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Permeability-Thickness Determination from Transient Production Response at the Southeast Geysers

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Abstract

The Fetkovich production decline curve analysis method was extended for application to vapor-dominated geothermal reservoirs for the purpose of estimating the permeability-thickness product (kh) from the transient production response. The analytic dimensionless terms for pressure, production rate, decline rate, and decline time were derived for saturated steam using the real gas potential and customary geothermal production units of pounds-mass per hour. The derived terms were numerically validated using "Geysers-like" reservoir properties at initial water saturation of 0 and at permeabilities of 1, 10, and 100 mD. The production data for 48 wells in the Southeast Geysers were analyzed and the permeability-thickness products determined from the transient production response using the Fetkovich production decline type curve. The kh results were in very good agreement with the published range at the Southeast Geysers and show regions of high permeability-thickness.

Introduction

Reservoir engineering studies of The Geysers are hampered by a lack of formation evaluation techniques and measurements typically used to characterize hydrocarbon reservoirs. The permeability distribution in the reservoir is poorly understood, limiting efforts to develop a conceptual reservoir description and model.

The goal of this study is to extend the Fetkovich production decline method to vapor-dominated geothermal reservoirs using customary geothermal production units. Analytic expressions for dimensionless pressure, dimensionless production rate, dimensionless decline time, and dimensionless decline rate are derived for saturated steam. A "Geysers-like" numerical model is used to validated the analytic terms. The derived dimensionless terms are applied to a set of wells located in the southeast Geysers to demonstrate the practical utility of this approach for estimating the permeability-thickness from the transient production response.

Literature Review

Production decline curve analysis has been used at The Geysers since 1969 when Ramey (1970) demonstrated through the use of material balance calculations, the p/z method from gas reservoir engineering (Whiting and Ramey, 1969), and production decline curve analysis, that The Geysers shallow steam reservoir was undergoing depletion. Empirical rate-time semi-log analysis using Arps method (Arps, 1945) is the standard method used to forecast remaining steam reserves for individual wells and leases at The Geysers, (Enedy, 1987; Enedy, 1989; Goyal and Box, 1990; Goyal and Box, 1992). The hyperbolic exponent b in the Arps equation can vary from $b = 0$ for exponential decline to $b = 1$ for harmonic decline. In areas responding to water injection, semi-log incline rates have been used to quantify the production response, (Goyal, 1994).

Fetkovich (1980) noted that the concepts of dimensionless pressure and dimensionless time, used in pressure transient analysis could be used to analyze the transient production response of a well. A dimensionless production rate was defined as the reciprocal of dimensionless pressure. Fetkovich defined two additional dimensionless terms; the dimensionless decline time and the dimensionless decline rate. These two terms were combined to describe the transient production response and the depletion or pseudo-steady state period. The dimensionless decline time and dimensionless decline rate

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were used to construct a type curve covering the entire production response of a well producing at a constant backpressure, see Figure 1. The transition from transient to pseudo-steady state production for a bounded system occurs at a dimensionless decline time of 0.3. A type curve match can be used to characterize reservoir properties during the transient flow period and to determine the Arps exponent b during the pseudo-steady state period. Thus, from the production response of a well, several parameters of use for reservoir engineering can be obtained, namely the kh and the Arps exponent b. In practice, the exponent b is generally solved for, as it can be used to forecast a production schedule and estimate remaining reserves.

While not commonly used for analysis at The Geysers, the Fetkovich method has been reviewed by Zais and Bodvarsson (1980), Enedy (1987), Ripperda and Bodvarsson (1987), Enedy (1989), and Sanyal et al. (1989). Enedy (1987) presented a modification of the black oil Fetkovich equations using geothermal field units by converting the steam mass production rate in pounds-mass per hour, m, to an equivalent reservoir volumetric rate in stock tank barrels using the specific volume of steam, $\bar{v}$, at an average reservoir pressure. This approach is limited by noting that the specific volume, viscosity, and density of steam are not constant at the range of pressures encountered in vapor-dominated systems.

Using this method Enedy (1987) and Enedy (1989) presented results for thirteen wells in the southeast Geysers. They compared the permeability-thickness product, kh, from pressure transient testing with that from the Fetkovich method during transient production response using steam properties at an average reservoir pressure. The results were generally close, with high kh wells (>200 darcy-ft from pressure build-up) having the greatest difference. The disagreement is probably due to a host of factors: the identification and selection of the infinite-acting radial-flow period for pressure transient analysis, a prolonged wellbore storage period due to large wellbore volumes, a highly compressible fluid, wellbore phase condensation, identification of the start of the pseudo-steady state production, and the simplifying assumptions noted above. Enedy (1989) states that for wells where it was necessary to re-initialize the Fetkovich type curve match, the re-initialized values of kh varied by 5-10% from the values estimated during the transient production response. This indicates that once the production response has entered pseudo steady-state flow, the re-initialized values are readily repeatable.

The large range of kh at The Geysers underscores the need to use an additional technique in addition to pressure transient data analysis (with the inherent difficulties of a two-phase steam reservoir) to estimate the permeability-thickness for a well. Extensive, high quality production records from the California Division of Oil and Gas Geothermal Resources Office, Santa Rosa are readily available in electronic format and can be useful to augment pressure transient testing for estimating the kh from the transient production response of a well.

Derivation of Dimensionless Terms for Saturated Steam

The dimensionless equations for saturated steam in geothermal field units have been derived from the radial diffusivity equation (Faulder, 1996). This derivation treated steam as a real gas using the real gas potential.

$$m(p) = 2\int_{p_b}^{p} \frac{p}{\mu z} dp \qquad \text{Eq. 1}$$

The dimensionless equations (Faulder, 1996) are:

$$m(p)_D = \frac{kh}{1207m}\left(\frac{\rho z}{p}\right)_{res}[m(p) - m(p_{wf})] \qquad \text{Eq. 2}$$

$$q_D = \frac{1207m}{kh}\left(\frac{p}{\rho z}\right)_{res}\frac{1}{[m(p) - m(p_{wf})]} \qquad \text{Eq. 3}$$

$$t_D = \frac{0.006329kt}{\phi\mu c_t r_w^2} \qquad \text{Eq. 4}$$

$$q_{Dd} = \frac{m(t)}{m_i} = \frac{m(t)}{\dfrac{kh}{1207}\left(\dfrac{\rho z}{p}\right)_{res}\dfrac{[m(p) - m(p_{wf})]}{\left[\ln\dfrac{r_e}{r_w} - \dfrac{1}{2} + s\right]}} \qquad \text{Eq. 5}$$

$$t_{Dd} = \frac{t_D}{\frac{1}{2}\left[\left(\frac{r_e}{r_w}\right)^2 - 1\right]\left[\ln\left(\frac{r_e}{r_w}\right) - \frac{1}{2}\right]} \qquad \textit{Eq. 6}$$

The productivity factor, kh, derived by Faulder (1996) is

$$kh = 1207\left(\frac{p}{pz}\right)_{res}\frac{\left[\ln\left(\frac{r_e}{r_w}\right) - \frac{1}{2}\right]}{\left[m(\bar{p}) - m(p_{wf})\right]}\left[\frac{m(t)}{q_{Dd}}\right]_{\text{match point}} \qquad \textit{Eq. 7}$$

Eq. 2, Eq. 3, Eq. 5, Eq. 6 and Eq. 7 form the basis for applying the Fetkovich type curve technique to saturated steam in customary geothermal mass rate units (Imperial units).

Numerical Validation of Analytic Terms

A series of simulations was performed using a "Geysers-like" reservoir properties. The results for a porous media rate-time response at a permeabilty of 10 mD are presented here for a reservoir thickness of 10,000 feet, resulting in a total kh of 100,000 mD-ft. The wellbore fully penetrated the entire reservoir thickness of 10,000 feet. The porosity was 3.38% (consistent with Gunderson, 1992). The well was set to produce at a constant wellhead backpressure of 115 psia. The system was assumed to be isothermal, with no vertical heat flux.

The simulated rate-time responses for the "Geysers-like" reservoir over a range of liquid saturations from 0 to 50% are presented in Figure 2. The produced fluid was saturated to superheated steam. An initial liquid saturation greater than zero resulted in greater flow rates compared to no liquid initially present and a longer period of steam production. The cases with the initial water saturation greater than zero overlie each other until the liquid reserves are exhausted. Upon the termination of boiling there is rapid reservoir decompression and an abrupt decrease in steam production.

The rate-time response for an initial liquid saturation of 0% was analyzed using the Fetkovich method and the derived analytic equations. Zero liquid saturation was chosen to avoid the high effective compressibility of a boiling liquid phase. The calculated permeability was +11.7% greater than the model permeability. The good agreement between the analytical and numerical solutions validates the derived analytic terms for saturated steam. Once the production has entered pseudo-steady state, the empirical Arps exponent b is 0.4. This is consistent with the observation of Fetkovich et al. (1994) that $b = 0.4$ is a good limiting value for gas wells.

The simulated rate-time curves were collapsed using the dimensionless production rate and dimensionless time derived for saturated steam, Eq. 3 and Eq. 4. It was necessary to account for the large effective compressibility of boiling water (Grant and Sorey, 1979) for initial liquid saturations greater than zero. The effective compressibility of boiling water is two orders of magnitude greater than saturated steam and is a strong function of porosity, (boiling water is 2.0E-1 psi^{-1} at a porosity of 3%, 500 psia and 480°F, while dry steam is 2.4E-3 psi^{-1} at 500 psia and 480°F). The collapsed dimensionless time-dimensionless rate curves are presented in Figure 3 and overlie each other for all liquid saturations greater than zero, until the exhaustion of liquid reserves. Adjusting the simulated rate-time response for boiling by the effective compressibility, shifts the dimensionless time to the left by approximately two orders of magnitude. This adjustment can also be verified by close examination of the dimensionless time equation, Eq. 4 and the inverse relationship between the term t_D and c_t. As c_t becomes larger, t_D becomes smaller, thus shifting the dimensionless time to the left by the two orders of magnitude difference in the compressibility between dry steam and a boiling liquid. Since the case where the initial water saturation is zero, the dimensionless time is not shifted to the left, thus making this case the limiting curve to the right.

Field Data Analysis

The study area is in the southeast area of The Geysers field. Over 40 wells in sections 22, 26, 27, 34, and 35 (Township 11 N, Range 8 W) were analyzed. A portion of the study area was previously reviewed for injection response and 13 years of production were history matched (Faulder, 1992).

The real gas potential was used for all reservoir engineering calculations. The production data from a well was first reviewed using the Rawlins and Schellhardt equation modified for the real gas potential (Poettmann, 1986), Eq. 8.

$$m = C[m(p_i) - m(p_{wf})]^n \qquad \textit{Eq. 8}$$

Values of C and n were estimated during the first few months of initial production to history match the transient deliverability. Typically, n was equal to one. Once C and n were estimated, Eq. 8 was rearranged to estimate the static reservoir pressure using Eq. 9.

$$m(p_s) = \left(\frac{m}{C}\right)^{(1/n)} + m(p_{wf}) \qquad \textit{Eq. 9}$$

The calculated static wellhead pressure was compared to the measured wellhead pressure during periods of extended shut-in to provide a check on the calculated pressure. Finally, the production rate was normalized to a constant producing wellhead pressure of 115 psia), Eq. 10.

$$m_n = m\frac{[m(p_{st}) - m(p_{std})]^n}{[m(p_{st}) - m(p_{wf})]^n} \qquad \textit{Eq. 10}$$

The normalized steam production rate was used for the Fetkovich type-curve analysis.

One of the inherent difficulties in performing a type curve match of real production data containing noise is estimating the end of transient flow and the start of pseudo steady-state flow. Hinchman et al. (1987) presented a method of plotting $1/C^n$ against the log of time using isochronal test data to estimate the stabilized gas well deliverability. During transient flow, the data plots on a line of constant slope. At the onset of pseudo steady-state flow the slope increases to a new line. An apparent $1/C^n$ for The Geysers production data was calculated using the initial reservoir pressure and each month's measured mass rate and wellhead pressure. The change in slope was used to estimate the time for the onset of pseudo steady state flow which corresponds to a dimensionless decline time of 0.3 (Fetkovich, 1980). One of the practical advantages of this approach is that it avoids the use of dimensionless radius, r_D, to match one of the transient dimensionless radius curves. Instead, the onset of pseudo steady-state flow is estimated directly and a type curve match performed of the transient production data, reducing one of the degrees of freedom in the match process.

Production data from well Abel 1 is used to illustrate the methodology. Abel 1 is located in section 26 of the study area. The actual production, adjusted production, wellhead pressure history and calculated static pressure history are presented in Figure 4. Note that during the first 2500 days, the calculated static reservoir pressure (measured at the wellhead) closely approximates the measured wellhead pressure during periods of extended shut-in.

This example demonstrates the utility of the calculated static pressure from the modified Rawlins and Schellhardt equation for estimating the reservoir pressure history. The first 2500 days of production is characterized by numerous periods of well shut-in and fluctuating producing wellhead pressures with corresponding variations in production rate. The normalized production rate (at a constant backpressure) exhibits a smoother trend for type curve matching.

One of the difficulties in interpreting decline data at The Geysers is the extended transient flow period due to boiling water. The extended transient period coupled with variations in production rate due to fluctuating wellhead pressures introduces uncertainty in estimating the time of transition from transient to pseudo steady-state flow. The $1/C^n$ vs. log time plot was used to estimate this transition time for Abel 1 and is presented in Figure 5. The slope for the first 2500 days was constant, indicating the well was in transient flow. After 2500 days, a sharp break is experienced and $1/C^n$ begins to change rapidly with time, indicating the onset of pseudo steady-state flow and changing fluid properties as the reservoir pressure begins to decline. The adjusted production rate on a log time vs. log mass rate is presented in Figure 7. The type curve matching procedure used this observation to set dimensionless decline time equal to 0.3 at a time of 2500 days to match the adjusted production data on the Fetkovich type decline curve. The practical effect of this technique is an improved time match. The above procedure was used for all the study wells.

This method was used to determine the permeability-thickness product for 48 wells in the southeast Geysers study area. The kh results ranged from 18,000 to 270,000 mD-ft and closely replicated the published range from both pressure transient testing and earlier Fetkovich studies (Enedy, 1987; Enedy, 1989) in this portion of The Geysers. A histogram of the kh results is presented in.

Summary

The dimensionless equations for pressure, production rate, decline rate and decline time have been derived for saturated steam and numerically validated. The analytic dimensionless equations have been used to analyze the production responses of 48 wells in the southeast Geysers and to estimate the kh of each well's drainage volume. The results are in good agreement with previous estimates for this study area. The methodology developed can be readily applied to other vapor-dominated reservoirs and the calculated kh can be compared to other reservoir engineering and geologic information to provide an improved description of the reservoir.

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Nomenclature

Latin Symbols

b	hyperbolic decline exponent
C	Rawlins and Schellhardt backpressure term
D_i	initial decline factor
h	reservoir thickness, ft
k	permeability, mD
m	mass rate, lbm/hr
$m(p)$	real gas potential, psia^2/cp
p	pressure, psi
r	radius, ft
s	wellbore skin factor, dimensionless
S	saturation, fraction
t	time, days
z	real gas deviation factor, dimensionless

Greek Symbols

μ	dynamic viscosity, cp
v	specific volume, ft^3/lbm
ρ	density, lbm/ft^3
ϕ	porosity, fraction

Subscripts

b	base
Dd	dimensionless decline
e	external
n	normalized
res	reservoir conditions
sc	standard conditions
st	static
std	standard producing pressure
wf	well flowing

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FIGURE 1. Fetkovich Type Curve, (from Fetkovich et al., 1994)

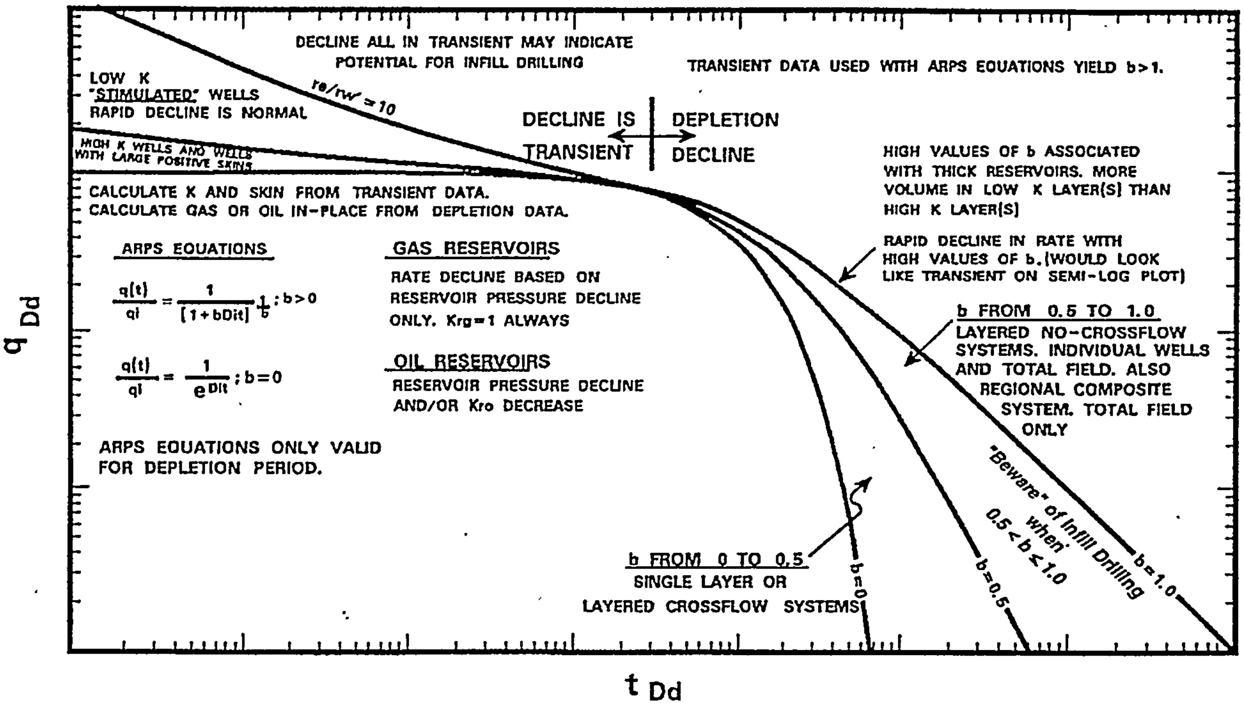

FIGURE 2. Simulated Rate-Time Response for Matrix Permeability Equal 10 mD

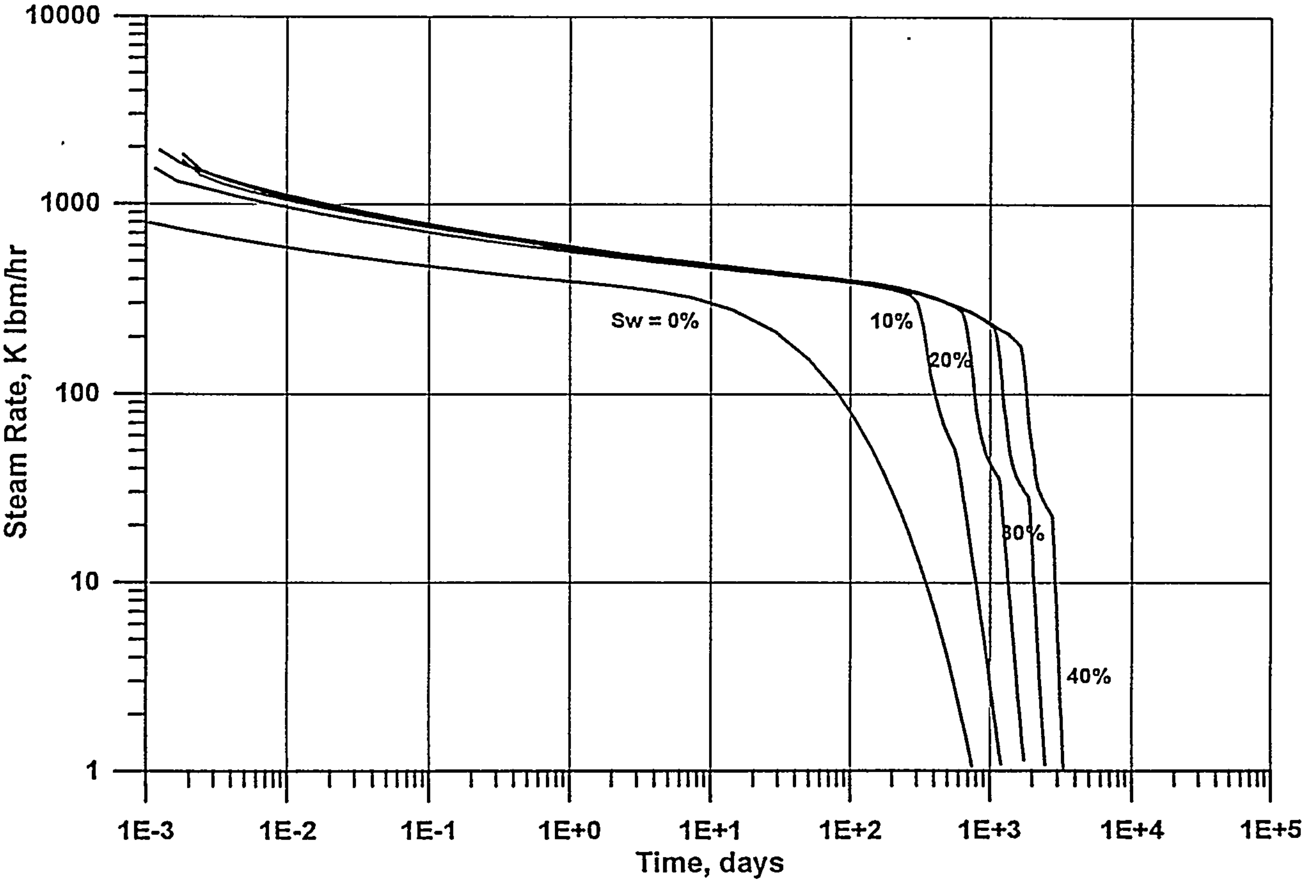

FIGURE 3. Dimensionless Time vs. Dimensionless Rate for 10 mD Matrix Permeability

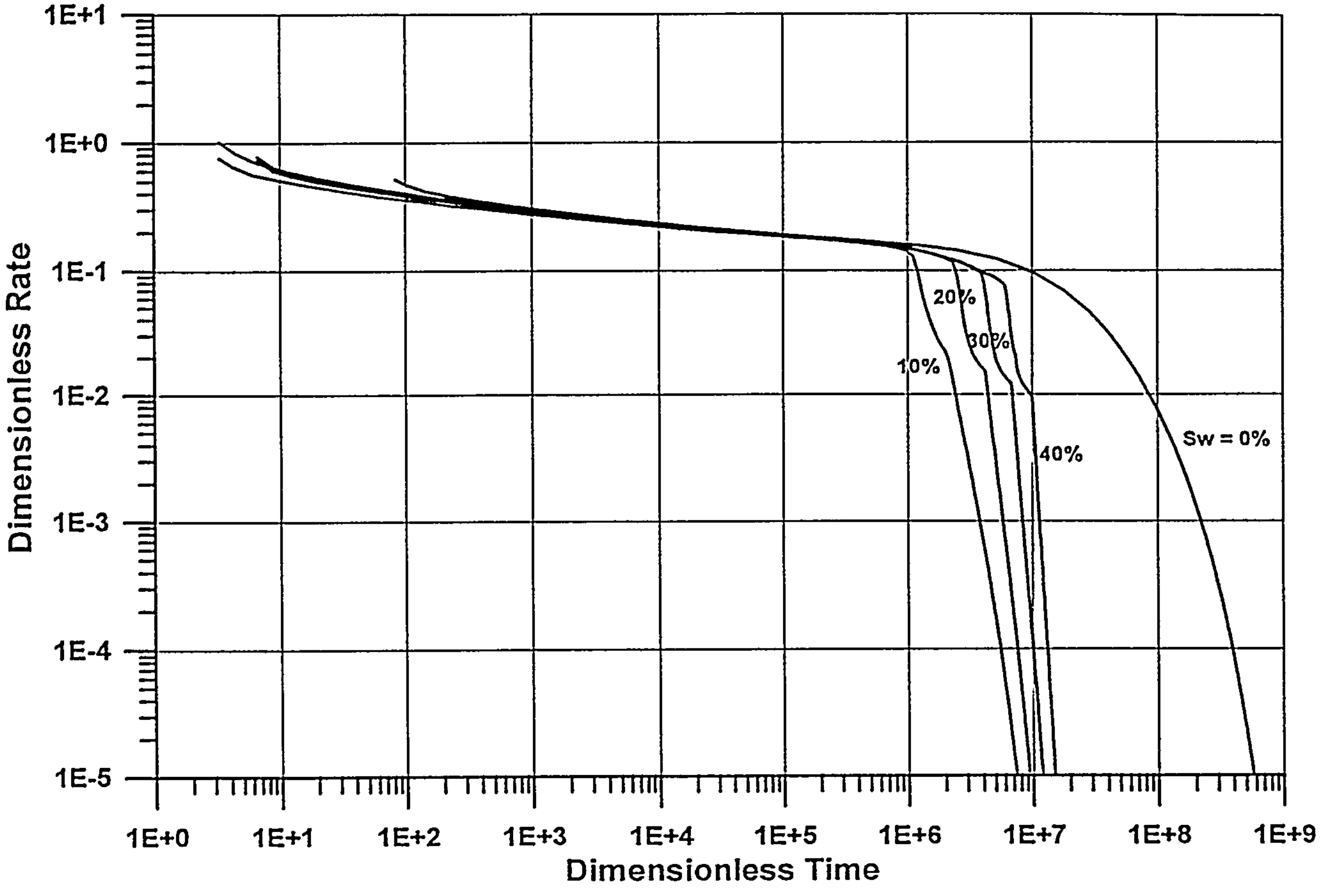

FIGURE 4. Production History for Abel 1

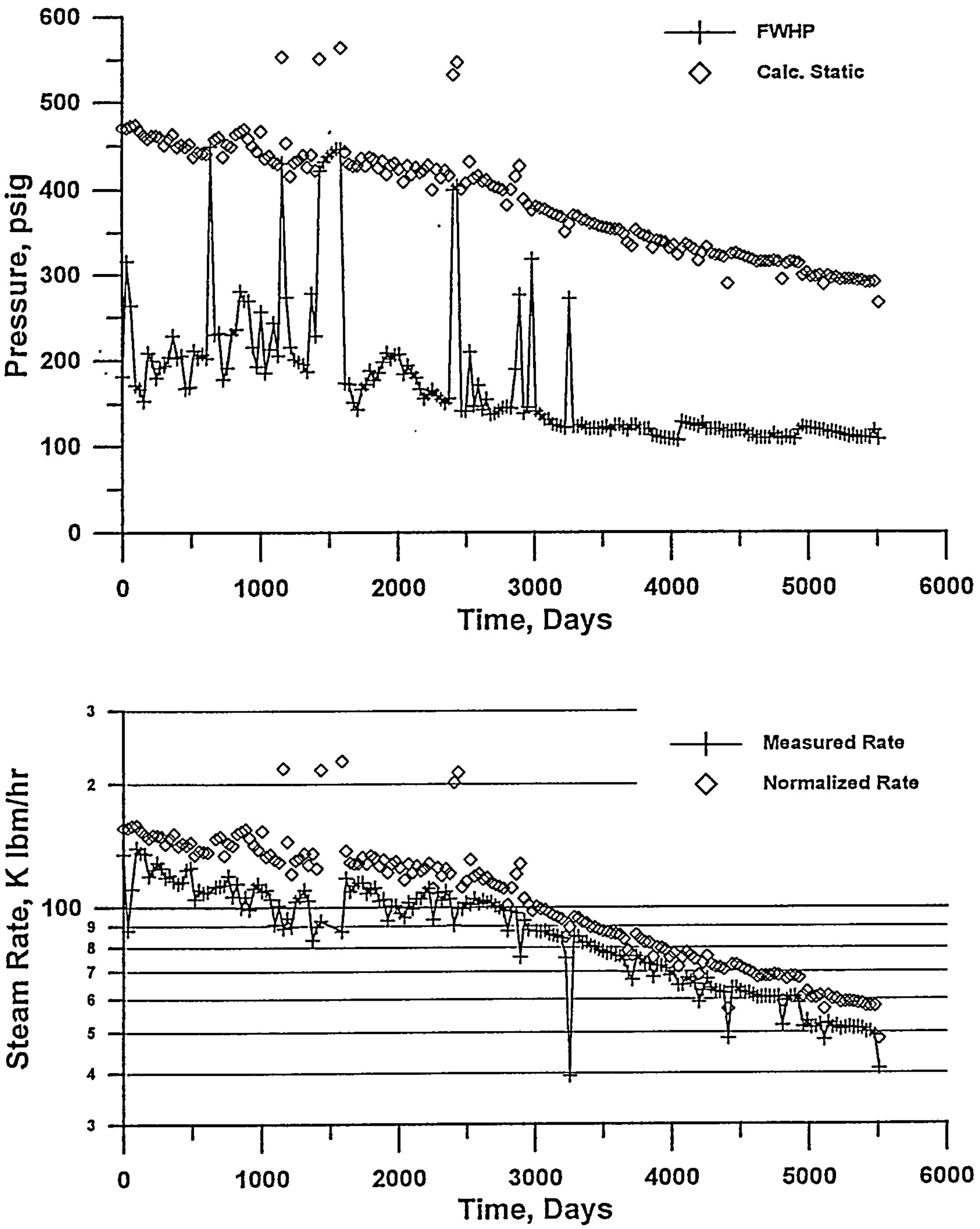

FIGURE 5. $1/C^n$ vs. log Time for Abel 1

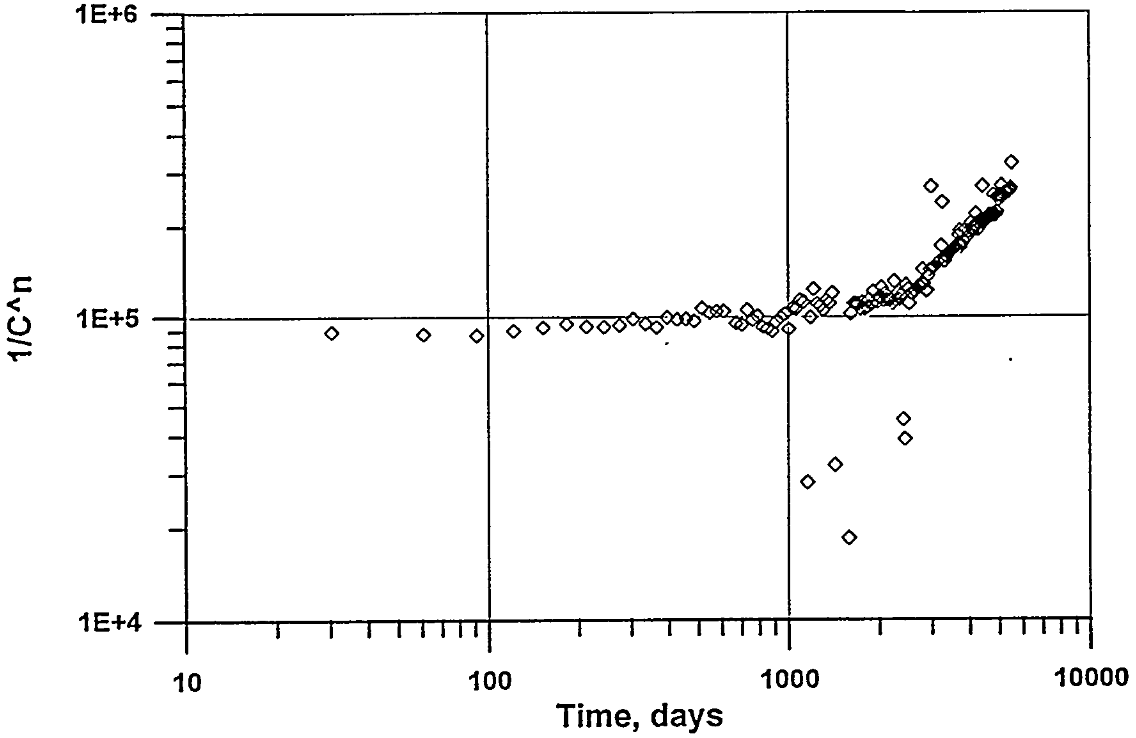

FIGURE 6. Abel 1 Adjusted Production

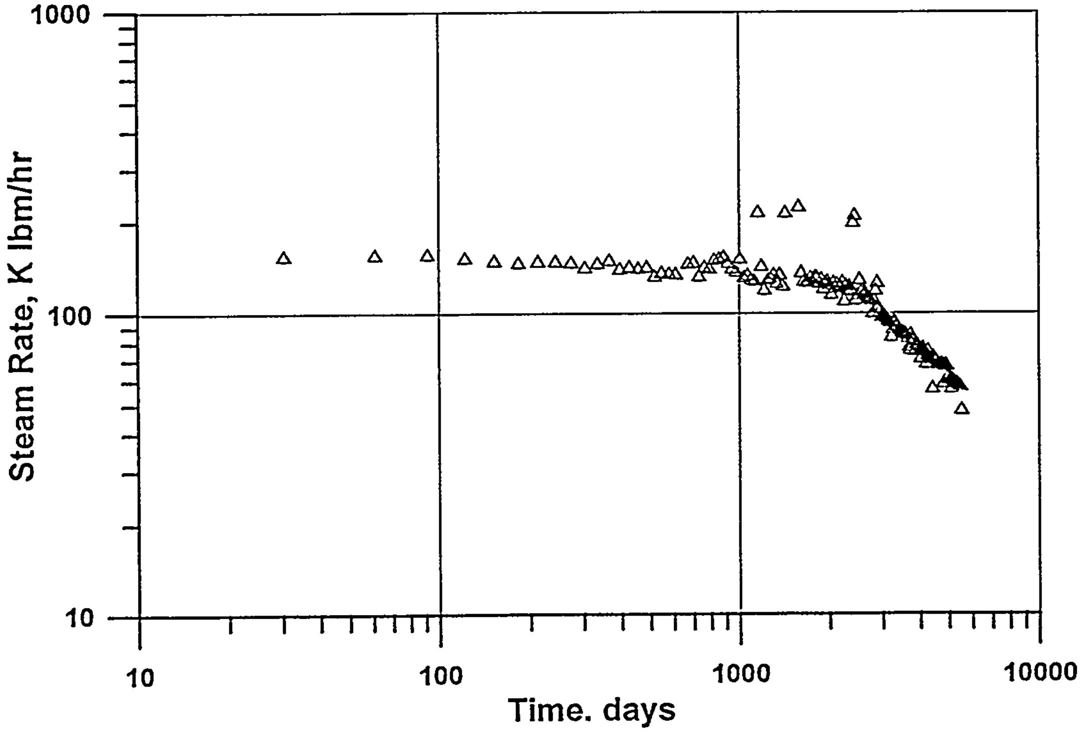

FIGURE 7. Histogram of *kh* Results in Southeast Geysers Study Area