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A SYSTEMATIC APPROACH TO DECLINE CURVE ANALYSIS FOR THE GEYSERS STEAM FIELD, CALIFORNIA

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ABSTRACT

A methodology is derived for calculating the static pressure normalized flow rate histories of wells from the usual production records kept by operators, namely, flow rate and flowing wellhead pressure as functions of time. Then, a generalized approach is developed for analyzing the flow rate decline trend to estimate the future decline in well productivity, make-up well requirement, remaining reserves, and well life. The authors have observed, based on data from several hundred wells, that the usual decline trend at The Geysers is "harmonic" with occasional episodes of "exponential" decline in response to new power plants coming on line. In the approach presented here, two decline curves are prepared for each well: flow rate versus cumulative production and the logarithm of flow rate versus cumulative production; the former plot shows a linear data trend if the decline trend is exponential and the latter if the decline trend is harmonic. The authors have observed from well histories as well as numerical simulation that forecasting based on either a linear p/z trend with cumulative production or an assumed exponential decline is conservative, while forecasting based on a harmonic decline trend is optimistic. Because of data scatter or too short a history, in many cases the flow rate decline trend of a well may be fitted to either exponential or harmonic equation; in such cases the lower and upper limits of the decline trend can be established.

INTRODUCTION

The term "decline curve analysis" is used in the petroleum industry to describe graphical projection of the flow rate decline trend of a well into the future, and, from that projection, estimation of the remaining reserves and well life (Hughes, 1967). Such projection is based on visual curve fitting of the data and does not involve any trial-and-error process, such as history matching by reservoir simulation. In this paper, the term "decline curve analysis" is used to describe empirical projection of both flow rate and pressure trends.

There are two common approaches to decline curve analysis at The Geysers steam field in California:

1. <u>p/z versus cumulative production plotting</u>. This method is derived from natural gas engineering practices and consists of plotting "p/z" (the ratio of the static reservoir pressure to the "gas deviation factor") against the cumulative mass production from the reservoir (Hughes, 1967). Such a plot should exhibit a linear trend if the following are true: (1) the reservoir is bounded; (2) there is no natural recharge or injection; and (3) the reservoir contains only a gas phase. One can extrapolate such a linear trend to the abandonment pressure level to estimate the recoverable reserves of steam. None of the above conditions is completely satisfied at The Geysers. Since the leasehold dedicated to a particular power plant is not hydrologically isolated from the surrounding leases, the first condition is not satisfied for p/z versus cumulative production plots based on a specific leasehold. The second condition is not valid, for there may be natural recharge and/or injection. The third condition is not satisfied because water co-exists with steam in The Geysers reservoir.

There are 3 practical shortcomings in applying this method. First, it is difficult to estimate the average static reservoir pressure within a leasehold without shutting down the plant (or plants) within that leasehold for a long time; therefore, the static pressure (p) values used are approximate. Second, this method does not often yield a clear linear trend because of the theoretical limitations mentioned before and data scatter. Third, the estimated reserve is sensitive to the slope of the linear trend which cannot always be defined accurately. In spite of these shortcomings, the p/z method has become a standard practice at The Geysers for reserve estimation. Dee and Brigham (1985) presented a modified p/z versus cumulative production approach; it involves trial-and-error history matching and, therefore, is not a decline curve analysis method, and not discussed in this paper.

2. Decline of Flow Rate With Time.
(Hughes, 1967). The method is empirical and consists of plotting the production rate of a well as a function of time; the data may be plotted on either cartesian or logarithmic scale (Hughes, 1967). The usual goal of such plotting is to establish a linear trend through the data points; this trend can then be extrapolated to an abandonment production rate level to estimate either the life of a production well or the cumulative production to be derived from it. Alternately, such a plot may be used for "type curve matching" (Fetkovitch, 1973), rather than establishing a linear trend, to project the decline trend into the future.

The flow-rate decline curve analysis method is a standard practice at The Geysers for well behavior forecasting, identifying wells that may need workover and formulating make-up well drilling programs.

Decline curve analysis requires a continuous history of static pressure and/or flow rate (at a constant flowing wellhead pressure). Such histories are not readily available for the following reasons:

1. Static pressures are measured only occasionally, typically during power plant outages; therefore a continuous static pressure history is unavailable for most wells.

2. Wellhead pressure is usually not constant; therefore, the flow rate history does not directly reflect the true decline in productivity.

Based on our experience in analyzing pressure and production data from many parts of The Geysers we have developed the following procedure for defining the static pressure and flow rate histories of steam wells; this procedure has always proven effective.

ESTABLISHING THE STATIC PRESSURE HISTORY

The following empirical equation, adapted from gas well engineering practices (Energy Resources Conservation Board, 1975), is usually applied at The Geysers to relate the steam production rate (W) and the flowing wellhead pressure (p_f) of a steam well:

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

where: p = static wellhead pressure,
C = an empirical parameter, and
n = an empirical parameter, often known as the "turbulence factor", lying between 0.5 to 1.0.

As production continues from a well, p declines steadily; but in comparison to p, C declines slowly with time, while n remains nearly constant. One may calculate the static wellhead pressure (p) of a well at any time in its production history from (1) as follows:

$$p^2 = \left(\frac{W}{C}\right)^{1/n} + p_f^2 \qquad (2)$$

If we assume C to be nearly constant, we can replace C in (2) by the initial value of C given by

$$C_i = \frac{W_i}{(p_i^2 - p_{fi}^2)^n} \qquad (3)$$

where subscript 'i' denotes initial conditions. We estimate a statistically representative value of C_i, based on the first few weeks of production of a well, after discarding any flow rate data during those weeks that correspond to bleed rates rather than normal production rates.

Using (2) and (3) and assuming a value for n, we can calculate the static wellhead pressure as a function of time for any well. For example, figure 1 compares the measured and calculated static pressure histories of a typical well at The Geysers assuming both n=0.5 and n=1. The value of n may be estimated from a deliverability test or an isochronal test. It is often reasonable to conduct decline curve analysis using n=1. The assumption of n=1 rather than n=0.5 (or any other n value between 0.5 and 1) overestimates the p values; however, this overestimation is often acceptable because the assumption that C is constant causes a small underestimation of the p value, partly compensating for the overestimation due to assuming n=1. In figure 1, the p values calculated assuming n=1 are closer to the measured values.

The method of static pressure calculation proposed above allows continuous monitoring of the static wellhead pressure of a producing well; from this a p/z history can be calculated. For example, figure 2 presents the p/z versus cumulative production history of a typical well at The Geysers.

ESTABLISHING THE FLOW RATE HISTORY

Since the production rate data from a well correspond to various values of flowing wellhead pressure, it is difficult to decipher the true decline trend in well productivity without first normalizing the flow rates with respect to a standard p_f. The normalization can be accomplished by using equation (1) as follows:

$$W_n = \frac{(p^2 - p_{std}^2)^n}{(p^2 - p_f^2)^n} \cdot W \qquad (4)$$

where W_n = normalized production rate, and
P_{std} = a standard flowing wellhead pressure.

The p value here represents the true static pressure, calculated as described in the last section.

To facilitate comparison of the productivity decline trend of various wells, it is preferable to define a dimensionless normalized production rate, such as the ratio $W_n/W_{i,n}$, where $W_{i,n}$ is the normalized initial production rate. For example, figure 3 shows the ratio $W_n/W_{i,n}$ calculated for a typical well at The Geysers using both n=1 and n=0.5; in this case the assumption of the n value has little effect on the calculated value of $W_n/W_{i,n}$.

TYPES OF FLOW RATE DECLINE TRENDS

It is generally accepted that the flow rate per well declines at the Geysers typically with a "harmonic" trend (Dykstra, 1981; and Sanyal and Che, 1982), given by:

$$-\frac{1}{W}\cdot\frac{dW}{dt} = D(t) \qquad (5)$$

where t is the time (in years) and D(t) is the decline rate per year, which is a function of time. Harmonic decline trend in productivity, implies that the productivity decline rate at any instant is directly proportional to the productivity at that instant. That is,

$$D(t) = b\cdot W, \qquad (6)$$

where b is a constant. The initial harmonic decline rate, D_i, at The Geysers has ranged historically from 3% to 15% per year, but has reached up to 30% in the last few years.

While a harmonic decline trend in productivity is expected for all wells over their life, our experience at The Geysers indicates that during the first year or so of production, a well at The Geysers suffers exponential decline, the rate being typically 10% to 30%. Exponential decline is defined by (Hughes, 1967):

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

where D is the constant decline rate. It should be noted that some operators at The Geysers believe exponential decline to be the only trend observed in flow rate decline.

We have further observed that wells at The Geysers for which a harmonic trend has been established may exhibit, after the initial exponential decline period, transient episodes of exponential decline for several months at a time in response to the start-up of new plants within several miles.

By integrating (7), it can be shown that if the decline trend is exponential, one should get a linear data trend by plotting the logarithm of W versus time (the slope of the trend being equal to -D); this is the common method of decline curve analysis at The Geysers. As shown in the Appendix, a plot of flow rate versus cumulative production should also be linear (the slope being equal to $-D/W_i$), if the decline trend is exponential. If there is a harmonic decline trend, equations (5) and (6) can be used to estimate the initial decline rate (D_i) from the production history of a well. This is usually accomplished at The Geysers by using a type-curve, such as one in the family of curves shown on figure 4 for a range of D_i values. A plot of the calculated $W_n/W_{i,n}$ versus time can be overlain on a family of type-curves, a type-curve match obtained, and the value of D_i estimated. However, the plots such as figure 4 may not be amenable to type-curve analysis because of data scatter and/or the presence of multiple, alternate episodes of exponential and harmonic trends. Instead of type-curve matching, we prefer plotting log W versus cumulative production, which should be linear if the decline trend is harmonic, the slope being D_i/W_i (see Appendix).

A SYSTEMATIC APPROACH TO ANALYSIS OF FLOW RATE DECLINE TRENDS

For the general case of alternate exponential and harmonic episodes (schematically shown in figure 5) we have derived some general equations that can be used to estimate the decline rate in productivity at any time in a well's production life (see Appendix). In figure 5, the well shows exponential decline in rate from W_i to W_1 during the time 0 to t_1, then harmonic decline in rate from W_1 to W_2 during time t_1 to t_2, then exponential decline in rate from W_2 to W_3 from time t_2 to t_3, and so on. The initial decline rate is D_i. If M is the cumulative mass of steam produced up to a time t, the following general relations can be established (see Appendix).

During the last harmonic decline, the plot of W versus M should be linear, the slope (S_h) being:

$$S_h = -\frac{D_i}{W_i}\cdot\frac{W_i}{W_1}\cdot\frac{W_2}{W_3}\cdot\frac{W_4}{W_5}\cdots\frac{W_{n-1}}{W_n} \qquad (8)$$

where W_n is the last production rate before harmonic decline began and n is an odd integer.

Similarly, during the last exponential decline, a plot of log W versus M should be linear, the slope (S_e) being:

$$S_e = -\frac{D_i}{W_i}\cdot\frac{W_i}{W_1}\cdot\frac{W_2}{W_3}\cdot\frac{W_4}{W_5}\cdots W_n \qquad (9)$$

where W_n is the last production rate before exponential decline began and n is an even integer.

After the last exponential decline, well productivity will decline further as:

$$W = \frac{W_n}{1 - S_h W_n t}, \qquad (10)$$

where W_n = Last production rate before the harmonic decline phase began (n odd).

Under harmonic decline, the annual make-up well drilling will remain constant with time, and

Future Annual Well Requirement = $-N_o S_h W_n$, (11)

where N_o is the number of wells at the beginning of the harmonic decline phase.

$$\text{Also, Time to Abandonment} = \frac{1 - \frac{W_n}{W_a}}{S_h W_n}, \qquad (12)$$

where W_a is the lowest acceptable commercial rate.

During any exponential decline phase, the well productivity will decline as:

$$W = W_n e^{S_e t}, \qquad (13)$$

where W_n = Last production rate before the exponential phase began (n even).

Under exponential decline, the annual make-up well requirement increases with time. At time t after the beginning of the exponential phase,

$$\text{Future Well Requirement} = N_o e^{-S_e t} \qquad (14)$$

where N_o is the number of wells at the beginning of the exponential decline phase.

$$\text{Also, Time to Abandonment} = \frac{\ln\left(\frac{W_a}{W_n}\right)}{S_e}. \qquad (15)$$

The above approach can be used for flow rate forecasting during either the harmonic or the exponential decline phase of a well's history. Although the above method can not forecast when harmonic decline may resume following an exponential decline episode, the assumption that harmonic decline trend may never resume can still provide a conservative flow rate forecast.

EXAMPLES

Figures 6 through 8 present the log W versus t plot, W versus M plot and log W versus M plot, respectively, for a typical well at The Geysers for which the p/z versus cumulative production plot is shown in figure 2. These figures also indicate the linear trends chosen, projections of which to abandonment conditions (140 psig and 10,000 lbs per hour) yield the following results:

Plotting Method	Remaining Reserves (Million lbs)	Abandonment In Year
p/z vs. M	1,970	1991.7
Log W vs. t (exponential)	1,880	1993.1
W vs. M (exponential)	1,860	1993.0
Log W vs. M (harmonic)	2,470	1998.7
Type-curve (harmonic)	2,510	1998.8

In the above table, the results of fitting a harmonic decline trend appears more optimistic than the results from the other two methods. We have observed this to be the case in all wells. Comparing the results of decline curve analyses with the results of numerical reservoir simulation as well as actual well histories we have concluded that the true decline trend is closer to harmonic than exponential.

CONCLUSIONS

1. It is possible to calculate continuous static pressure and flow-rate decline histories of wells from conventional production records.

2. It is theoretically possible to conduct decline curve analysis for a series of alternate episodes of exponential and harmonic decline trends.

3. Assumption of an exponential decline trend in flow rate or a linear trend in p/z versus cumulative production underestimates reserves.

4. Assumption of a harmonic decline trend overestimates reserves.

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APPENDIX

Combining (5) and (6), rearranging and integrating,

$$b\int_0^t dt = -\int_{W_i}^{W} \frac{dW}{W^2} \qquad \text{(A1)}$$

$$\text{or, } bt = \frac{1}{W} - \frac{1}{W_i} \qquad \text{(A2)}$$

Rearranging (A2) and noting that $D_i = bW_i$,

$$W = \frac{W_i}{1 + D_i t} \qquad \text{(A3)}$$

Equation (A3) describes harmonic decline.

Integrating (7) in a similar way,

$$W = W_i e^{-Dt} \qquad \text{(A4)}$$

Equation (A4) describes exponential decline.

For the general case shown in figure 5 equations (A3) and (A4) can be utilized as follows. During the harmonic decline episode starting at time t_n when the production rate is W_n, the cumulative production is given by (n being odd):

$$M = \int_0^{t_1} W_i e^{-D_i t} + \int_{t1}^{t_2} \frac{W_1}{1 + D_1(t_2 - t_1)} dt + \int_{t_2}^{t_3} W_2 e^{-D_2 t}\, dt + \int_{t_3}^{t_4} \frac{W_3}{1 + D_3(t_4 - t_3)} + \ldots + \int_{t_{n-1}}^{t_n} W_{n-1} e^{-D_{n-1} t}\, dt + \int_{t_n}^{t} \frac{W_n}{1 + D_n(t - t_n)} dt \qquad \text{(A5)}$$

It can be shown that in (A5),

$$D_1 = D_i \qquad \text{(A6)}$$

$$D_2 = D_i \cdot \frac{W_2}{W_1} \qquad \text{(A7)}$$

$$D_3 = D_2 \qquad \text{(A8)}$$

$$\vdots$$

$$D_{n-1} = D_i \cdot \frac{W_2}{W_1} \cdot \frac{W_4}{W_3} \cdots \frac{W_{n-1}}{W_{n-2}} \qquad \text{(A9)}$$

$$D_n = D_{n-1} \qquad \text{(A10)}$$

Integrations in (A5) can be completed by substitution of relations (A6) through (A10). It should be noted that only the last integral in (A5) is a function of an arbitrary time t, the other integrals being constant. Therefore, to understand the decline behavior for $t > t_5$, it is sufficient to complete the last integral in (A5), which gives:

$$M = A + \frac{W_n}{D_n} \ln\,[1 + D_n(t - t_n)] \qquad \text{(A11)}$$

$$= A + \frac{W_n}{D_n} \ln\left(\frac{W_n}{W}\right)\text{[using (A3)]}, \qquad \text{(A12)}$$

where A is a constant, being dependent on the decline history of the well up to time t_5 only.

Rearranging (A12),

$$\ln W = B - \frac{D_n}{W_n} \cdot M, \qquad \text{(A13)}$$

where B is another constant dependent only on the decline history of the well up to time t_5. Therefore, for $t > t_5$, a plot of ln W versus M should be linear, the slope being

$$S_h = -\frac{D_n}{W_n} \qquad \text{(A14)}$$

$$\text{or, } D_n = -S_h W_n \qquad \text{(A15)}$$

Substituting (A9) and (A10) in (A14) and rearranging,

$$S_h = -\frac{D_i}{W_i} \cdot \frac{W_i}{W_1} \cdot \frac{W_2}{W_2} \cdot \frac{W_4}{W_3} \cdots \frac{W_{n-1}}{W_n} \qquad \text{(A16)}$$

If W_a is the abandonment flow rate, and t_a is the abandonment time, from (A3),

$$t_a = \frac{\frac{W_n}{W_a} - 1}{D_n} \qquad \text{(A17)}$$

From (A14) and (A17),

$$t_a = \frac{1 - \frac{W_n}{W_a}}{S_h W_n} \qquad \text{(A18)}$$

If N_o is the number of wells required to supply a plant at the beginning of the harmonic decline phase, the well requirement at any time t after the start of the harmonic decline phase will be given by

$$N = \frac{N_o W_n}{W} \qquad \text{(A19)}$$

or, $$N = N_o(1 + D_n t) \qquad \text{(A20)}$$

Equation (A20) shows that during harmonic decline, the annual makeup well requirement remains constant, being equal to $N_o D_n$ or, $-N_o S_h \cdot W_n$.

Similar equations can be developed for an exponential decline phase. For an exponential episode starting at time t_n (n is even), it can be shown that:

$$M = C - \frac{W_n}{D_n}\left[e^{-D_n(t-t_n)} - 1\right], \qquad \text{(A21)}$$

where C is a constant, being dependent on the decline history up to time t_n only.

From (A21),

$$M = C - \frac{W_n}{D_n}\left[\frac{W}{W_n} - 1\right]. \qquad \text{(A22)}$$

Rearranging (A22),

$$W = E - D_n \cdot M, \qquad \text{(A23)}$$

Where E is another constant dependent on the decline history up to time t_n only.

Therefore, a plot of W versus M should be constant during an exponential decline phase, the slope being

$$Se = -D_n \qquad \text{(A24)}$$

or, $$Se = -D_i \cdot \frac{W_2}{W_1} \cdot \frac{W_4}{W_3} \cdots \frac{W_n}{W_{n-1}} \qquad \text{(A25)}$$

Rearranging (A25),

$$S_e = \frac{D_i}{W_i} \cdot \frac{W_i}{W_1} \cdot \frac{W_2}{W_3} \cdot \frac{W_4}{W_5} \cdots \frac{W_{n-2}}{W_{n-1}} \qquad \text{(A26)}$$

From (A4),

$$W_a = W_n e^{-D_n t_a} \qquad \text{(A27)}$$

From (A27),

$$t_a = \frac{\ln\left(\frac{W_a}{W_n}\right)}{-D_n} = \frac{\ln\left(\frac{W_a}{W_n}\right)}{S_e} \qquad \text{(A28)}$$

From (A19),

$$N = \frac{N_o W_n}{W_n e^{-D_n t}} \qquad \text{(A29)}$$

or, $$N = N_o e^{D_n t} \qquad \text{(A30)}$$

Equation (A30) shows that the annual makeup well drilling requirement will increase continuously under exponential decline.

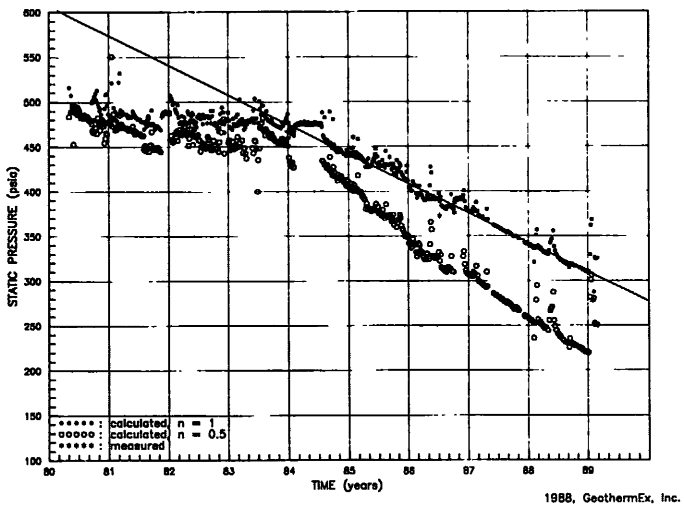

Figure 1. Calculated and measured p_s vs. time

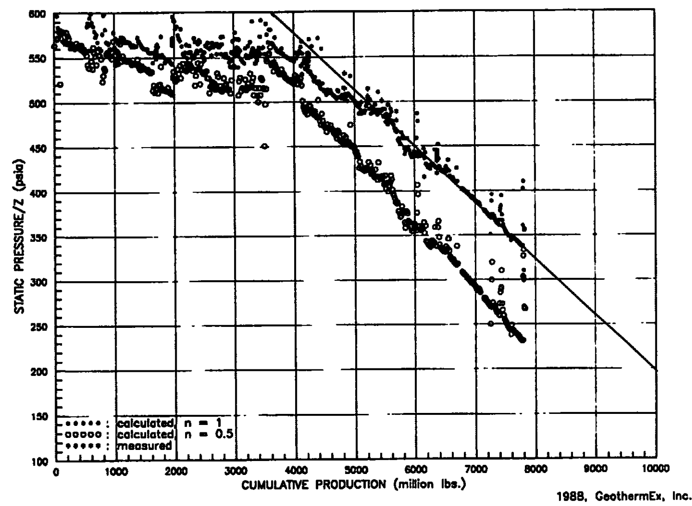

Figure 2. Plot of p/Z vs. cumulative production

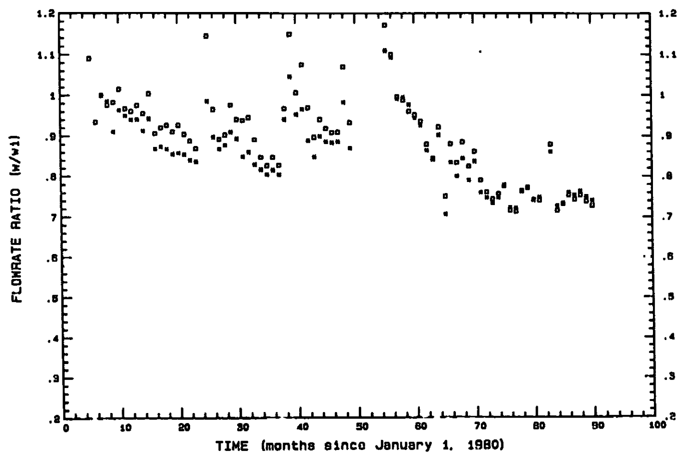

Figure 3. Plot of flowrate vs. time

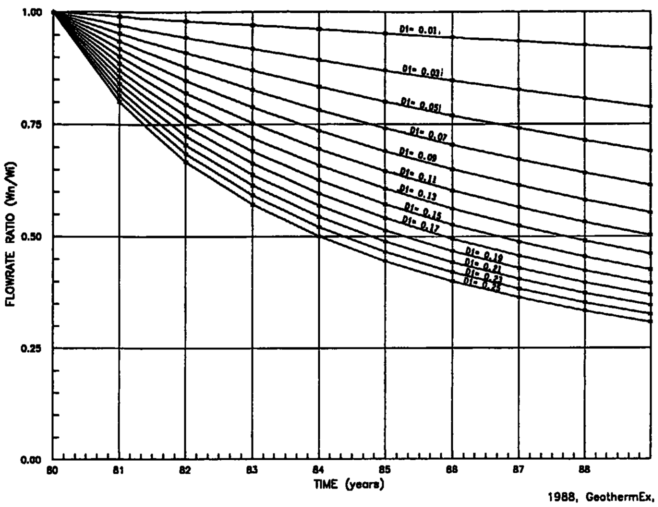

Figure 4. Harmonic productivity decline curves

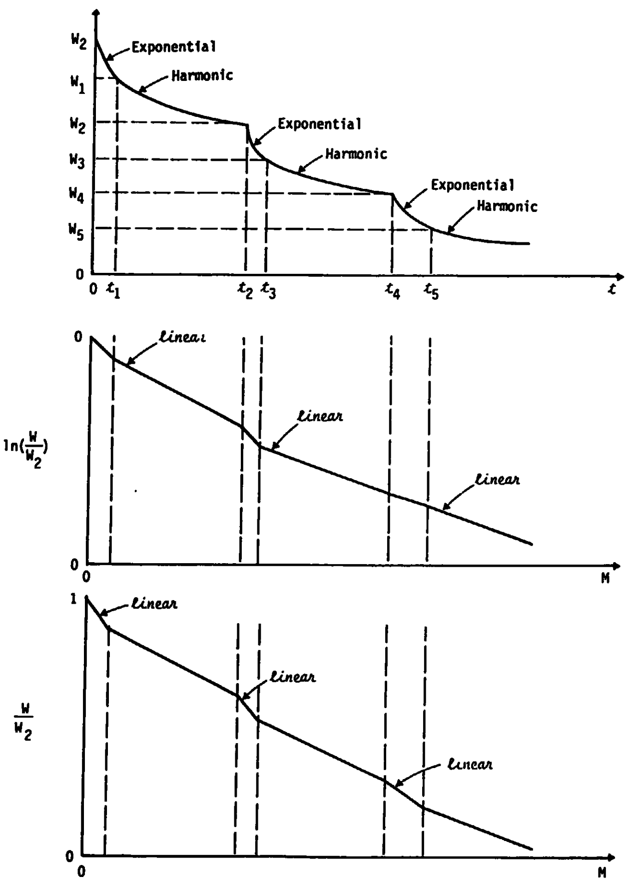

Figure 5. Schematic presentation of decline trends

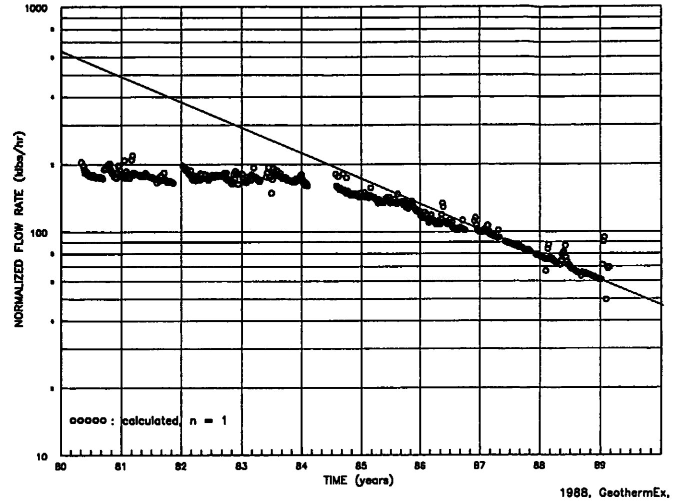

Figure 6. Plot of log W vs. time

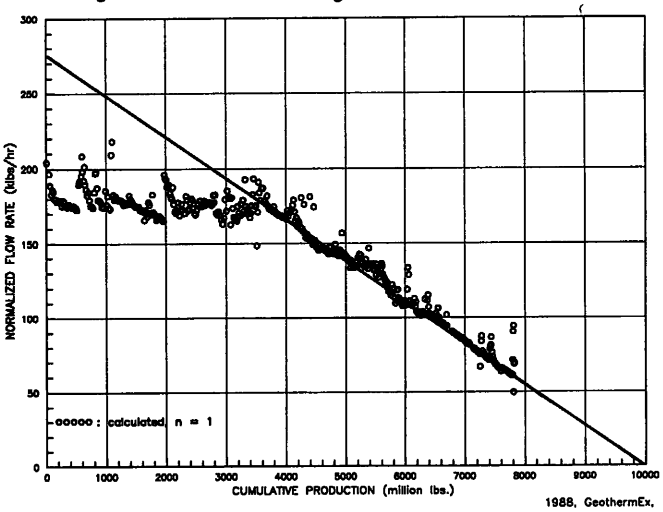

Figure 7. Plot of W vs. M

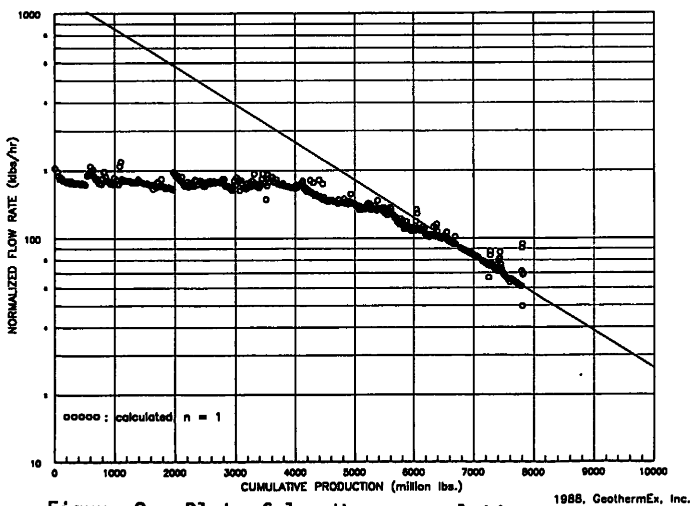

Figure 8. Plot of log W vs. cumulative production