Proceedings World Geothermal Congress 2000
Kyushu - Tohoku, Japan, May 28 - June 10, 2000

AN INVESTIGATION OF PRODUCTIVITY AND PRESSURE DECLINE TRENDS IN GEOTHERMAL STEAM RESERVOIRS

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Key Words: steam reservoir, pressure decline, productivity decline, The Geysers

ABSTRACT

This paper derives the relation between productivity and pressure decline trends in a geothermal steam reservoir. At all stages of a geothermal project, the economics is affected by the rate of productivity decline. The rate of pressure decline becomes a critical issue when the reservoir pressure declines to the point that wells have to be flowed wide open to supply the turbine; at that stage, maintaining reservoir pressure and well productivity by redistribution and/or augmentation of injection becomes a strategic issue in field management. Therefore, the issues considered in this paper have significant practical implications.

The decline rate (*D*) in the productivity of a steam well (normalized for a constant flowing wellhead pressure) and the decline rate in static wellhead pressure is shown to be related by a simple equation derived from standard the gas deliverability equation. The application of this equation is verified against the productivity and pressure decline data from wells at The Geysers steam field in California. Wells in steam reservoirs usually show harmonic decline in productivity (that is, the decline rate in productivity declines with time). Another simple equation has been derived relating the initial harmonic decline rate of a steam well and the decline rate in static wellhead pressure at any time. It is further shown that if the productivity decline rate is constant over a period, a plot of the difference between the squares of the static wellhead pressure and the normalizing pressure on log scale versus time yields a linear trend over the period, the slope of the trend being equal to *D/n*, where *n* is the "turbulence factor" of the well (between 0.5 and 1.0). This equation is verified against data from steam wells at The Geysers.

Estimating the productivity decline rate from the static wellhead pressure decline rate using the above approach avoids the need for normalizing the production history of the well and is independent of the productivity index of the well or wells involved.

1. THE RELATION BETWEEN PRODUCTIVITY AND PRESSURE DECLINE TRENDS

1.1 Derivation of the Relation

The conventional gas deliverability equation relates the production rate and the wellhead pressure of a well as follows:

$$W = C\,(p_s^2 - p^2)^n \qquad (1)$$

where W = production rate,
p_s = static wellhead pressure,
p = flowing wellhead pressure,
n = the "turbulence" factor (a dimensionless number between 0.5 to 1.0).
C = an empirical constant unique to a well and nearly independent of time (Sanyal *et al.*, 1989). This parameter is a steam well's prductivity index.

The definition of a well's productivity decline rate (*D*) is :

$$D = -\frac{1}{W}\frac{dW}{dt} \qquad (2)$$

where t represents time.

Combining equation (1) and (2), and differentiating,

$$D = \left(\frac{2n}{p_s^2 - p^2}\right)\left(p_s\frac{dp_s}{dt} - p\frac{dp}{dt}\right) \qquad (3)$$

The decline rate D of a well is calculated by normalizing the well's productivity decline with respect to a fixed wellhead pressure; therefore,

$$\frac{dp}{dt} = 0 \qquad (4)$$

Hence,

$$D = \left(\frac{2np_s}{p_s^2 - p^2}\right)\frac{dp_s}{dt} \qquad (5)$$

The above equation implies a constant decline rate (*D*), that is, the decline trend is exponential, being given by:

$$W = W_i e^{-Dt}, \qquad (6)$$

which is a solution of (2). However, geothermal wells usually decline in productivity harmonically rather than exponentially. The harmonic decline trend implies that the decline rate itself declines with time as follows:

$$D = \frac{1}{W}\frac{dW}{dt} = b \cdot W \qquad (7)$$

where b is a constant. As production continues, the decline rate declines from its initial value of D_i. From (7),

$$D_i = \frac{Wi}{W} \cdot D \qquad (8)$$

where W_i is the initial production rate and D_i is the initial harmonic decline rate.

From (1) and (8),

$$D_i = \left(\frac{p_{si}^2 - p^2}{p_s^2 - p^2}\right)^n \cdot D \qquad (9)$$

Therefore, from (5) and (9), we get:

$$D_i = \left(\frac{2np_s}{p_s^2 - p^2}\right)\frac{dp_s}{dt}\left(\frac{p_{si}^2 - p^2}{p_s^2 - p^2}\right)^n \qquad (10)$$

Therefore, if the productivity decline trend is harmonic, the initial harmonic decline rate can be calculated from an estimate of p_s and dp_s/dt at any time.

1.2 Examples

Figure 1 is a plot of the averaged static downhole reservoir pressure (P_{sr}) versus time for the Unit 13 and 16 areas of The Geysers steam field in California; this figure averages the static pressure history of a total of about 50 wells that supply the two power plants (with a total installed capacity of 245 MW). From figure 1 one can estimate the values of the static pressure (p_s) versus time using the relation between p_s and the static downhole pressure for a gas well:

$$\ln\left(\frac{p_{sr}}{p_s}\right) = 6.47 \times 10^{-4}\, M \int_0^D \frac{dh}{zT} \qquad (11)$$

where M = molecular weight,
h = depth from the wellhead (ft),
D = total well depth (ft),
z = real gas deviation factor, and
T = temperature (ER).

Using figure 1 and equations (5) and (11), one can then calculate the trend in well productivity decline with time. The productivity decline trend we have thus calculated is shown in figure 2. For simplicity we have assumed the wellheads in this area to be 2,500 ft above mean sea level, which is the average wellhead elevation of the wells supplying the Unit 13 and Unit 16 plants. We have used a value of 1.0 for n in developing figure 2; we have found the assumption of n=1 to be generally valid for most wells in this part of The Geysers. In figure 2, the calculated decline rate is shown for a normalizing pressure of 100 psia as well as 153 psia; we have used various normalizing pressures at various times over the life of these plants. As the flowing wellhead pressure has declined over the years, the normalizing pressure has been reduced; the highest value (153 psia) was used in the late 1980's.

As figure 2 shows, the normalizing pressure chosen had little impact on the calculated decline rates until 1987. In fact, normalizing production rates for decline curve analysis was not in vogue until the late 1980's; the first systematic approach to normalized decline curve analysis for steam wells was published only in 1989 (Sanyal, et al., 1989). Following the peak decline rates of 1988 at The Geysers steam field, the difference between the decline rates calculated for normalizing pressures of 100 psia and 153 psia has increased progressively, as to be expected. Figure 2 also shows the averaged observed decline rates of wells supplying Unit 13 (solid circles) and Unit 16 (solid squares), as estimated at various times in the past.

Given that the estimation of the decline rate of a well is inaccurate at best, let alone estimation of the average decline trend of a group of wells, the observed decline rates generally agree with those calculated. With a better smoothing of the pressure data and better estimation of the average productivity decline trend, a better match between the calculated and observed decline trends should be achievable.

2. ANOTHER RELATION BETWEEN WELL PRODUCTIVITY AND WELLHEAD PRESSURE DECLINE

2.1 Derivation of the Relation

Integrating both sides of (5), we get

$$\int_{p_{si}}^{p_s} \frac{d(p_s^2)}{p_s^2 - p^2} = -\frac{D}{n}\int_o^t dt \qquad (12)$$

or,

$$\ln\left(\frac{p_s^2 - p^2}{p_{si}^2 - p^2}\right) = \frac{D}{n}\cdot t \qquad (13)$$

or,

$$\ln\left(p_s^2 - p^2\right) = \ln(p_{si}^2 - p^2) - \frac{D}{n}\cdot t \qquad (14)$$

Equation (14), which can also be derived from equations (1) and (6), indicates that a plot of $\ln(p_s^2 - p^2)$ should be linear with a slope equal to $-D/n$. Therefore, one should be able to estimate the decline rate of a well (normalized to a flowing wellhead pressure of p) from a semi-logarithmic plot of $(p_s^2 - p^2)$ versus time.

By integrating (7) one can show that:

$$D = \frac{W}{W_i}\cdot D_i = \frac{D_i}{1 + D_i t} \qquad (15)$$

Substituting (15) in (5) and integrating both sides, we get:

$$\int_{p_{si}}^{p_s} \frac{d(p_s^2)}{p_s^2 - p^2} = -\frac{1}{n}\int_o^t \frac{D_i}{1 + D_i t}dt \qquad (16)$$

or,

$$\ln\left(\frac{p_s^2 - p^2}{p_{si}^2 - p^2}\right) = -\frac{1}{n}\cdot \ln(1 + D_i t) \qquad (17)$$

or,

$$\left(\frac{p_{si}^2 - p^2}{p_s^2 - p^2}\right)^n = 1 + D_i t \qquad (18)$$

or,

$$D_i = \frac{1}{t}\left[\left(\frac{p_{si}^2 - p^2}{p_s^2 - p^2}\right)^n - 1\right] \qquad (19)$$

The above equation shows that if the decline rate is harmonic, a semilogarithmic plot of $(p_s^2 - p^2)$ versus t will not be linear. However, as the harmonic decline trend can be represented as a succession of exponential decline trends with decreasing decline rates, on a semilogarithmic plot of $(p_s^2 - p^2)$ versus time, one can define linear segments or draw tangents to estimate the decline rate at various times.

2.2 Examples

Figure 3 is a plot of the flow rate history (normalized at 100 psia wellhead pressure) of a well (well GDC-10) at The Geysers field. The plot presents the flow rate on a logarithmic scale to allow deciphering of any exponential decline trends. Figure 3 shows that between 1980 and 1986, the well showed a nearly constant decline rate of about 9% per year. From 1986 to 1990, the well had a clearly accelerated decline rate of about 23% per year. Finally, after 1990, it slowed down to 1.2%. This acceleration in well productivity decline at The Geysers field between 1986 and 1990 was seen in nearly all wells (as was the case for Units 13 and 16 mentioned earlier) due to a sudden increase in generation capacity (from 900 to 1900 MW) within two years (1985-87). After 1990, the decline rate eased because of major cutbacks in generation and augmentation of injection throughout The Geysers.

Figure 4 shows the static wellhead pressure (p_s) history of the same well (GDC-10) for the same period. Although there were some observed static wellhead pressure values for this well (indicated on figure 4), most of the p_s values in the figure are calculated (for n values of both 0.5 and 1.0) using the methodology of Sanyal, et al (1989). Figure 5 is a plot of (ps^2-100^2) versus time based on data from figure 4. It is clear from figure 5 that the plot shows a slope of about 9 during 1980 and 1986, about 23 during 1986 to 1990 and about 1.2 after 1990. Therefore, assessing an n value of unity, figure 5 implies a decline rate in well productivity of 9% per year during 1980-1986, 23% per year during 1986-1990 and 1.2% per year after 1990, as verified from actual flow rate data in figure 3.

A further example of this approach is presented from the history of a well (Curry 85-13) from the margin of the exploited part of The Geysers field. This well is at the margin of the field and far from the areas where additional plants were installed during 1985-87, causing the precipitous decline in well productivity seen in the previous examples of Unit 13 and 16 wells and well GDC-10. Therefore, well Curry 85-13 did not show any steepening of static pressure decline after 1986. Figure 6 shows the static wellhead pressure history of this well over a 30-year period.

Well Curry 85-13 has been kept shut in for 30 years as an observation well except for very short production episodes in 1968 and in 1979 (the sudden lowering of wellhead pressure in 1979 shown in figure 6 is due to such production). Figure 7 is a plot of (ps^2-100^2) on log scale versus time for this well; it shows an unbroken linear trend with a slope of –5.5 over the entire 30 years. Therefore, this implies that a production well in the vicinity of 85-13 would have declined in production at a rate of 5.5% per year between 1968 and 1998. The productivity decline rate in this part of the field was indeed of this magnitude from 1968 until 1985. While the decline rate accelerated in the other parts of the field starting in 1986 because of over development, the area near Curry 85-13 did not experience an acceleration in productivity decline presumably because of its location at the field margin and far from the areas of additional developments.

3 PRACTICAL APPLICATIONS

The methods presented here provide quick ways to derive the decline trend in normalized productivity from the decline trend in the static wellhead pressure. Normalizing well production histories is more involved than estimating the static wellhead pressure history, either from well pressure build-up records during plant downtime or calculated from the production history data, as proposed in Sanyal *et al.* (1989). Once the p_s history is available, either equation (5) or the semilogarithmic plotting approach could be used.

To facilitate quick estimates, figure 8 provides a family of graphs calculated from equation (5) assuming n is unity. If the current pressure decline rate and the static wellhead pressure of a well is known, its current decline rate is easily read from figure 8. This is a simple and quick way to monitor a well's normalized flow rate decline rate in spite of the apparent fluctuations in the flowing wellhead pressure that masks the true trend in flow rate decline. Alternatively, the decline rate can be estimated from semilogarithmical plotting. The advantage of the methods proposed in this paper is that they are independent of a well's productivity index (C). Although a value of unity is usually assured for *n*, in some cases an *n* value of as low as 0.75 may be required, if the deliverability test data of the wells so indicates.

Another example of the quick reference value of this methodology is given below from the 80 MW Calistoga project area at The Geysers. Figure 9 shows the average production rate history (normalized to a flowing wellhead pressure of 85 psia) of 32 wells from this project during the period 1986-1995. During this period the productivity decline rate was nearly constant at 15% per year (as shown by the linear trend on the semilogarithmic plot of figure 9). During 1986-1995, the average p_s fell from 400 to 180 psia. From figure 8 it is seen that for a 15% decline rate in well productivity one would expect a change in p_s decline rate from 28 to about 10 psi per year. However, figure 8 was prepared assuming n=1. In the Calistoga area, well deliverability data indicate an n value of about 0.75 to be more appropriate. Therefore, a 15% decline trend in well productivity in htat area should be represented by the 15% / 0.75 or 20% decline line in figure 8. Therefore, the decline trend in p_s should have changed from 37 psi per year to 13 psi per year during 1989-1995; the field data from the Calistoga wells verify this to have been the case.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge Calpine Corporation's permission to publish this work, and thank Dr. Marcelo Lippmann of Lawrence Berkeley National Laboratory for providing a very useful review of this paper.

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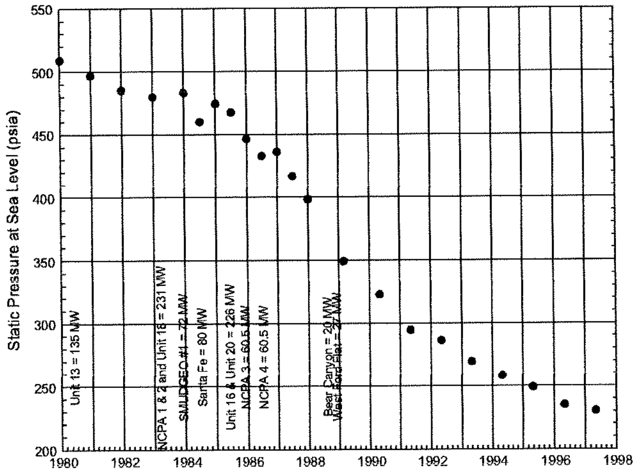

Figure 1. Static pressure history in the Unit 13 and 16 areas

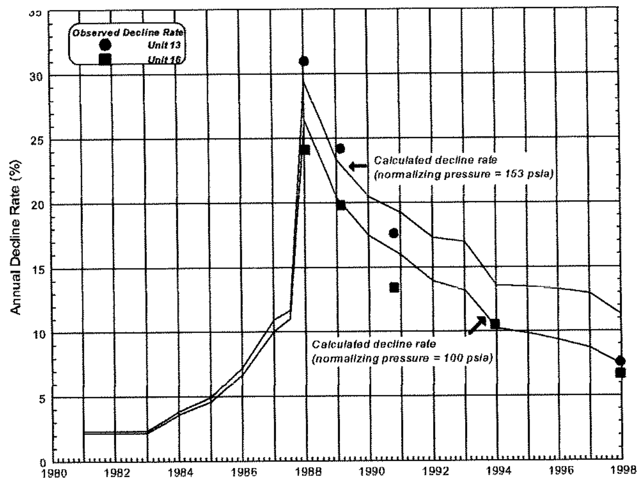

Figure 2. Annual decline rate vs. time in the Unit 13 and 16 areas

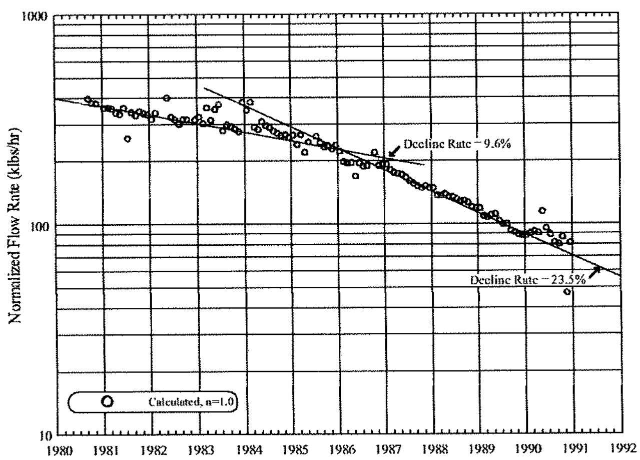

Figure 3. Log normalized flow rate vs. time, well GDC-10

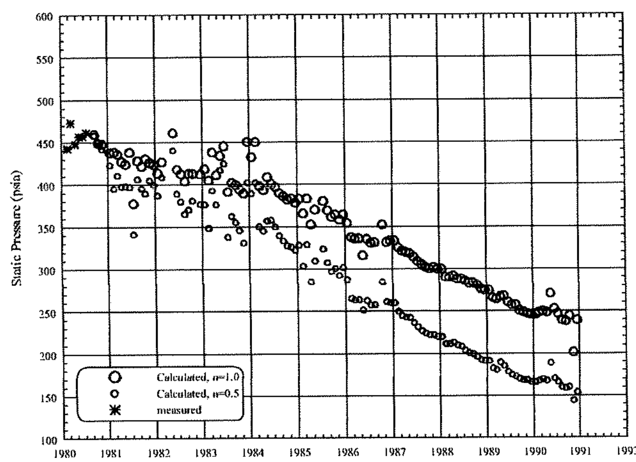

Figure 4. Changes in static pressure vs. time, well GDC-10

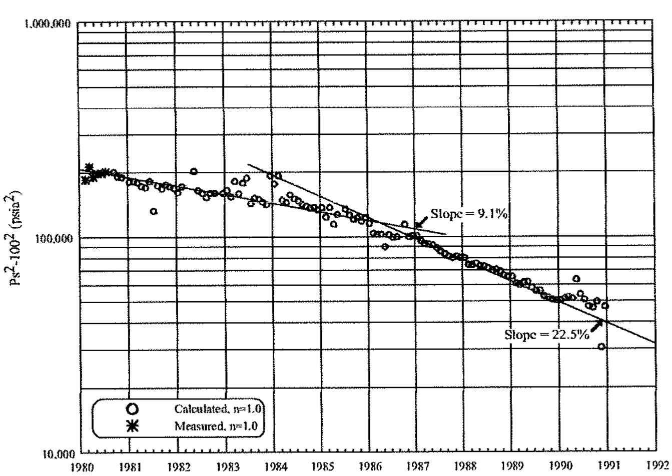

Figure 5. Log (Ps^2-100^2) vs. time, well GDC-10

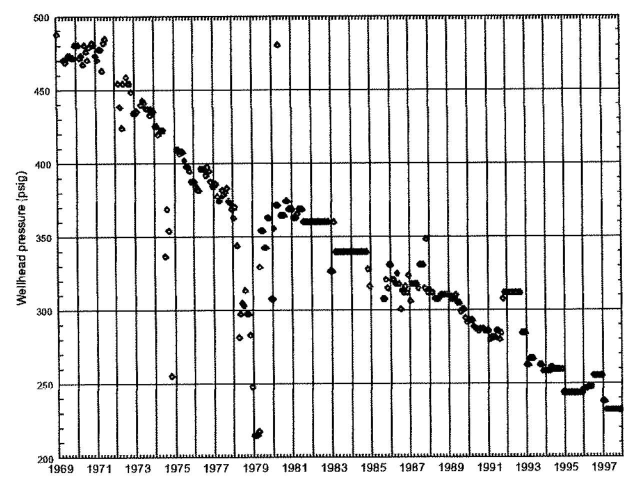

Figure 6. Wellhead pressure vs. time, well Curry 85-13

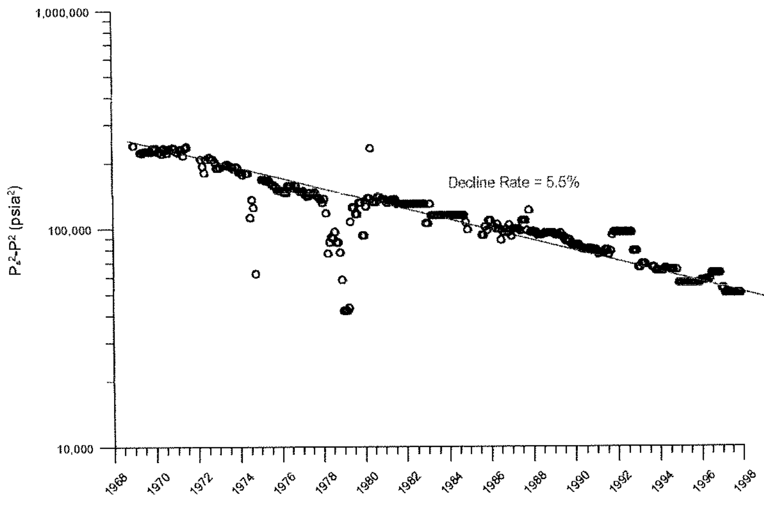

Figure 7. Semilog plot of (p_s^2 - p^2) versus time, well Curry 85-13

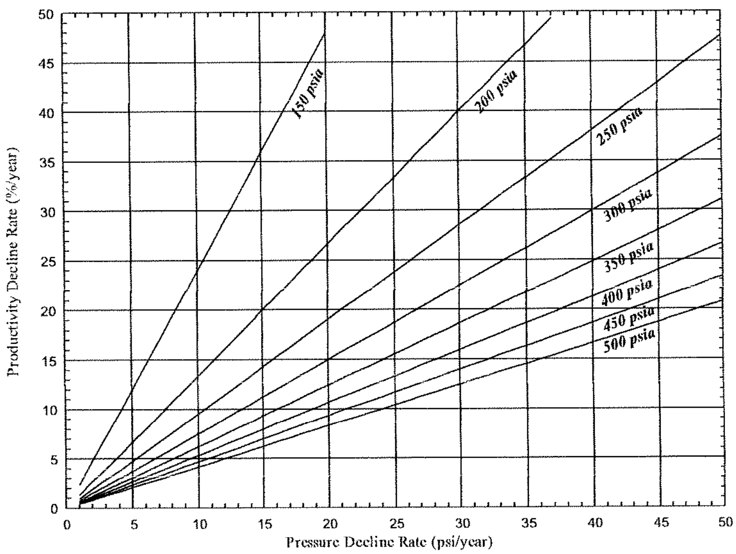

Figure 8. Pressure decline rate versus productivity decline rate

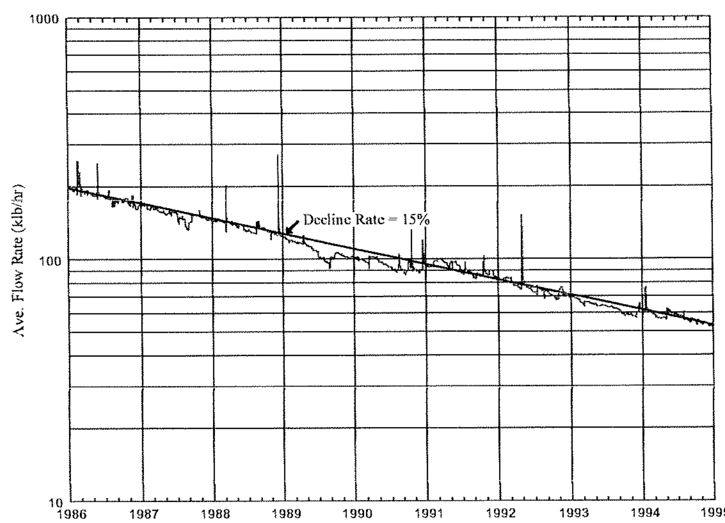

Figure 9. Semi-log plot of average daily flow rates versus time, Calistoga area