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DECLINE CURVE ANALYSIS OF PRODUCTION DATA FROM THE GEYSERS GEOTHERMAL FIELD

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ABSTRACT

Production data for over two hundred wells at The Geysers geothermal field were compiled and analysed. Decline curves for groups of wells with 5, 10, and 40 acre spacing are presented and compared to curves published previously by Budd (1972) and Dykstra (1981). Decline curves for several individual wells and leases are discussed to illustrate the effects of well spacing and location, as well as the heterogeneous nature of the reservoir.

INTRODUCTION

Production rate decline curves are widely used in the petroleum and geothermal industries to assess individual well or field performance and to predict future production. The primary purpose of decline analysis at The Geysers is to determine the infill drilling requirements for maintaining a constant supply of steam to the power plants. Unfortunately, much of the data from The Geysers are of a proprietary nature, and thus, only two sets of decline curves have been published in the open literature. Budd presented three curves illustrating the effects of well spacing on production decline. However, his curves are the results of a computer simulation using average reservoir characteristics for The Geysers and do not necessarily represent actual production behavior. Dykstra published a curve based on production from 18 wells, which suggested that after 8 years, production rate from an average well had declined by 50 percent. However, due to the small number of wells included in the analysis, Dykstra's results do not discriminate between various well spacings or locations within the field.

The Earth Sciences Division of the Lawrence Berkeley Laboratory (LBL) has started a project with the California State Lands Commision (CSLC) to research fluid and heat flow behavior at The Geysers. As a part of this work, a data base for The Geysers field has been developed (Bodvarsson et al., 1986) and various reservoir engineering studies performed. This work has laid the necessary background for research into field conditions and behavior during exploitation.

This paper describes the results of decline curve analysis performed on over 150 open file wells at The Geysers.

PRODUCTION BACKGROUND

Several hundred wells have been completed at The Geysers since drilling commenced in the 1920s. Large amounts of reservoir engineering data have been collected, especially since the late 1960s, when large-scale power production began. These data include temperature/pressure surveys, rig test data, wellhead data, production/injection histories and pressure transient test data. Many of the wells have been producing for over a decade, yielding flow rate and shut-in pressure histories that reflect changes in reservoir conditions. Much of the reservoir engineering data from The Geysers field are proprietary and not available in the open literature. However, papers and reports have been published that describe in general terms the reservoir behavior prior to and during exploitation. The most comprehensive reviews include those of Ramey (1970), Lipman et al. (1977) and Dykstra. Mogen and Maney (1985) give a very detailed description of the characteristics and behavior of the Thermal shallow reservoir. There are also data available from the California Division of Oil and Gas for over 150 open file wells (a well is put on open file after 5 years of production). The data for these open file wells include flow rates, wellhead pressures, wellhead temperatures, and drilling information.

It is estimated that over 1400 billion lbs (640 billion kg) of steam have been produced at The Geysers since 1968 (modified from California Division of Oil and Gas, 1985). Although initially it was believed that steam production would remain fairly constant with time and no significant pressure decline would occur at The Geysers, it is now well established that the wells decline in productivity with time and that significant pressure drop has occurred (Ramey, 1970; Lipman et al., 1977; Dykstra, 1981). The well flow rate decline is offset by infill drilling or expansion of the wellfield feeding a given power plant. Lipman et al. (1977) state that on the average, one make-up well per year must be drilled for each 100 MW_e unit.

DECLINE CURVE ANALYSIS

A very brief description of the decline curve equations will be presented here; a complete derivation and detailed explanation may be found in Arps (1945), Zais and Bodvarsson (1981), or Fetcovich (1980). The three equations generally used for analyzing flow rate decline are the so called exponential, hyperbolic, and harmonic equations. These equations stem from the empirical assumption that the decline rate is proportional to the production rate raised to some exponent, i.e.,

$$\left(\frac{1}{q}\right)\frac{dq}{dt} = -D^{*}q^{b}. \qquad (1)$$

Integration of this equation yields the hyperbolic rate-time equation

$$\frac{q(t)}{q_i} = \frac{1}{(1 + bDt)^{1/b}}. \qquad (2)$$

The special cases of b = 0.0 and b = 1.0 yield the following equations:

$$\frac{q(t)}{q_i} = \frac{1}{e^{Dt}} \qquad (3)$$

$$\frac{q(t)}{q_i} = \frac{1}{(1 + Dt)}, \qquad (4)$$

which are called the exponential and harmonic equations, respectively. The exponential equation leads to conservative estimates of future recovery because the decline rate does not decrease as the flow rate decreases with time. An harmonic equation, on the other hand, leads to more optimistic estimates of recovery because the decline rate decreases as the flow rate decreases. The hyperbolic equation usually has an exponent between zero and one, though Gentry and McCray (1978) have shown that in special cases it can be greater than one.

The decline curves may be calculated statistically using a nonlinear least squares type approach, or they may be found from type curves such as those presented by Fetcovich. A stastistical computer program provides unbiased determination of the coefficients for the decline curve equations, but offers little physical insight and does not allow the application of engineering judgement. Type curves, on the other hand, allows one to see the effects of various parameters, as well as providing reasonable estimates of the formation permeability-thickness product (Enedy, 1987). Another important feature of type curves is the determination of the minimum production history necessary for distinguishing the type of behavior for each well. This is necessary because the results from the three different equations are very similar at early times, while their projections may differ by up to 50 percent after 10 years. We used both methods in our analysis and found that, in general, the type curve method provided more reliable results.

Causes of Flow Rate Decline

Wells at The Geysers show flow rate decline with time, due to pressure reduction in the reservoir in response to fluid extraction (Budd, 1972). Ramey (1970) noted that all of the wells available in 1968 showed measureable pressure decline. The rate of production decline varies greatly between wells and also from region to region within The Geysers area. Budd published decline curves for various well spacings based upon a theoretical model and estimated that a 50% flow rate decline would occur in 5, 15 and 25 years for well spacings of 5, 20 and 45 acres, respectively. Dykstra used actual flow histories from 18 wells at The Geysers and concluded that, on the average, a 50% decline in flow rate occurs after about 8 years of production. He also concluded that an harmonic-type model best represented the observed flow rate decline. However, one must be aware that the wells used by Dykstra were completed in areas with different well spacings, varying from 40 acres to about 5 acres.

In addition to well spacing, many other factors affect the flow rate decline. Using a fracture model proposed by Pruess and Narasimhan (1982) that assumes significant fluid reserves in the rock matrix, Bodvarsson and Witherspoon (1985) evaluated the effects of various parameters on the flow rate decline. They concluded that the main parameter controlling the flow rate decline is k_m/D^2, where k_m is the matrix permeability and D is the average fracture spacing. Brigham and Dee (1985), on the other hand, used a model that assumes that the fluid reserves are primarily associated with a deep water table. They found that the long term flow rate decline depends primarily on the flow resistance in the primary pathways from deep water table to the steam entries table, hence, the fracture permeabilities.

Individual Well Rates and Decline

Well productivity varies greatly from one well to another, which is to be expected given the heterogeneous, fractured nature of the reservoir. The variability of initial flow rates is illustrated in Figure 1, which shows the number of wells with a given initial steam flow rate. A typical well produces some 150,000 lbs/hr (19 kg/s), but the productivity is highly dependent upon characteristics such as the reservoir pressure, the fracture spacing and permeability. Steam rates in excess of 300,000 lbs/hr (38 kg/s) have been reported for some of the best producers at The Geysers.

Most of the wells for which we have data show a near-harmonic flow rate decline, which is in

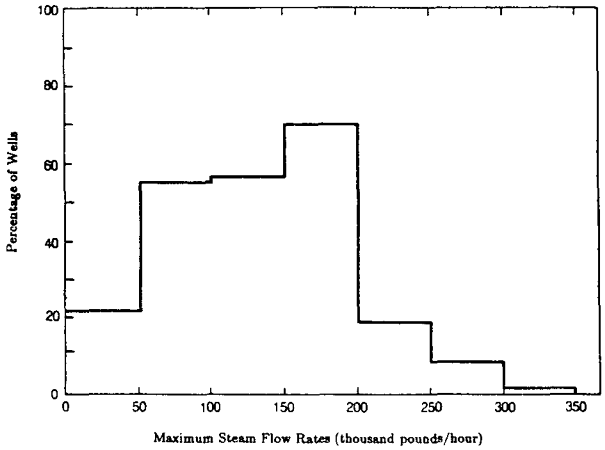

Figure 1. Number of wells with a given maximum flow rate.

agreement with earlier results (Dykstra, 1981). Also, Gentry and McCray (1978) have shown that the hyperbolic constant increases with reservoir heterogeneity, which implies that the flow behavoir in a highly fractured reservoir such as The Geysers should be either harmonic or hyperbolic with an high exponent. A determination of the proper decline behavior is important for making predictions of future flow rates. This is illustrated by Figure 2, which is a type curve match for a well on the Sulphur Bank lease. The flow rate for this well appears to exhibit a hyperbolic decline with b = 0.8. An extrapolation based on b = 0.8 predicts a flow rate of 29,000 kg/hr after 20 years, while a standard semi-log (b = 0) extrapolation predicts a flow rate of only 16,000 kg/hr after an equal amount of time.

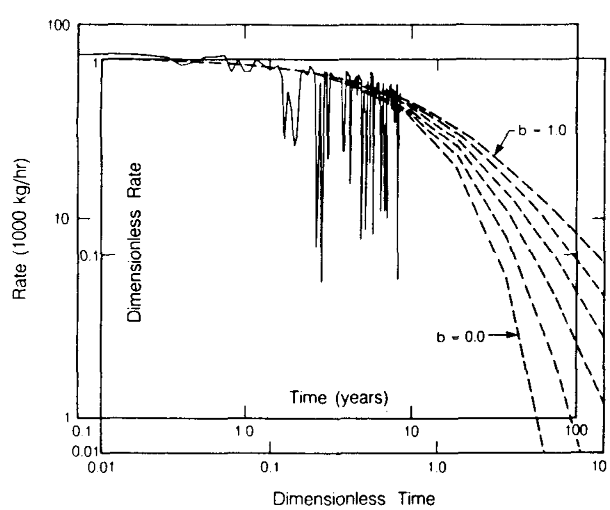

Figure 2. Flow rate decline type curve match for a well located on the Sulphur Bank lease.

Any extrapolations of flow rates, however, are valid only as long as operating conditions remain constant. Figure 3 is a decline curve for a well on State Lands lease PRC 4596. The flow rate from this well exhibits a near-harmonic decline for the first 6 to 8 years of its production history, but then experiences a drastic change, with the decline rate becoming much slower. This behavior is shown by other wells in the immediate vicinity and is probably due to injection which was begun in that area just prior to the change in flow behavior. Figure 4 shows an opposite behavior for a well on State Lands lease PRC 4597. The flow rate for this well has a significant increase in decline rate after about 8 years of production, which is usually indicative of problems in the wellbore. However, because the change in decline rate for this well is rather small and many wells on this lease exhibit a similar change in their flow rates, this case may be due to a change in reservoir conditions. Several power plants have been brought on line over the past 6 years in the areas surrounding this lease, thus reducing the reservoir pressure and the available fluid recharge. It has been seen in other areas of The Geysers that there is an initial transition period with a rapid decrease in pressure when a new power plant is brought on line, but that eventually a psuedo-equilibrium is reached with the available recharge and the pressure declines at a much slower rate. Thus, when the areas around this lease are fully developed, the flow rates should resume a harmonic type decline, but at reduced rates.

Average Decline Curves

To investigate the effects of well spacing, average decline curves were computed for 40-, 10-, and 5-acre spacings. Production rates from 14 wells in SLC lease PRC 4597 and 16 wells in SLC lease PRC 4956 were combined to compute a decline

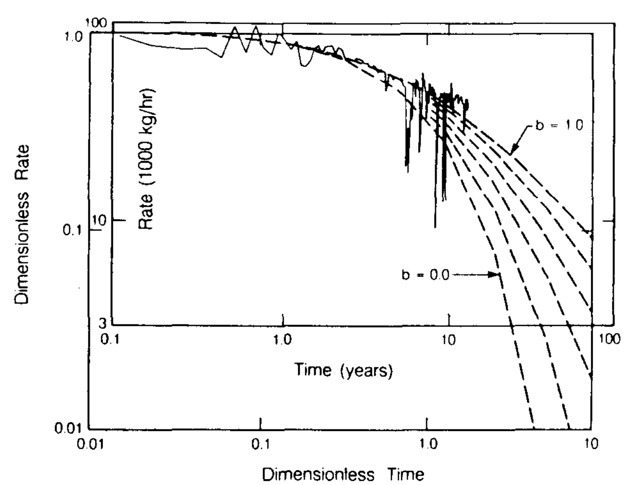

Figure 3. Flow rate decline type curve match for a well located on State lease PRC 4596.

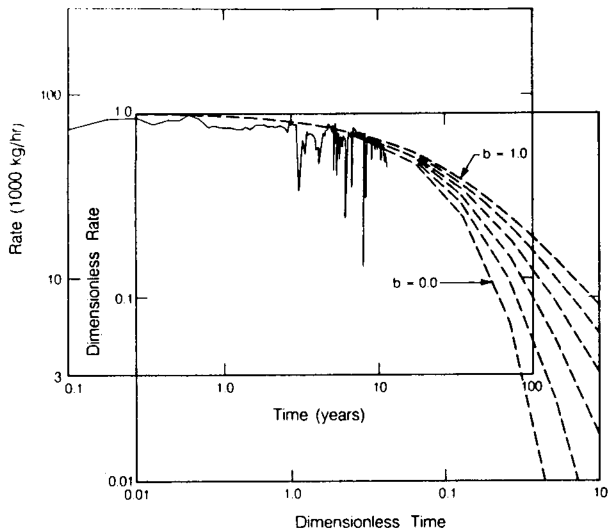

Figure 4. Flow rate decline type curve match for a well located on State lease PRC 4597.

curve for 40-acre spacing. Rates from 23 wells from the Sulphur Bank lease and 10 wells from the Happy Jack lease were used to compute a curve for 5-acre spacing, and 9 wells from the Rorabaugh lease were used to compute a curve for 10-acre spacing. The Rorabaugh wells had production histories of 5 to 7 years , while the rest of the wells had been flowing for at least 7 years. Production data for all the wells were included only up to the time that infill drilling significantly changed the well spacing.

The averaged, normalized decline curves for the five leases are plotted in Figure 5 and the combined values for 40-, 10-, and 5-acre spacing are summarized in Table 1. The leases with 40- and 5-acre spacings behave as expected, with production declining to 50 percent in approximately 8 years for the wells with 5-acre spacing, and 12 years for the wells with 40-acre spacing. However, the wells in the Rorabough lease with 10-acre spacing show a more rapid production rate decline. Several reasons could account for this. The Rorabaugh lease is in the far western edge of the developed field and is bordered to the east by older producing leases such as Sulphur Bank, Happy Jack, and Thermal, and bounded to the west by the edge of the field. This could limit the amount of recharge available to the Rorabaugh wells, decrease the static reservoir pressure and increase the rate at which their production declines. Thus, the flowrate decline in the Rorabaugh lease illustrates the importance of accounting for location with respect to the field boundaries and other producing areas.

A comparison of Budd's, Dykstra's, and our curves is presented in Figure 6. Our 5-acre curve is very similar to Dykstra's curve, which is to be expected, since his curve is primarily based on wells in densely drilled areas. Budd's curves exhibit a much greater dependence on well spacing than is indicated by our data. The dependence of the flow rate decline on well spacing may be smaller than expected because of the significant and rapid communication that exists within the reservoir due to its extensive fracture network. This communication may also be seen in pressure maps of The Geysers reservoir (Lipman, 1977), showing reduced pressures in areas distant from regions with significant production.

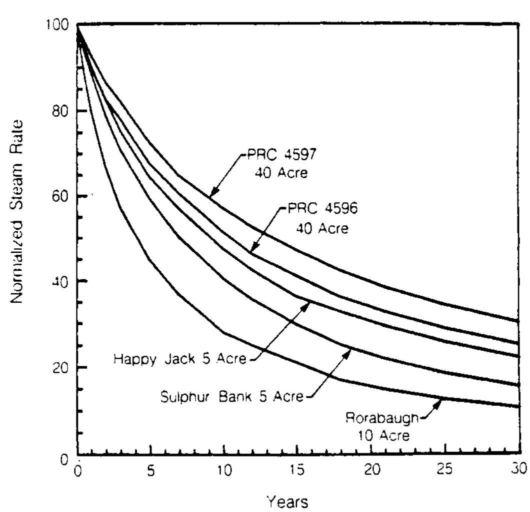

Figure 5. Normalized flow rate decline curves for leases with 5, 10, and 40 acre spacing.

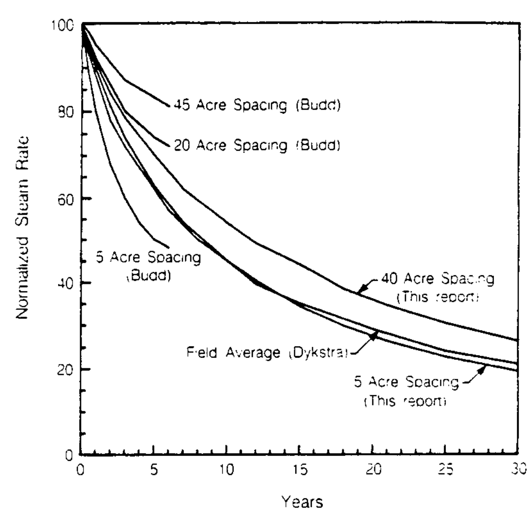

Figure 6. Comparison of normalized flow rate decline curves from Budd (1972), Dykstra (1981), and this report.

Table 1.
Normalized production rates for three different well spacings.

Number of Years	Well Spacing 40-acre	10-acre	5-acre
0.0	100.0	100.0	100.0
1.0	92.5	80.2	89.7
5.0	70.7	43.9	62.6
8.0	59.6	32.4	50.5
12.0	49.1	23.8	39.8
20.0	35.7	15.4	27.4
30.0	26.2	10.5	19.3

CONCLUSIONS

A preliminary investigation of flow rate behavior for wells from The Geysers field has been presented. Steam rates from production wells at The Geysers vary from 30,000 to over 300,000 lbs/hour, with a typical well producing at a rate of about 150,000 lbs/hour. The flow rate decline in these production wells depends on many factors including reservoir heterogeneities (primarily matrix permeability and fracture spacing), well density, and well location with respect to field boundaries and major producing areas. The flow rate decline is usually near-harmonic and a minimum production history of 5 years is required to determine an accurate value for b. On the average, the flow rate declines by 50% in 8 and 12 years for wells with 5- and 40-acre spacing, respectively. This somewhat small dependence on well spacing is explained by the high fracture permeabilities and the resulting near uniform pressure decline over large areas.

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