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ABSTRACT

For equal flows of hot water wells, the electric power which can be generated increases with feed water temperature. However, high temperature wells discharge greater flows than that of lower temperature wells of similar permeability, with the result of enhanced power potential.

In fact, where fluids are exploited utilising two-stage flash, these factors combine to give a power potential which is proportional to the cube of the feed water temperature in degrees celsius. Hence a feed of 315°C would generate twice the power of that of water at 250°C for wells of good permeability and where the reservoir exists under conditions of boiling point with depth.

Higher temperature water (exceeding 300°C) has, however, a commensurate higher tendency to mineral deposition in reinjection water lines and this disposes design to single-stage flash with slightly reduced power, compared with the two-stage alternative.

INTRODUCTION

After the discovery and exploitation of the Larderello field in Italy, drillers have sought reservoirs which produce dry or superheated steam and have had successes with The Geysers (U.S.A.), Kamojang (Indonesia), Matsukawa (Japan) and others. Most reservoirs penetrated, however, have proved to contain hot water at or near the boiling point for depth and many have been developed since the building of the Wairakei station. Early theory, James (1966), urged shallow drilling (order of 350 m) into hot water reservoirs, so as to exploit the 'top of the boiler' and tap the thin layer of steam believed to exist there. By this means a steadily increasing volume of vapour should spread over the top reaches of the reservoir supplied by the underlying water which boils and draws heat from the rock matrix. The efficiency of such an approach was calculated as far higher than the alternative of simply discharging boiling water as the latter would have less than half the power-life of the former which more effectively utilizes the rock heat. To judge by the power generated at Larderello and The Geysers, this may be so, especially as it is believed that such dry steam reservoirs are indeed under-pinned by large volumes of water either beneath the steam zone, James (1968) or co-mingling with it, Truesdell and White (1973). In the initial development of a hot water field, a putative steam zone may be of small thickness or possibly non-existent and in the latter case, a well drilled to about 350 m would merely initially tap hot water at about 236°C whereas deeper drilling would most probably find higher temperature water capable of greater power potential even though having to discharge through a longer length of borehole. Statistics indicate that this is so, as the average depth of hundreds of wells drilled in geothermal regions in the U.S.A. over the last few years has reached 2 km, which, for a classical boiling point with depth (BPD) reservoir would attain 339°C. This would be an attractive result so long as bottom hole permeability was good and that the mineral concentration in the brine was not too high to present problems with reinjection or in-hole scaling. And nowadays, reinjection is a mandatory part of nearly all world-wide geothermal schemes, even for dry steam reservoirs with their relatively small quantity of condensate to be disposed.

It may be appropriate to reassess drilling strategy and make a determined effort to exploit the top of water reservoirs in the expectation of evolving a steam zone with fewer problems and more energy efficiency potential. However, one cannot be dogmatic, as drilling is an exacting and expensive business with first discharge awaited with nervous anticipation, and reputations dependent, to some extent, on the results. Higher temperature water does, of course, produce more steam than lower temperature water and consequently more electric power can be generated. It is also found that higher temperature water, even though at greater depth, discharges greater flows than lower temperature water for equivalent feed-zone permeabilities, hence the trend to tap deeper horizons is a logical one. Up to now, no quantitative assessment has been possible into the comparative merits of higher water temperature with depth except to be aware that deeper is better. This is because it has
not been possible to sensibly compare the discharge of wells which are drilled to various depths without being aware that permeability variation controls, more often than not, whether a well is a good producer, and so a low temperature shallow well can have a greater discharge and power potential than a deeper higher temperature well drilled into tighter formations. Although, as has been pointed out, statistics indicate that the deeper wells are generally a better investment, this may be because unknown factors conspire to increase permeability at around a depth of 2 km in a similar way that good permeability is found at about 350 m depth, James (1984a).

Therefore, for equivalent permeabilities, and assuming that boiling point with depth (BPD) obtains, a good deep well is superior to a shallow well within the depth common to geothermal drilling, which is down to about 2.5 km. At greater depths, the cost of drilling increases rapidly and begins to exert its influence on the cost-benefit analysis, but in this study that aspect will be ignored, and will only be resurrected if deeper drilling becomes an intrinsic part of geothermal technology.

MAXIMUM WELL DISCHARGE

This has been calculated, James (1980) for infinite permeability at the feed zone, boiling point with depth, and wide-open stable vertical discharge. The following formula is employed.

\[ P = d^{0.602} \left( \frac{C}{72.2} \right)^{2.195} \text{ for } 180 < C < 350 \]  

(P = lip pressure in bar; C = the feed temperature, degree celcius. For the boiling point with depth relationship where H is depth in metres, James (1980).

\[ C = 69.56 H^{0.2085} \text{ for } 30 < H < 3000 \]  

Formula (1) has been confirmed in practice James (1984b), and applies whether the feed is reservoir water which is just at the boiling point (for the hydrostatic pressure), or whether it is dry saturated steam at the same temperature. The relationship between flow, lip pressure, pipe diameter and fluid enthalpy is derived from James (1962) and in the metric form:

\[ W = 5.2 \times 10^6 \frac{P^{0.96} d^2}{h_o^{1.102} C} \]  

(3)

\( W = \) Flow t/h;
\( d_c = \) Inside diameter of well and discharge pipe, m
\( h_o = \) Enthalpy of discharge, kJ/kg

We now require a relationship between water enthalpy and temperature and a plot of these factors derived from steam tables, gives:

\[ h_o = 1.475 C^{1.197} \text{ for } 210 < C < 350 \]  

(4)

Substituting (1) in (3), we have

\[ W = 5.2 \times 10^6 \frac{d^2}{h_o^{1.102} C^{0.5}} \]  

(5)

Now substitute (4) in (5),

\[ W = \frac{5.2 \times 10^6 d^2}{h_o^{1.102} C^{0.5}} \]  

(6)

W = 410.82 \( \frac{d^2}{C^{0.5}} \) tonne/hr

Although this result gives the maximum flow from a well which can be expected, it can increase with displacement upwards of boiling point with depth in the reservoir; also for low enthalpy wells, high gas content can boost flow to higher values than that determined from equation (6), James (1982). Lower discharge than the maximum can be due to (a) mineral deposition which reduces the well diameter, (b) impermeability of the feed horizon, or (c) displacement downwards of the boiling point with depth relationship.

Equation (6) shows that flow is directly proportional to both the diameter of well and feed water (or steam) temperature; however, the index of diameter is greater than the expected square law and emphasises the importance of increasing well diameters where excellent permeability exists.

To determine the amount of electric power which can be generated from the flow of equation (6), we require the specific power rate for hot water expanding by two-stage flash into turbo-condensers under optimum design conditions. Fortunately, this has been accomplished, James and Meidav (1977) who present the following relationship:

Megawatt (electrical) = \( W \left( \frac{C}{1260} \right)^{2.2233} \) for \( 210 < C < 350 \)  

(7)

Substituting (6) in (7), we obtain:

Megawatt (electrical) = \( \frac{5.26 d^2}{C^{0.5}} \) tonne/hr

This shows that the electrical power which can be generated from hot water reservoirs is proportional to the cube of the feed temperature, and tapping a reservoir at 315°C for example, should give twice the power of a
reservoir at 250°C, all other factors being equal.

Interestingly enough, James (1986) shows that at these reservoir temperatures, the amount of silica transported in the separate steam and water pipelines (for power and injection) is also twice as high for the higher temperature reservoir when exploited for equal electricity generated. Because of potential scaling problems anticipated in the reinjection water lines of higher temperature fields (exceeding about 300°C), it may be that only single-stage flash will be employed rather than the more efficient two-stage flash, in which case the power relationship of equation (7) will have to be replaced with that derived for single-stage, James and Meidav (1977), as:-

$$\text{Megawatt (electrical)} = \frac{W}{d_c} = \frac{2.611}{1055} \text{ for } 235 < C < 365 \quad (9)$$

Substituting (6) in (9), we obtain:-

$$\text{Megawatt (electrical)} = \frac{2.578}{c^{3.399}} \quad (10)$$

For single-stage flash and condensing sets, the relationship of equation (10) shows that a reservoir temperature of 306.6°C would generate twice the power of a reservoir of 250°C. It should be noted that, although the index of temperature now exceeds the cube, the power will be less than that of the two-stage alternative, due to the equation constant being smaller by approximately 10.

For example, if a well diameter of 0.2 m is taken and a reservoir hot water temperature of 250°C, then the power potential of hotter water at deeper horizons, there is considerable incentive to ignore shallow drilling. However, high temperature water usually contains increased concentrations of dissolved minerals which can lead to scaling of reinjection water lines,
reinjection wells, and the surrounding reservoir, with serious consequences for the "life" of a project.

As reinjection is an inherent part of most future power developments and the problem of scaling not yet solved technically and economically, it is recommended that a sustained effort be made into locating (and subsequently exploiting) the dry steam believed to exist close to the critical temperature of 236°C, James (1986). Such steam horizons would be situated above hot water reservoirs and ideally located at a depth of about 350 m. Even if hot water is found at this level, it will most probably be temporary or at least have a relatively low level of dissolved minerals which will permit two-stage flash exploitation, with reinjection free from scaling problems: a not unattractive scenario. And continued production of water will lead (it is hoped) to eventual changeover to steam flows with development of a spreading vapour-filled zone.

REFERENCES