# DEDUCTIONS OF THE CHARACTER OF STEAM-WATER WELLS FROM THE SHAPE OF THE OUTPUT CURVE

Russell James

Department of Scientific & Industrial Research
Wairakei, New Zealand

## ABSTRACT

The output curve of a borehole should tell us much about its character, and the speculations presented here suggest that an early quantitative estimate can be made of the permeability of the rock formation supplying the well, together with its water temperature and hence the discharge enthalpy.

Other derived factors are whether the fluid is high in non-condensible gas and if there is more than one permeable formation tapped by the well; these deductions are based on changes in wellhead pressure which occur after the well is closed.

## INTRODUCTION

On the face of it geothermal wells seem to be of unmanageable complexity; this is because some are supplied with dry steam, others with pressurised hot water while still others with intermediate mixtures. And not only does pressure vary within holes but gas concentration in the steam and chemical content of the water can lead to scaling deposits in some wells and corrosion in others, with various feed-back effects. Flow-rate is extremely sensitive to the permeability of the supplying formation due to the tightness of granulated material or the width of fissures in hard rock, and both restrictions may be operating simultaneously or even sequentially in the same well. Time is of importance too, and identical measurements in the same well at different dates can give different results, due to, for instance, decline in the pressure or temperature of the reservoir fluid.

Besides these and other complexities, when attempting to estimate flows from wells based on reservoir conditions, we are also faced with the variability of. borehole geometry in that no two profiles are the same, with depths, casing diameters and slotted liners usually present in different mixes. when we couple these factors with the inevitable inaccuracies of measuring instruments such as pressure gauges (due to vibration fatigue) and pipeline thermometers (low readings caused by heat losses), we can be forgiven for turning our attention to other aspects of geothermal science.

Aware of the magnitude of these problems, the sympathetic reader will not expect much in the way of accuracy or predictive ability when studying the performance of geothermal wells; in fact, he may consider it unwarranted optimism to even attempt it. With these substantial qualifications having to some extent insured against the penalties of gross errors, it may still be possible to gain some useful insight helpful to the understanding and exploitation of geothermal fields.

## ASSUMPTIONS

In order to accomplish this aim, I have limited the field of geothermal wells studied here to those deriving their flows from reservoirs containing hot water, the top portion of which, up to the ground surface, exists under conditions of BPD (Boiling Point with Depth). This is because most worldwide geothermal fields are, in fact, of this type and even the so-called vapour dominated fields may be underlain with such systems. The maximum depth H (in metres) at which boiling point starts, for a reservoir of a given deep water temperature C (in degrees Celcius) can be obtained from the integrated boiling-point-with-depth curve which is accurately summarised in the equation:

$$C = 69.56\ H^{0.2085} \quad \text{for } 30 < H < 3\,000 \qquad \text{(i)}$$

For example, for a reservoir of hot water at 250° circulating at depth within permeable rock strata, some steam will coexist with hot water over a depth of 461 m from the ground surface with depths and temperature over this distance related in the above equation if we ignore the cooling effects of sub-surface meteoric water. Deeper than 461 m only hot water at 250° exists with increasing hydrostatic head, although in actual reservoirs, limited temperature variation does occur.

As suggested elsewhere (James, 1979), a permeable layer is to be expected at the depth at which boiling first commences but even if a well is drilled to deeper permeability, the rising hot water in the well starts to flash at close to the external boiling point depth within the reservoir. If these assumptions are accepted, we have a relationship between the depth to the flash point in a well, and the reservoir temperature (the so-called base temperature), and this is the same relationship as that for the reservoir given in equation (i) above.

To minimise the effect of permeability in these calculations it is necessary to operate a well at the lowest flow possible, this occurs at the highest obtainable wellhead pressure - known as the Maximum Discharge-Pressure (MDP) and is given the symbol $P_m$ here.

The relationship between reservoir temperature C and $P_m$ (bars) has already been determined (James, 1970) and is as follows:

$$C = 99.75\ P_m^{0.283} \quad \text{for } 8 < P_m < 80 \qquad \text{(ii)}$$

This equation is surprisingly accurate (within about 1%) and has been used in many countries to estimate the reservoir water temperature from a simple reading of the highest wellhead pressure that flow can sustain. A study of discharge at $P_m$ for actual wells shows it is not negligible and can be estimated by the simple formula:

$$W_t = \frac{h_o}{10} \qquad \text{(iii)}$$

where $W_t$ is in tonnes/h and $h_o$ (the well enthalpy) is in kj/kg.

The validity of equation (ii) would appear to substantiate the various assumptions leading up to it; its theoretical ramifications and practical usefulness make it one of the most important in Geothermal science. Departures from its correctness can be due to a number of reasons such as a very high gas concentration in the reservoir water (order of 1 wt %) or low hydrostatic pressure due to the presence of a steam layer above, and of themselves provide important insights into the reservoir condition.

Because C and H are related in equation (i) the depth of the well does not appear in equation (ii); the reason the pipe diameter is also not involved is because at $P_m$ the discharge is poised at the point of collapse and is precisely in dynamic balance. Hence the geometry of the well is eliminated from the equation as is also the possible restrictive effects of bottom hole impermeability.

## MAXIMUM FLOW FROM A WELL

Having already described the case where the minimum sustainable discharge is obtained, we now consider the well discharging wide-open vertically, which is the other extreme of flow. The most accurate pressure reading under this condition is the Lip pressure $P_c$ which is read from a tapping at the very end of the vertical discharge pipe just where the flow hits the atmosphere. The wellhead pressure is not such a good choice as it varies sensitively with the length of the discharge pipe.

As bottom-hole impermeability exerts its influence more significantly on unrestricted discharge, results were plotted from a few powerful wells whose permeabilities were guessed as near-perfect (10 on an arbitrary scale from 1 to 10). The most successful configuration found was when the ratio $\frac{P_m}{P_c}$ was plotted against the enthalpy of the reservoir supply water $h_o$.

This is shown in Figure 1 where a straight line is obtained having the equation:

$$\frac{P_m}{P_c} = \frac{h_o}{244} \qquad \text{(iv)}$$

Not only does this line pass through the origin but when extended to the enthalpy of steam (2804 kj/kg at 30 bars) agrees with values applied to Larderello dry steam wells (Rumi, 1972). I have taken the full-depth well internal diameter as 0.2032 m (8 inches) as an approximation and compromise for internal restrictions (slotted liner etc.) on standard $9\frac{5}{8}$ inch cased wells but have also marked the estimated location for well diameters of 0.1 and 0.3 metres. These are based on direct calculations of unrestricted vertical flow to be published elsewhere.

The Lip pressure $P_c$ has world-wide use in geothermal projects and is related (James, 1962) to well enthalpy $h_o$, total discharge $W_t$ and discharge pipe inside diameter $d_c$ in the equation:

$$\frac{W_t\ h_o^{1.102}}{d_c^2\ P_c^{0.96}} = 5.2\ (10)^6 \qquad \text{(v)}$$

Perhaps it would be best at this point to consider the use of the various formulae on an imaginary test case.

## ILLUSTRATIVE EXAMPLE

Assume we have available a well believed to be drilled into a hot water reservoir and having the simplest of wellhead equipment, namely a throttle valve and vertical discharge pipe to which is attached a Lip pressure gauge; below the throttle valve is a wellhead pressure gauge.

First we discharge at the highest wellhead pressure possible $P_m$ and let us suppose this reads as 27 bars (we have, of course, added the atmospheric pressure to that of the pressure gauge). Employing equation (ii) we obtain the water temperature C = 253.5° and from steam tables the water enthalpy $h_o$ = 1102.4 kj/kg. Equation (iii) gives the discharge as $\frac{1102.4}{10}$ = 110 t/h which we plot as point A on Figure 2. Now we discharge the well wide-open vertically (if the peripheral agricultural lands permit) and let us suppose the value of Lip pressure comes to 3.5 bars. This is then compared with the value of 5.98 bars which is the theoretical maximum estimated from equation (iv) where $P_m$ and $h_o$ are from above,

$d_c$ = 0.2 m, and where bottom-hole permeability is 10 (the highest value on our scale of 1 to 10). Our actual reading of 3.5 bars indicates that permeability is restricting flow and has a value on our scale of $\frac{(3.5)}{(5.98)}$ (10) = 5.85 hence we should seek better permeability to improve flow or perhaps consider employinq 'hydrofrac' in this well.

The maximum discharge is calculated from equation (v) as $W_t$ = 317 t/h for $P_c$ = 3.5.

We may now throttle the flow to various wellhead and Lip pressures and then calculate appropriate discharges as shown above, for plotting curve (b) on Figure 2. This can be compared with curve (a) based on a Lip pressure of 5.98 bars with a flow of 531 t/h and considered as the greatest possible. For plotting purposes, it has been found that for wide-open vertical flow, the value of wellhead pressure is approximately twice the value of Lip pressure. For the cases examined here Lip pressures of 3.5 and 5.98 bars would have wellhead pressures respectively of 7.0 and 11.96 bars as shown on curves (a) and (b).

## CLOSED-IN WELL

Many wells on closure hold their wellhead pressures fairly constant at the $P_m$ value, In our example, on Figure 2, point A would move to B. However, some closed-in pressures gradually rise over a period of days to a much higher reading,as at point D on the diagram, and the wellhead becomes cool to the touch. This is because of gas bubbling into the well from the permeable horizon and unless this is bled at the wellhead, the pressure will rise to match that at the formation. In our example, this would probably be at 42 bars which, from steam tables, is the vapour pressure at 253.5$^o$; hence this qas pressure at the wellhead provides a valuable check on the reservoir temperature estimated from equation (ii). As this phenomenon often indicates a high gas concentration in the reservoir water, this can be tentatively estimated by taking a wellhead temperature at MDP to identify and utilise the partial gas pressure.

If the wellhead pressure on closure decreases from B to, say, C, this is probably because of a downward drain of lower-temperature water from a hiqher, sliqhtly permeable layer. Often this has no significant influence on the discharging well which is supplied mainly from the lower, permeable,, higher-temperature zone. In the example taken point C is at 22 bars and equation (ii)gives a temperature of the draining water of 239.2$^o$ which, from equation (i), would be expected from a depth of 373 m as compared with 493 m from the water at 253.5'. These temperatures are, of course, only taken as examples.

## CHANGES WITH TIME

Suppose we have a well characterised by curve (a) of Figure 2 and after some years of production, this has altered to curve (b); then we may provisionally infer that as the MDP is constant, there has been no decline in supply water temperature and hence that deposition of chemicals within the well has been responsible for the change. Deposition in the strata outside the well is highly unlikely according to an earlier study (James, 1975).

If, however, curve (a) had changed to (c) with the new MDP at point E, it would appear that the supply water temperature had fallen to 239.2$^o$ with no change in the excellent downhole permeability. A change from curve (a) to (d) however, would mean both a decline in water temperature and chemical deposition in the well.

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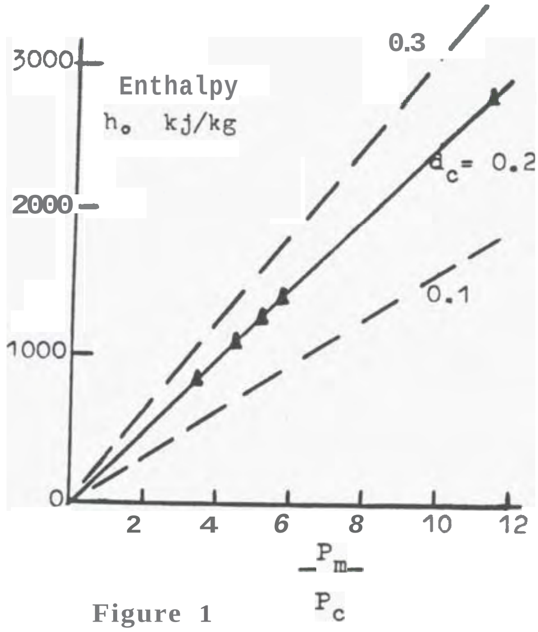


Figure 1

Ratio of Maximum Discharge-Pres to Maximum Lip Pres at various Well Enthalpies and diameters.

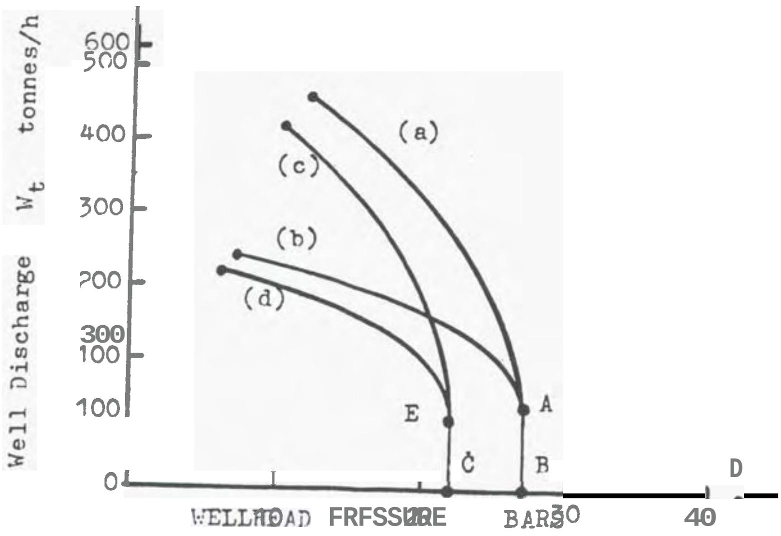


Figure 2 Examples of Output Curves and Closed-In Wellhead Pressures for $d_c$ = 0.2 metres