

# RESERVOIR ENGINEERING FOR GEOLOGISTS

## Part 4 – Production Decline Analysis

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Production decline analysis is a basic tool for forecasting production from a well or well group once there is sufficient production to establish a decline trend as a function of time or cumulative production. The technique is more accurate than volumetric methods when sufficient data is available to establish a reliable trend and is applicable to both oil and gas wells.

Accordingly, production decline analysis is most applicable to producing pools with well established trends. It is most often used to estimate remaining recoverable reserves for corporate evaluations but it is also useful for waterflood and enhanced oil recovery (EOR) performance assessments and in identifying production issues/mechanical problems. Deviations from theoretical performance can help identify underperforming wells and areas and highlight where well workovers and/or changes in operating practices could enhance performance and increase recovery.

To the geologist, production decline analysis of an analogous producing pool provides a basis for forecasting production and ultimate recovery from an exploration prospect or stepout drilling location. A well's production capability declines as it is produced, mainly due to some combination of pressure depletion, displacement of another fluid (i.e.,

gas and/or water) and changes in relative fluid permeability. Plots of production rate versus production history (time or cumulative production) illustrate declining production rates as cumulative production increases (Figures 1-4).

In theory, production decline analysis is only applicable to individual wells but in practice extrapolations of group production trends often provide acceptable approximations for group performance. The estimated ultimate recovery (EUR) for a producing entity is obtained by extrapolating the trend to an economic production limit. The extrapolation is valid provided that:

- Past trend(s) were developed with the well producing at capacity.
- Volumetric expansion was the primary drive mechanism. The technique is not valid when there is significant pressure support from an underlying aquifer.
- The drive mechanism and operating practices continue into the future.

Production decline curves are a simple visual representation of a complex production process that can be quickly developed, particularly with today's software and production databases. Curves that can be used for production forecasting include:

- a) production rate versus time,
- b) production rate versus cumulative production,

- c) water cut percentage versus cumulative production,
- d) water level versus cumulative production,
- e) cumulative gas versus cumulative oil,
- f) and pressure versus cumulative production.

Decline curves a) and b) are the most common because the trend for wells producing from conventional reservoirs under primary production will be "exponential," in engineering jargon. In English, it means that the data will present a straight line trend when production rate vs. time is plotted on a semi-logarithmic scale. The data will also present a straight line trend when production rate versus cumulative production is plotted on regular Cartesian coordinates. The well's ultimate production volume can be read directly from the plot by extrapolating the straight line trend to the production rate economic limit.

The rate versus time plot is commonly used to diagnose well and reservoir performance. Figure 1 presents a gas well with an exponential "straight line" trend for much of its production life. But in 2004 the actual performance is considerably below the expected exponential decline rate, indicating a non-reservoir problem. Wellbore modelling suggests that under the current operating conditions, the well cannot produce liquids to surface below a critical gas rate of about 700 Mscfd, which is about the rate when well performance started deviating from the expected exponential decline. Water vapour is probably condensing in the wellbore and impeding production from the well. Removing the water would restore the well's production rate to the exponential trend.

Figure 2 is an example of a pumping oil well that encountered a pump problem. A rapid decline in production rate to below the exponential decline rate cannot be a reservoir issue and must therefore be due to equipment failure and/or near wellbore issues such as wax plugging or solids deposition in the perforations. In this case, the pump was replaced and the fluid rate returned to the value expected for exponential decline.

Arps (1945, 1956) developed the initial series of decline curve equations to model well performance. The equations were initially considered as empirical and were classified

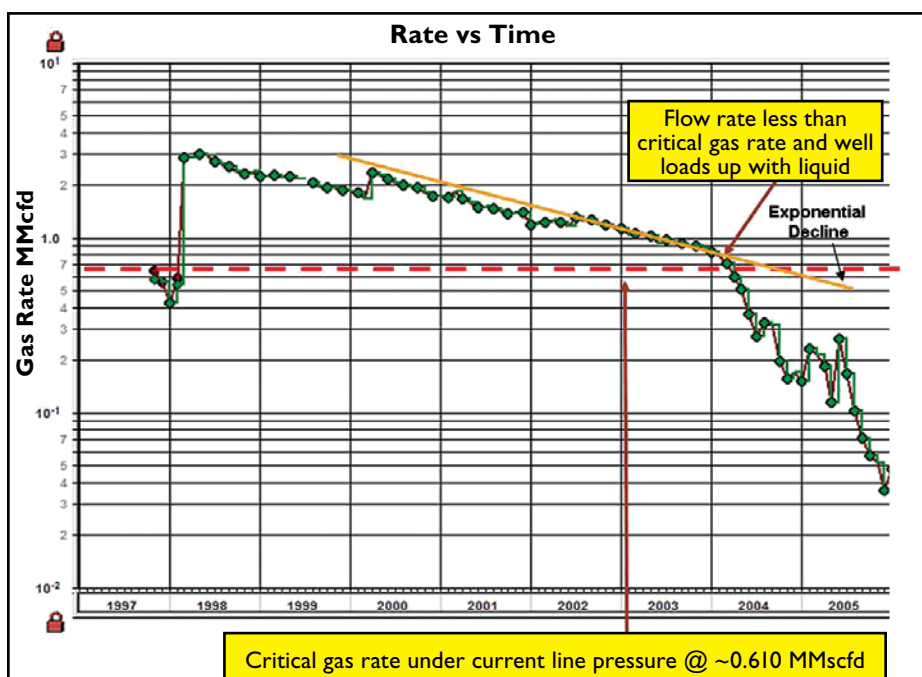


Figure 1. Gas well example showing liquid loading in the wellbore.

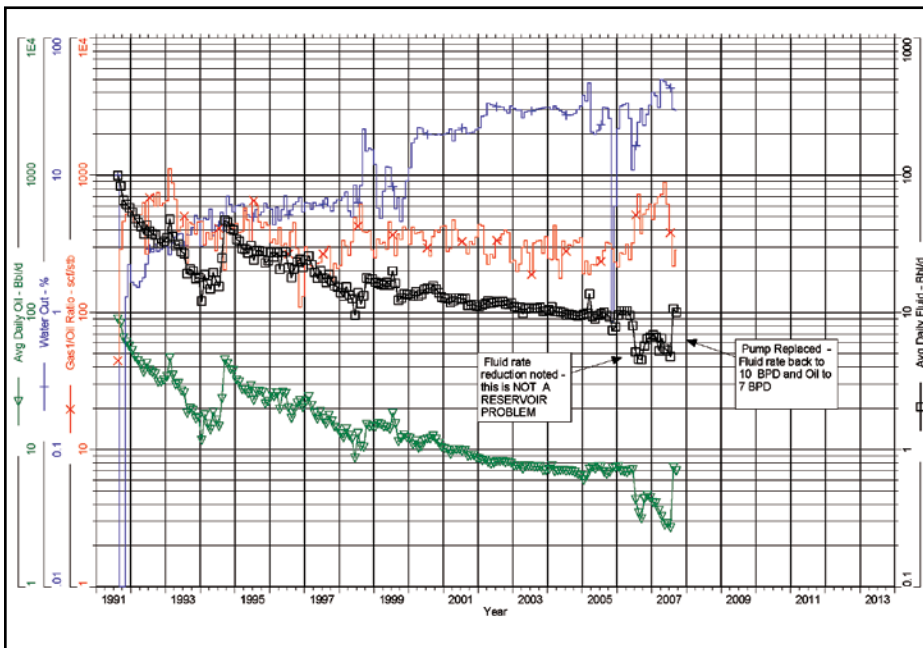


Figure 2. Pumping oil well where pump capability is decreasing.

as exponential, hyperbolic, or harmonic, depending on the value of the exponent 'b' that characterizes the change in production decline rate with the rate of production (see Figure 3 and equations at the end of the article). For exponential decline 'b'=0; for hyperbolic 'b' is generally between 0 and 1. Harmonic decline is a special case of hyperbolic decline where 'b'=1.

The decline curve equations assume that reservoir rock and fluid properties (porosity, permeability, formation volume factor, viscosity, and saturation) governing the flow rate will not change with time or pressure. While the assumption is not entirely correct, industry experience has proven that decline curves present a practical way to forecast well production in all but the most unusual circumstances.

Figure 3 illustrates the difference between exponential, hyperbolic, and harmonic decline when production rate vs. cumulative production is plotted on Cartesian scales. The "straight" orange line extrapolates an exponential decline from the data. The green and blue lines present hyperbolic extrapolations of the data trend with 'b' values of 0.3 and 0.6, respectively. Note that the curvature of the line increases as the 'b' value increases.

Figure 3 also illustrates the main challenges in decline analysis – data scatter and the type of extrapolation that is appropriate for the well under consideration. Data scatter is an unavoidable consequence of dealing with real data. In Western Canada, the permanent record of production and injection consists of monthly totals for

gas, oil, and water production; operated hours; and wellhead pressure. For oil wells at least, monthly production at the battery is routinely pro-rated back to the individual wells, based on sequential 1-2 days tests of individual well capability. Depending on the number of wells and test capability at each battery, it can take up to several months to obtain a test on each well in the group.

Factors that determine the rate of decline and whether declines are exponential, hyperbolic, or harmonic include rock and fluid properties, reservoir geometry, drive mechanisms, completion techniques, operating practices, and wellbore type. These factors must be understood prior to analyzing the production decline trends or serious errors in the ultimate production estimates can result (see Figure 4).

As stated previously, oil and gas wells producing conventional (>10 md) permeability reservoirs under primary depletion (or fluid expansion) generally exhibit exponential decline trends. But the performance of some waterfloods and unconventional low permeability gas reservoirs are better modeled using hyperbolic decline trends.

Figure 4 presents an example of well production from a "tight" gas reservoir. These reservoirs are becoming increasingly important to the industry but they typically have permeability below 0.1 md and are generally not productive without some form of mechanical fracture stimulation. From Fig 4A, a slightly hyperbolic (approximately exponential) extrapolation of the most recent production data yields an ultimate recovery of approximately 1.8 BCF. But the hyperbolic decline trend of Figure 4b provides a good fit for the complete production history and indicates an ultimate recovery of 7.6 BCF.

The typical range of 'b' values is approximately 0.3 to 0.8. A 'b' value of 2 represents an upper limit to the volume of gas that will ultimately be produced. The uncertainty in the trend that should be used to forecast well performance can be reflected in the assigned reserves as follows:

- Proven 1.8 BCF
- Proven plus Probable plus Possible 7.6 BCF

Based on the reserve definitions, the assignment suggests there is a 95% chance that the actual volume recovered will be greater than 1.8 BCF and less than 7.6 BCF. An estimate for the proven plus probable volume can be developed by integrating the well pressure history and material balance gas-in-place (OGIP) estimate with the decline analysis trend.

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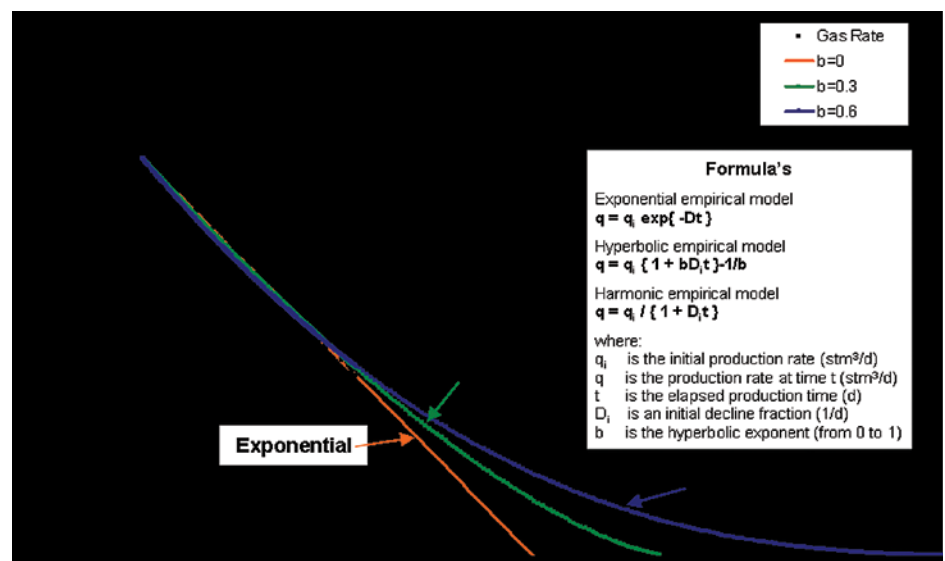


Figure 3. Production history rate versus cumulative production with associated decline formulas.

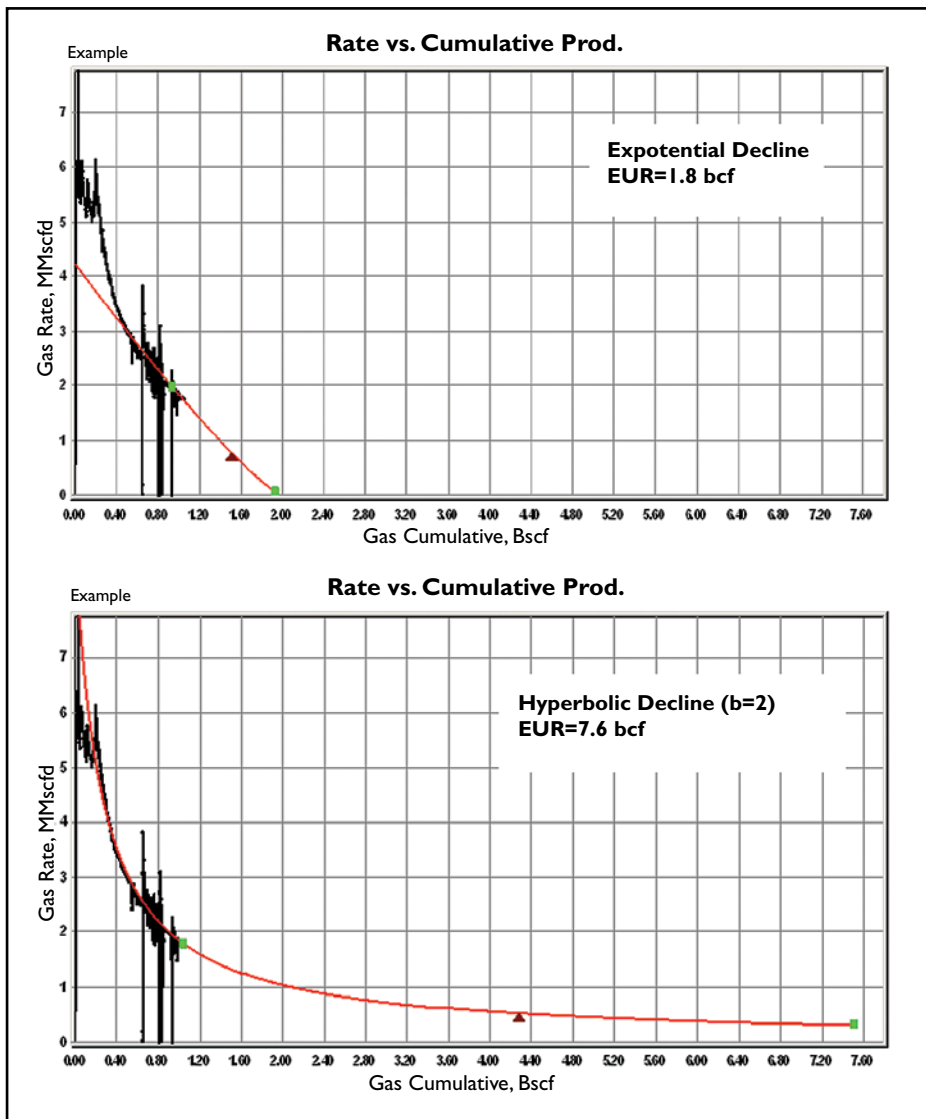


Figure 4. Tight gas well example illustrating minimum and maximum values for EUR depending on decline methodology.

## REFERENCES

Arps, J.J., (1945) *Analysis of Decline Curves*, Trans. AIME, Vol 160, pp 228-247.

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Canadian Oil and Gas Evaluation Handbook, First Edition, November 1, 2005, Volume 2, Detailed Guidelines for Estimation and Classification of Oil and Gas Resources and Reserves. Section 6: Procedures for Estimation and Classification of Reserves, 2005.

Stotts, W.J., Anderson, David M. and Mattar, Louis: "Evaluating and Developing Tight Gas Reserves – Best Practices", SPE paper # 108183 presented at the 2007 SPE Rocky Mountain Oil and Gas Technology Symposium, Denver, CO, USA, 16-18 April, 2007.

## FORMULAS:

The Exponential decline equation is:  
 $q = q_i \exp\{-Dt\}$

where:

$q_i$  is the initial production rate (stm<sup>3</sup>/d),  
 $q$  is the production rate at time  $t$  (stm<sup>3</sup>/d),  
 $t$  is the elapsed production time (d),  
 $D$  is an exponent or decline fraction (1/d).

Solving for  $D$  and  $t$  gives:

$$D = -\ln\{q/q_i\} / t \text{ and } t = -\ln\{q/q_i\} / D$$

The cumulative production to time  $t$  ( $N_p$ ) is given by:  
 $N_p = \int q \, dt = \int q_i \exp\{-Dt\} \, dt = (q_i - q) / D$

The Hyperbolic decline equation is:  
 $q = q_i \{1 + bD_i t\}^{-1/b}$

where:

$q_i$  is the initial production rate (stm<sup>3</sup>/d),  
 $q$  is the production rate at time  $t$  (stm<sup>3</sup>/d),  
 $t$  is the elapsed production time (d),

$D_i$  is an initial decline fraction (1/d),  
 $b$  is the hyperbolic exponent (from 0 to 1).

Solving for  $D_i$  and  $t$  gives:

$$D_i = \left[ \frac{(q_i/q)^b - 1}{bt} \right] \text{ and } t = \left[ \frac{(q_i/q)^b - 1}{D_i b} \right]$$

The cumulative production to time  $t$  ( $N_p$ ) is given by:

$$N_p = \int q \, dt = \int q_i \{1 + bD_i t\}^{-1/b} \, dt = \left\{ \frac{q_i^b}{(1-b)D_i} \right\} [q_i^{1-b} - q^{1-b}]$$

The Harmonic decline equation is:

$$q = q_i / \{1 + D_i t\}$$

where:

$q_i$  is the initial production rate (stm<sup>3</sup>/d),  
 $q$  is the production rate at time  $t$  (stm<sup>3</sup>/d),  
 $t$  is the elapsed production time (d),  
 $D_i$  is an initial decline fraction (1/d).

Solving for  $D_i$  and  $t$  gives:

$$D_i = \left[ \frac{(q_i/q) - 1}{t} \right] \text{ and } t = \left[ \frac{(q_i/q) - 1}{D_i} \right]$$

The cumulative production to time  $t$  ( $N_p$ ) is given by:

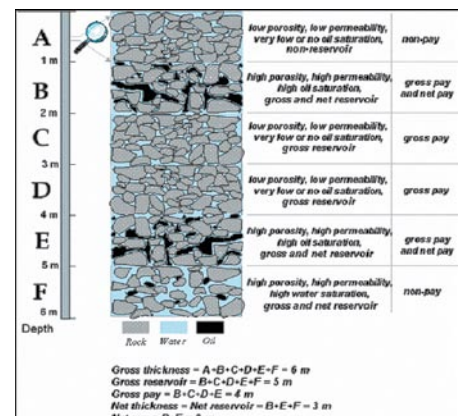
$$N_p = \int q \, dt = \int q_i \{1 + D_i t\}^{-1} \, dt = \left\{ \frac{q_i}{D_i} \right\} \ln \left\{ \frac{q_i}{q} \right\}$$

Look for our next article on "Material Balance" in the February issue of the Reservoir.

This article was contributed by Fekete Associates, Inc. For more information, contact Lisa Dean at Fekete Associates, Inc.



## ERRATA



In last month's installment of Fekete's Reservoir Engineering For Geologists, Part 3 - Volumetric Estimation, the source reference for Figure 4 was inadvertently missed. The figure caption should have read, "Figure 4. Gross and Net Pay Distinction (Etris and Stewart, 2003). The source reference is: Etris, Ned, and Stewart, Bruce, 2003. Net-to-Gross Ratio. CSPG Reservoir, Vol. 30, Issue 4, pp. 24-25.