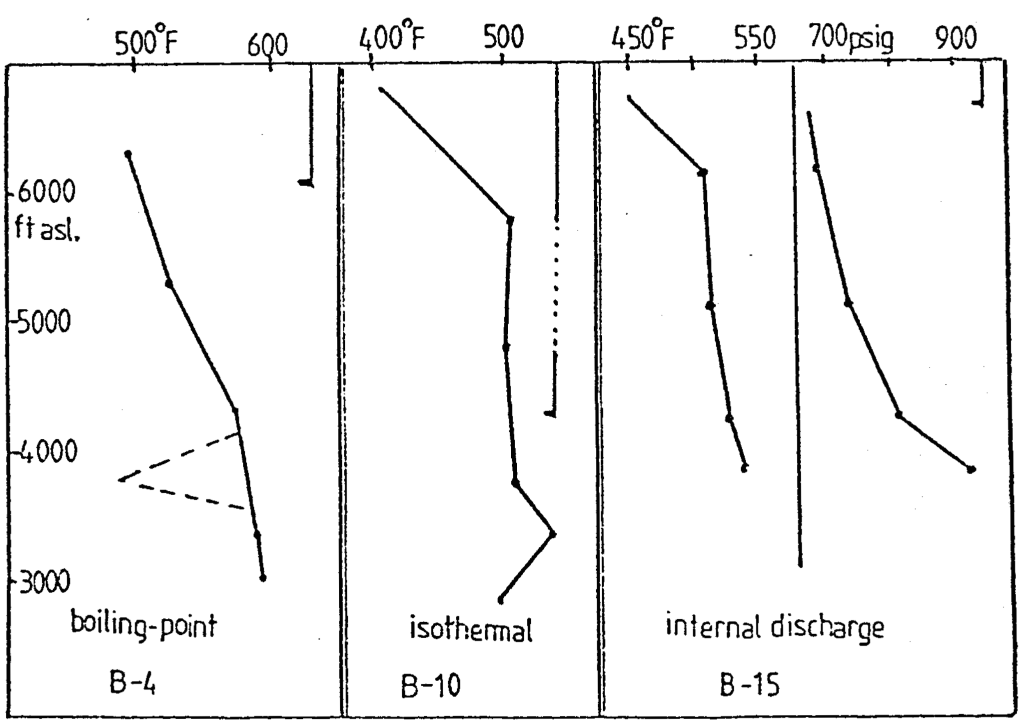

FIGURE 2 STABLE PROFILES

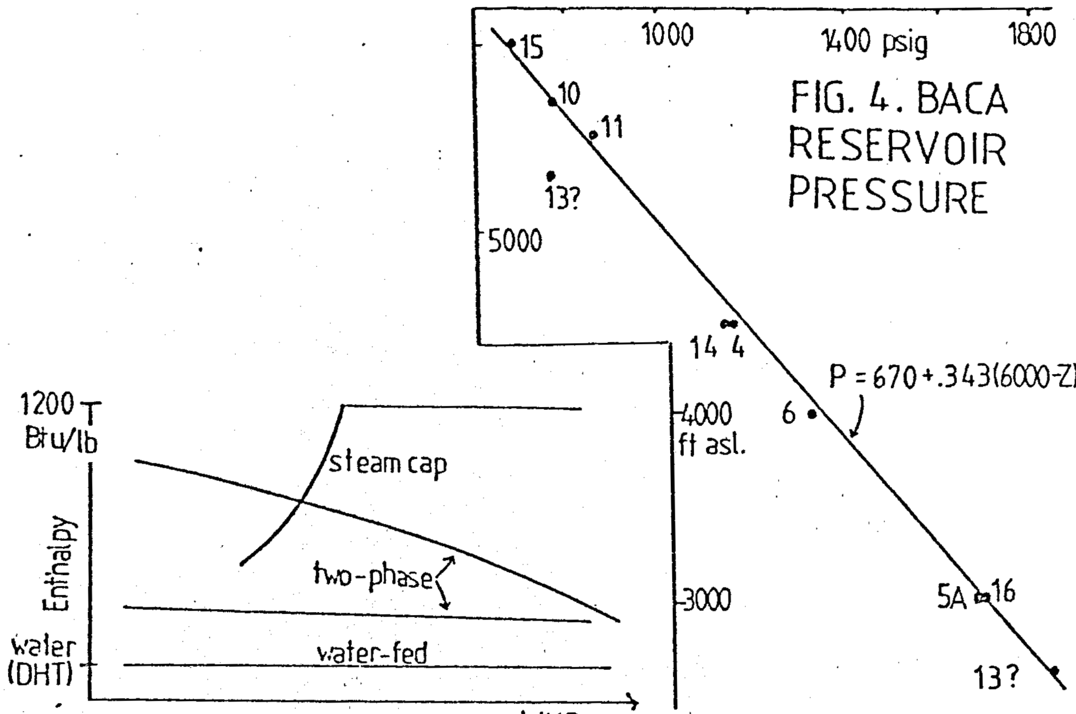

FIG. 4. BACA RESERVOIR PRESSURE

FIGURE 3

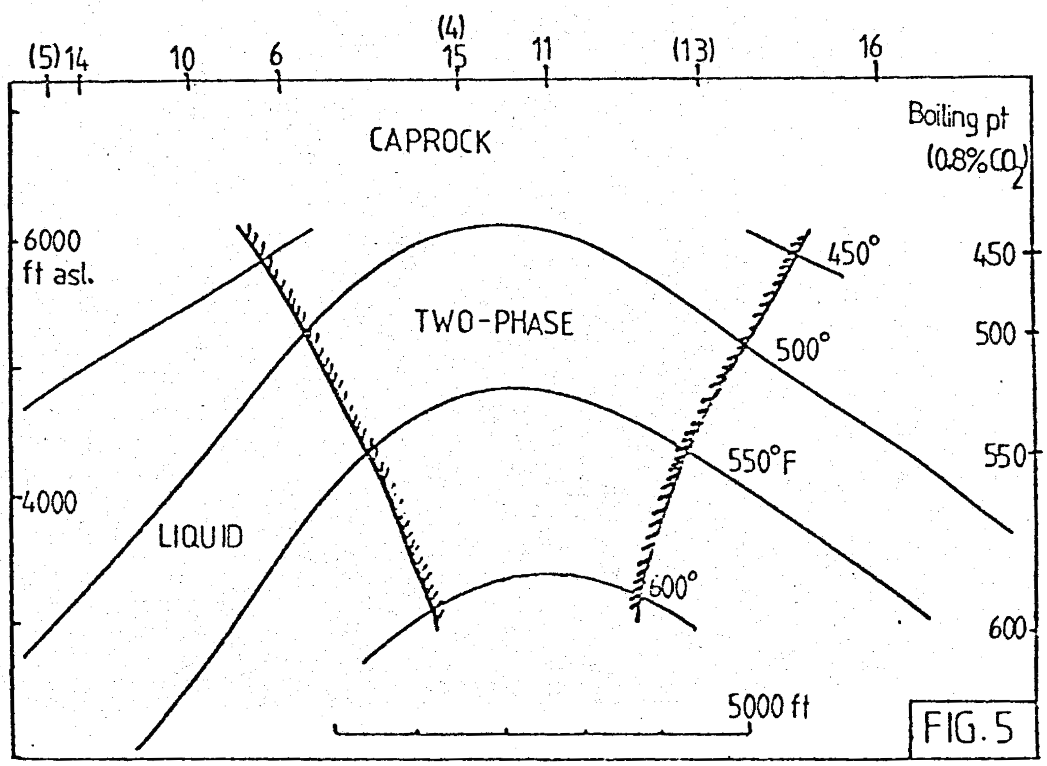

FIG. 5