Probabilistic Method for Estimating Future Growth of Oil and Gas Reserves

Chapter C of
Geologic, Engineering, and Assessment Studies of Reserve Growth

U.S. Geological Survey Bulletin 2172–C
**Cover.** This map represents historical oil and gas exploration and production data for the conterminous United States. It was derived from data used in U.S. Geological Survey Geologic Investigations Series I-2582.* The map was compiled using Petroleum Information Corporation’s (currently IHS Corporation) database of more than 2.2 million wells drilled in the U.S. as of June 1993. The area of the U.S. was subdivided into 1 mi$^2$ grid cells for which oil and gas well completion data were available. Each colored symbol represents a 1 mi$^2$ cell (to scale) for which exploration has occurred. Each cell is identified by color as follows: red, a gas-producing cell; green, an oil-producing cell; yellow, an oil- and gas-producing cell; gray, a cell that has been explored through drilling, but no production has been reported. Mast and others (1998) gives details on map construction.

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By Robert A. Crovelli and James W. Schmoker

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Geologic, Engineering, and Assessment Studies of Reserve Growth

Edited by T.S. Dyman, J.W. Schmoker, and Mahendra Verma

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U.S. Department of the Interior
U.S. Geological Survey
# Contents

Introduction ............................................................................................................................................. 1  
Acknowledgments .................................................................................................................................... 1  
Deterministic Method .............................................................................................................................. 1  
    Input Data ........................................................................................................................................... 1  
    Calculations ...................................................................................................................................... 2  
Probabilistic Method ............................................................................................................................... 2  
Spreadsheet System ............................................................................................................................... 6  
Summary .............................................................................................................................................. 11  
References Cited ..................................................................................................................................... 12

# Figures

1. Spreadsheet illustrating program for estimating future oil and gas reserve growth .......................................................................................................................... 3  
2. Diagram showing left-triangular probability distribution of growth variable (dimensionless) ........................................................................................................ 4  
3. Graph of probabilistic estimates of future reserve growth of Lower 48 United States gas fields ........................................................................................................ 12
Probabilistic Method for Estimating Future Growth of Oil and Gas Reserves

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Introduction

In the United States, the estimated size (cumulative production plus remaining reserves) of oil and gas fields typically increases through time as fields are discovered, developed, and produced. (See, for example, Arrington, 1960; Attanasi and Root, 1994.) This phenomenon is usually referred to as reserve growth or field growth; the term “reserve growth” is used here.

Reserve-growth patterns of individual fields are highly variable. Indeed, the sizes of some fields are observed to decrease through time. However, for United States fields as a whole, collective reserve growth is strongly positive and is a major component of remaining United States oil and natural-gas resources (Gautier and others, 1995; U.S. Geological Survey National Oil and Gas Resource Assessment Team, 1995; Schmoker and Attanasi, 1997).

International oil and gas fields also show clear evidence of reserve growth (for example, Root and Attanasi, 1993; Oil & Gas Journal, 1996, p. 37; U.S. Geological Survey World Energy Assessment Team, 2000), even though criteria for estimating and reporting field sizes can be quite different from those of the United States. Worldwide, reserve growth has the potential to become important in the future, especially for gas, as demand increases and opportunities for new large-field discoveries decrease. Projections of the future reserve growth of known fields have thus become important, and in our view, necessary components of petroleum resource assessments.

Many algorithms for estimating the future growth of known fields utilize the age of fields (years since discovery) as a predictive variable, on the assumption that age is a surrogate for the degree of the development activity that generates reserve growth. Two additional assumptions implicit in most reserve-growth models are as follows: (1) reserve growth of a field is proportional to its field size, and (2) patterns of past reserve growth provide some basis for forecasting future reserve growth.

Schmoker and Crovelli (1998) presented an algorithm (a deterministic method) for estimating future reserve growth of oil and gas fields that incorporates the fundamental reserve-growth assumptions listed in the preceding paragraph, but which is programmed for a personal computer in the form of formulas for a Microsoft® Excel spreadsheet. Major advantages of this spreadsheet program include its simplicity and ease of use. However, like all other published reserve-growth models of which we are aware, this program (Schmoker and Crovelli, 1998) generates single-value (point) estimates of future reserve growth, in contrast to estimates in the form of probability distributions.

The purpose of this report is to explain an analytic probabilistic method and spreadsheet software system called probabilistic reserve growth spreadsheet (PREGS). The probabilistic method herein is a probabilistic extension of the deterministic method of Schmoker and Crovelli (1998). The PREGS method is based upon mathematical equations derived from probability theory. The PREGS spreadsheet can be used to calculate probabilistic estimates of reserve growth of oil and gas reserves.

Acknowledgments

The authors wish to acknowledge the helpful reviews of T.S. Dyman and Mahendra Verma of the U.S. Geological Survey.

Deterministic Method

The spreadsheet that implements the deterministic method (Schmoker and Crovelli, 1998) for estimating future growth of oil and gas reserves is shown in figure 1. The data used to illustrate the spreadsheet system are based on successive annual estimates made between 1977 and 1991 of the sizes of Lower 48 United States gas fields. These data were compiled by the U.S. Department of Energy and summarized in table 2 of Attanasi and Root (1994).

Input Data

Column A of figure 1A and 1B identifies the age classes to which the input data of columns B and C apply, and is not used in the spreadsheet calculations. Age (column A) is defined as years since discovery.

In the deterministic method, a growth function is composed of a set of growth factors. A growth factor is a dimensionless parameter, that is, a multiplicative constant representing proportional growth. The growth function of column B is composed of seventeen 10-year growth factors (rows 2 through 18). Each 10-year growth factor applies to fields of a particular age or range of ages, as indicated by column A. For example, the 10-year growth factor of 1.529 in cell B7 applies to fields that are 5 years old. The size of fields 5 years of age would be multiplied by 1.529 to forecast the size of these same fields 10 years later, when they have become 15 years old.
Rows 2 through 18 of column C (fig. 1A and 1B) list the volumes of petroleum that will be “grown” by the 10-year growth factors of column B. In this illustration, the values in column C are the totals of the estimated sizes of Lower 48 United States gas fields as of 1977 for each of the 17 field-age classes of column A. For example, the size as estimated in 1977 of Lower 48 gas fields 5 years of age (those discovered in 1972) is 5,400 billion cubic feet of gas (bcfg) (cell C7).

Calculations

The formulas shown in columns D through L (fig. 1A) are used to calculate future growth of the petroleum volumes tabulated in column C. The headings of columns D through L (row 1) indicate that the spreadsheet program calculates reserve growth from 10 to 90 years beyond the date associated with the field-size estimates of column C, at 10-year increments.

The spreadsheet algorithm can be explained by considering how reserve growth is calculated for the fields of a single age class. Consider the fields that were 5 years old (row 7) in 1977, when the field sizes of column C were estimated. To calculate the first growth increment of 10 years, the petroleum volume in cell C7 is multiplied by the 10-year growth factor that applies to 5-year-old fields (cell B7). This multiplication is done in cell D7. In the example used here, the total estimated size of 5-year-old fields of 5,400 bcfg grows to 8,257 bcfg (fig. 1B, cell D7), after the first 10-year growth period.

After 10 years of growth, fields that were 5 years old have become 15 years old. Therefore, to calculate the second growth increment of 10 years, the petroleum volume in cell D7 is multiplied by the 10-year growth factor that applies to 15-year-old fields, which is in cell B10. This multiplication is done in cell E7. The total estimated size of 5-year-old fields of 5,400 bcfg grows to 10,106 bcfg (fig. 1B, cell E7), after two 10-year growth periods.

Fields that were 5 years old have become 25 years old after two 10-year growth periods. The 10-year growth factor that applies to 25-year-old fields is in cell B11 and the multiplication process continues. The estimated size of 5-year-old fields grows from 5,400 bcfg to 20,129 bcfg (fig. 1B, cell L7) after nine 10-year growth periods. Reserve-growth calculations for the other age classes proceed similarly.

Rows 2 through 18 of each column (except columns A and B) are summed in row 20 (fig. 1). Thus, cell C20 contains the total initial volume of all the fields that are to be grown (463,656 bcfg in this example); cell D20 contains the total volume of these same fields increased by 10 years of reserve growth (557,163 bcfg); cell E20 contains the total volume of these same fields increased by 20 years of reserve growth (629,585 bcfg), and so on. The total volume of petroleum attributable to reserve growth following each 10-year growth increment is calculated in row 22 by subtracting cell C20 (the total initial volume) from cell D20 (the total volume after 10 years of reserve growth), from cell E20 (the total volume after 20 years of reserve growth), and so on. In this example, total reserve growth in the 90 years between 1977 and 2067 is projected to be 480,816 bcfg (fig. 1B, cell L22).

Probabilistic Method

In the probabilistic method, a growth function is composed of a set of growth variables. A growth variable is a dimensionless random variable having a probability distribution. In contrast, a growth factor (previous section) is a multiplicative constant. It is important to the understanding of this paper to keep these two definitions in mind. Each 10-year growth variable, like the corresponding 10-year growth factor, applies to fields of a particular age or range of ages. The growth variable in the probabilistic method is related to the growth factor in the deterministic method as follows: the mean value of a growth variable is set equal to its corresponding growth factor.

The mean-based left-triangular probability distribution (fig. 2) is used here as a probability model for the random variable $X$: growth variable (dimensionless). The right-skewed shape of the left-triangular probability distribution is appropriate as a probability model for a growth variable, whereby high probability of low growth values tapers off to low probability of high growth values. The left-triangular probability distribution is described in Law and Kelton (1991, p. 516). The defining parameters of the mean-based left-triangular probability distribution are the minimum ($a$) and mean ($\mu$). From the defining parameters, the standard characterizing parameters of the left-triangular probability distribution are obtained: minimum ($a$) and maximum ($b$). Namely, given the formula for the mean in terms of $a$ and $b$

$$\mu_X = a + (b - a)/3$$

We solve for the maximum, $b$, and get

$$b = 3\mu_X - 2a$$

The probability density function for the left-triangular distribution is given by

$$f(x) = \frac{2(b-x)}{(b-a)^2}, \quad a \leq x \leq b$$

The graph of the probability density function for the left-triangular distribution of the growth variable is displayed in figure 2.

The standard deviation is equal to

$$\sigma_X = (b-a)/(3\sqrt{2})$$

The fractiles can be computed from

$$F_{100p} = b - \sqrt{p(b-a)} \quad 0 \leq p \leq 1$$

where $P(X \geq F_{100p}) = p$
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**Figure 1.** Spreadsheet program for estimating future oil and gas reserve growth. A. Calculation formulas and example of input data (in this case representing Lower 48 United States gas fields). B. Results of calculations. See text for detailed explanation; growth funct, growth function (dimensionless); ESF, estimated size of fields (cumulative production plus remaining reserves); units for ESF and reserve growth in this example are billion cubic feet of gas. (Modified from Schmoker and Crovelli, 1998.)
PROBABILITY DENSITY

$\mu$ $F_{100} p$ $b$

GROWTH VARIABLE

Figure 2. Left-triangular probability distribution of growth variable (dimensionless) where $a$: minimum, $b$: maximum, $\mu$: mean, and fractile $F_{100} p$ for $0 \leq p \leq 1$.

For example, the median (where $p = 0.50$) can be shown to be

$$ F_{50} = a + 0.293(b - a) $$

Suppose we denote the parameter $c$: initial petroleum volume, that is, the volume of petroleum that will be “grown” (for example, column C of fig. 1). Then the random variable $cX$ represents the grown petroleum volume (total estimated size) after the first growth period. It can be proved that the random variable $cX$ is also distributed as a left-triangular probability distribution with characterizing parameters: minimum $(ca)$ and maximum $(cb)$. The mean, standard deviation, and fractiles of $cX$ are the following:

$$ \mu_{cX} = c \mu_X $$
$$ \sigma_{cX} = c \sigma_X $$
$$ F_{100} p = c \left[ b - \sqrt{p(b - a)} \right] \quad 0 \leq p \leq 1 $$

In general, the calculated future growth is based upon a series of multiplications by the appropriate growth variables, as in the case of the growth factors in the previous section and shown in figure 1A. Let us denote the random variable $Y_i$: grown petroleum volume (total estimated size) after the $i$th growth period. The growth process can be described as a stochastic process consisting of the set of random variables $\{Y_i\}$ where $i = 0, 1, 2, 3, \ldots, n$. Note that $Y_0$ represents the initial petroleum volume $c$. Also, $X_i$ represents the growth variable that is applied in the $i$th growth period, where $i = 1, 2, 3, \ldots, n$. Therefore, we have the following sequence of grown petroleum volumes after $i$ growth periods for $i = 0, 1, 2, 3, \ldots, n$:

$$ Y_0 = c $$
$$ Y_1 = Y_0 X_1 = c X_1 $$
$$ Y_2 = Y_1 X_2 = c X_1 X_2 $$
$$ Y_3 = Y_2 X_3 = c X_1 X_2 X_3 $$
$$ \vdots $$
$$ Y_i = Y_{i-1} X_i = c X_1 X_2 \cdots X_i $$
$$ \vdots $$
$$ Y_n = Y_{n-1} X_n = c X_1 X_2 \cdots X_n = c \prod_{i=1}^{n} X_i $$

This stochastic process can be viewed as an example of the law of proportionate effect. The law of proportionate effect as stated by Aitchison and Brown (1957) is:

A variate subject to a process of change is said to obey the law of proportionate effect if the change in the variate at any step of the process is a random proportion of the previous value of the variate.

The importance of the law is embodied in the following theorem:

A variate subject to the law of proportionate effect tends, for large $n$, to be distributed as a two-parameter lognormal distribution, that is, asymptotically lognormally distributed in a two-parameter form.

The lognormal probability distribution is a good approximate distribution for a product of independent random
variables—the approximation becoming better with more variables (multiplicative central limit theorem for independent random variables). Hence, the fractiles of \( Y_i \) where \( i = 2, 3, \ldots, n \) can be approximated by using the lognormal distribution. As derived in Crovelli (1992), the characterizing parameters of the lognormal distribution, namely \( \mu \) (\( \mu \)) and \( \sigma \) (\( \sigma \)), can be calculated from the mean \( \mu_Y \) and standard deviation \( \sigma_Y \) of a lognormal random variable \( Y \) as follows:

\[
\mu = \ln \left( \frac{\mu_Y^2}{\mu_Y^2 + \sigma_Y^2} \right)
\]

\[
\sigma = \sqrt{\ln \left( \frac{\sigma_Y^2}{\mu_Y^2 + 1} \right)}
\]

Knowing the lognormal characterizing parameters, the lognormal fractiles can be calculated from the formula

\[
F_{100p} = e^{\mu + z_p\sigma} \quad 0 \leq p \leq 1
\]

where \( Z \) is a standard normal random variable and \( P(Z > z_p) = p \).

The two fractiles of most interest in this report are

\[
F_{95} = e^{\mu - 1.645\sigma} \quad \text{and} \quad F_5 = e^{\mu + 1.645\sigma}
\]

At the core of the above stochastic process is the product of independent random variables in the form of \( YX \), where \( Y \) represents a petroleum volume and \( X \) represents a growth variable. The mean, standard deviation, minimum, and maximum of \( YX \) are as follows:

\[
\mu_{YX} = \mu_Y \mu_X
\]

\[
\sigma_{YX} = \sqrt{\sigma_Y^2 \sigma_X^2 + \sigma_Y^2 \mu_X^2 + \sigma_X^2 \mu_Y^2}
\]

\[
\text{Min}(YX) = \text{Min}(Y) \text{Min}(X)
\]

\[
\text{Max}(YX) = \text{Max}(Y) \text{Max}(X)
\]

Suppose there are \( m \) initial petroleum volumes, that is, we are now interested in \( m \) volumes of petroleum that will be “grown.” For example in the deterministic case, figure 1 (column C) lists \( m = 17 \) initial petroleum volumes, two of which are zero. Let us denote the random variable \( Y_{ij} \): \( j \)th grown petroleum volume (total estimated size) after the \( i \)th growth period, where \( j = 1, 2, 3, \ldots, m \). Note that \( Y_{ij} \) represents the \( j \)th initial petroleum volume \( c_j \). Then the total grown petroleum volume after the \( i \)th growth period \( (S_i) \) would be the sum

\[
S_i = \sum_{j=1}^{m} Y_{ij} \quad \text{for } i = 0, 1, 2, 3, \ldots, n
\]

Notice that the total initial petroleum volume is

\[
S_0 = \sum_{j=1}^{m} Y_{0j} = \sum_{j=1}^{m} c_j
\]

For example in the deterministic case, \( S_0 \) corresponds to cell C20 of figure 1.

Finally, the reserve growth after the \( i \)th growth period \( (R_i) \) = (total grown petroleum volume after the \( i \)th growth period) – (total initial petroleum volume). That is,

\[
\text{reserve growth}(i) = R_i = S_i - S_0 = \sum_{j=1}^{m} Y_{ij} - \sum_{j=1}^{m} c_j
\]

for \( i = 0, 1, 2, 3, \ldots, n \)

Also, we have total reserve growth after the \( n \)th growth period = reserve growth\( (n) \).

A simplifying assumption for purposes of mathematical tractability will be made concerning the nature of the \( Y_{ij} \) series for \( j = 1, 2, 3, \ldots, m \). The assumption of perfect positive correlation is made for these random variables. Under the assumption of perfect positive correlation, the standard deviations and fractiles are additive. (The means are always additive.) That is, the mean, standard deviation, and fractiles of \( S_i \) are

\[
\mu_i = \sum_{j=1}^{m} \mu_{ij}
\]

\[
\sigma_i = \sum_{j=1}^{m} \sigma_{ij}
\]

\[
(F_{100p})_i = \sum_{j=1}^{m} (F_{100p})_{ij} \quad 0 \leq p \leq 1
\]

Because of the simplifying assumption, we have

\[
P( (F_{95})_i \leq S_i \leq (F_5)_i ) \geq 0.90
\]

The probability of \( S_i \) being within the range from \((F_{95})_i \) to \((F_5)_i \) is at least 0.90.

Also under the assumption of perfect positive correlation, the mean, standard deviation, and fractiles of \( R_i \) are

\[
\mu_i = \sum_{j=1}^{m} \mu_{ij} - \sum_{j=1}^{m} c_j
\]

\[
\sigma_i = \sum_{j=1}^{m} \sigma_{ij}
\]

\[
(F_{100p})_i = \sum_{j=1}^{m} (F_{100p})_{ij} - \sum_{j=1}^{m} c_j \quad 0 \leq p \leq 1
\]
Because of the simplifying assumption, we have
\[ P\{ (F_{95})_i \leq R_i \leq (F_5)_i \} \geq 0.90 \]
The probability of \( R_i \) being within the range from \((F_{95})_i\) to \((F_5)_i\) is at least 0.90.

**Spreadsheet System**

The analytic probabilistic method described in the previous section is incorporated into a spreadsheet software system called probabilistic reserve growth spreadsheet (PREGS). PREGS consists of a series of 10 panels in the spreadsheet. A panel is a set of approximately 11 columns of related calculations.

Note that column A of Panel 1 in the probabilistic spreadsheet is the same as column A in the deterministic spreadsheet (fig. 1). Panel 1 includes the input of the defining parameters of the mean-based left-triangular probability distribution for each growth variable \( X \) in the growth function: mean (column B) and minimum (column D). Note that column B in the probabilistic spreadsheet is the same as column B in the deterministic spreadsheet. From the defining parameters, the maximum (column J) is computed, and then the other descriptive parameters: standard deviation (column C) and fractiles \( F_{95}, F_5, F_{50}, F_{25}, \) and \( F_5 \) (columns E through I). For example, the 10-year growth variable with parameters in cell B9 (mean of 1.529) through cell J9 applies to fields that are 5 years old. The known estimated size of fields to be grown is also entered (column K).

Note that column K in the probabilistic spreadsheet is the same as column C in the deterministic spreadsheet. For example, the size as estimated in 1977 of Lower 48 gas fields 5 years of age (those discovered in 1972) is 5,400 billion cubic feet of gas (bcfg) (cell K9). The total initial petroleum volume \( S_0 \) is 463,656 bcfg (cell K22).

Panel 2 comprises the computed descriptive parameters of the left-triangular probability distribution for the grown petroleum volumes after the first growth period \( Y_{1.5} \), and the corresponding estimates of reserve growth \( R_1 \) (row 24): mean, standard deviation, and fractiles. Note that column L in the probabilistic spreadsheet is the same as column D in the deterministic spreadsheet (fig 1 (values, 1B)). For example, the total estimated initial size of 5-year-old fields of 5,400 bcfg grows to 8,257 bcfg (mean estimate in cell L9, rounded) with a range from 5,617 bcfg (F95 estimate in cell O9) to 12,054 bcfg (F5 estimate in cell S9), after the first 10-year growth period. The reserve growth is projected to be 93,507 bcfg (mean estimate in cell L24) with a range from 7,103 bcfg (F95 estimate in cell O24) to 217,794 bcfg (F5 estimate in cell S24), after the first 10-year growth period.

Panel 3 includes the computed descriptive parameters of the lognormal probability distribution for the grown petroleum volumes after the second growth period \( Y_{2.5} \), and the corresponding estimates of reserve growth \( R_2 \): mean, standard deviation, and fractiles. The mean (column U) and standard deviation (column V) are used to compute the characterizing parameters of the lognormal distribution: \( \mu \) (column W) and sigma (column X), which, in turn, are used to compute the fractiles. Note that column U in the probabilistic spreadsheet is the same as

![Table](image-url)
Panel 2 of PREGS. Probabilistic spreadsheet system for estimating future oil and gas reserve growth: after one growth period (in this application, 10 years).

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Panel 3 of PREGS. Probabilistic spreadsheet system for estimating future oil and gas reserve growth: after two growth periods (in this application, 20 years).

Geologic, Engineering, and Assessment Studies of Reserve Growth 7
Panel 4 of PREGS. Probabilistic spreadsheet system for estimating future oil and gas reserve growth: after three growth periods (in this application, 30 years).

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Panel 5 of PREGS. Probabilistic spreadsheet system for estimating future oil and gas reserve growth: after four growth periods (in this application, 40 years).

8 Probabilistic Method, Growth of Oil and Gas Reserves
| Panel 6 of PREGS.  Probabilistic spreadsheet system for estimating future oil and gas reserve growth: after five growth periods (in this application, 50 years). | Panel 7 of PREGS.  Probabilistic spreadsheet system for estimating future oil and gas reserve growth: after six growth periods (in this application, 60 years). |
Probabilistic spreadsheet system for estimating future oil and gas reserve growth: after seven growth periods (in this application, 70 years).

Panel 8 of PREGS. Probabilistic spreadsheet system for estimating future oil and gas reserve growth: after eight growth periods (in this application, 80 years).

Panel 9 of PREGS. Probabilistic spreadsheet system for estimating future oil and gas reserve growth: after eight growth periods (in this application, 80 years).

10 Probabilistic Method, Growth of Oil and Gas Reserves
fields are in the form of a mean estimate with a range from a low estimate of future reserve growth of Lower 48 United States gas fields. The results of this application (Panels 1–10) are summarized in the graph displayed in figure 3. The probabilistic gas fields. The results of this application (Panels 1–10) are summarized in the graph displayed in figure 3. The probabilistic estimates of future reserve growth of Lower 48 United States gas fields are in the form of a mean estimate with a range from a low F95 estimate to a high F5 estimate for nine growth periods (10-year increments).

Summary

The objective of this report is the development and description of a probabilistic method and spreadsheet system, called the PREGS system, for estimating future growth of oil and gas reserves. The primary advantages of the PREGS system are several-fold. The probabilistic method utilizes the same data as required by its deterministic predecessor in Schmoker and Crovelli (1998); most importantly, no additional data are needed. All additional benefits accrue from incorporating an analytic probabilistic method into a computer software spreadsheet.

Panel 10 of PREGS. Probabilistic spreadsheet system for estimating future oil and gas reserve growth: after nine growth periods (in this application, 90 years).
Figure 3. Graph of probabilistic estimates of future reserve growth of Lower 48 United States gas fields in the form of a mean estimate together with a range from a low F95 estimate to a high F5 estimate for nine growth periods (10-year increments). Units for reserve growth are trillion cubic feet of gas. This example is derived from the results shown in Panels 1–10.

References Cited


Arrington, J.R., 1960, Predicting the size of crude reserves is key to evaluating exploration programs: Oil & Gas Journal, v. 58, no. 9 (February 29), p. 130–134.


