RESERVOIR ENGINEERING FOR GEOLOGISTS
Part 8 – Monte Carlo Simulation/Risk Assessment

by: Ray Mireault P. Eng. and Lisa Dean P. Geol., Fekete Associates Inc.

Geologist A is presenting a development prospect. Geologist B is presenting an exploration play. Which should you invest in?

This is a daily question in oil companies. A development prospect is generally considered a "safer" investment but the volume of hydrocarbons and its economic value is limited (Figure 1). The exploration prospect may carry more "dry hole" risk but a company has to make some exploration discoveries or it eventually runs out of development opportunities (Figure 2).

However, simply estimating the size of the deposit is not sufficient. Although Geologist A's development prospect has a P10 to P90 recoverable gas range of between 258 and 1,219 10^6 m^3 (10 to 43 BCF), it may or may not be a good investment. For example:

- Low permeability reservoir rock may restrict production rates so that each well recovers very little gas over time. The low rate/long life profile may actually have very little economic value.
- The combination of royalty rates, operating costs, processing fees, and transportation tariffs may mean that very little of the sales revenue is retained by the company, despite an apparently attractive commodity sale price outlook.
- Capital costs may simply be too great. If the prospect is located offshore (or at a remote onshore) location, the prospect may contain insufficient gas to offset the required investment capital.

Management needs to know the following about any exploration or development opportunity:

- What are the chances that at least the value of the capital investment will be recovered if we proceed?
- How much capital could be lost if events do not turn out as expected?
- What is the potential gain in economic value if events do unfold as expected?
- What is the total capital commitment required to realize production?

Answering the financial questions would be (relatively) easy if we knew exactly how much oil/gas is in place, the fraction that will be recovered, its sale price when produced, and the associated capital and operating costs. But prior to producing a deposit, we don't know any of the foregoing with any degree of precision. We need to assess and balance the uncertainty in our technical knowledge against the impact that the uncertainty has on the expected financial performance (and capital exposure) of the investment.

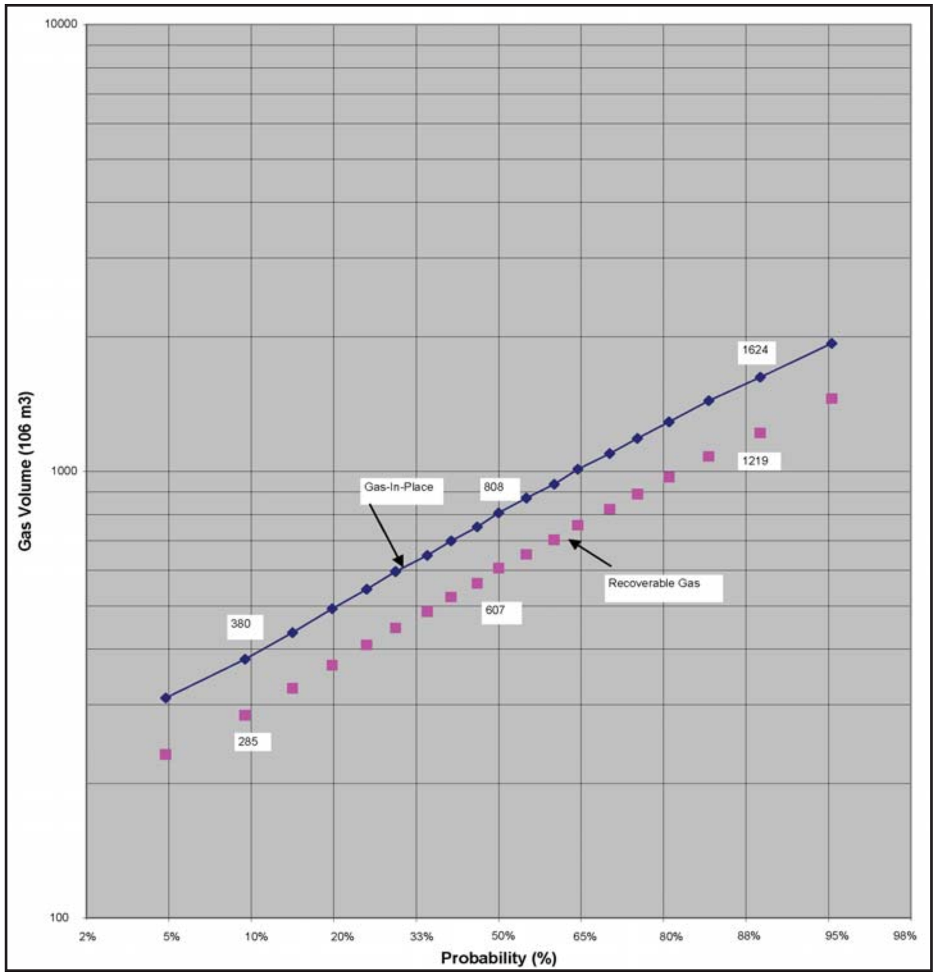

Figure 1. Probability Chart, Gas Development Prospect.

When consistently applied, Monte Carlo simulation provides a tool to systematically assess the impact of technical uncertainty on financial performance. A consistent approach also enables comparison and ranking of development and exploration opportunities, so a company can identify and pursue its better prospects.

In Fekete's experience, the following assessment procedure provides a consistent approach to prospect evaluation:

1. Estimate the probable range in OOIP/ OGIP from 3-point estimates for the input parameters in the volumetric equation.
2. Estimate the probable range in recovery factor from reservoir engineering principles, analogue performance, and/or reservoir simulation.
3. Estimate the total field/pool daily production rate range from the recoverable hydrocarbon range based on a seven year rate-of-take (deplete the field in about 15 years).
4. Estimate the number of wells required to achieve the projected daily production rate from reservoir rock characteristics and test well performance.
5. Estimate the type and size of pipelines, wellsite, and plant facilities required to produce at the forecasted production rates.
6. Estimate operating costs and assess the present day value of production from economic runs. This is the discounted present day value of the sales price less royalties, operating costs, processing fees, and transportation tariffs.
7. Estimate well and facility capital costs.

8. Compare the probable range in economic value to the required capital investment range. Quantify the chances of recovering the capital investment, the expected return on investment, the capital exposure, and the total capital commitment.

The job of the earth sciences (geology, geophysics, reservoir engineering) in a Monte Carlo evaluation is to develop input parameter ranges that reflect the current state of knowledge for the prospect. The recommended approach is an integrated approach that first develops minimum and maximum values that are consistent with the known facts. The end point values **must** encompass the true value with a high (90 to 95%) degree of certainty. The most likely value is estimated only after establishing the possible range in the parameter values.

Geologist A's development prospect is a structural trap with 4-way closure that contains a series of stacked fluvial sands at a depth of about 400 m. The sands were initially deposited in a broad valley and are capped with a thick shale sequence. Subsequent basement uplift created the present drape structure. Drilling results to date set the minimum area of the deposit at 600 ha. Based on the seismic interpretation, the areal extent is most likely about 1000 ha but it could be as large as 1,600 ha (the maximum closure area with the existing data).

The structure is estimated to contain about 46 m of gross sand thickness within a 60 m gross interval. Due to fluvial deposition, the areal extent of an individual sand body is expected to be limited and so not all sands are expected to be gas charged. Accordingly, the average net pay is estimated to be between 12 and 46 m but will most likely be about 21 m.

The geological model and limited cuttings analysis suggest that sand porosity also varies. If the deposit is dominated by argillaceous, highly cemented sands, then average porosity could be as low as 8%. However, porosity will be either better developed or better preserved when fluvial rock is saturated with hydrocarbons, so a large percentage of ultra-clean sands could push the average porosity value to as much as 18%. Assuming average quality sands, porosity will most likely be about 12%.

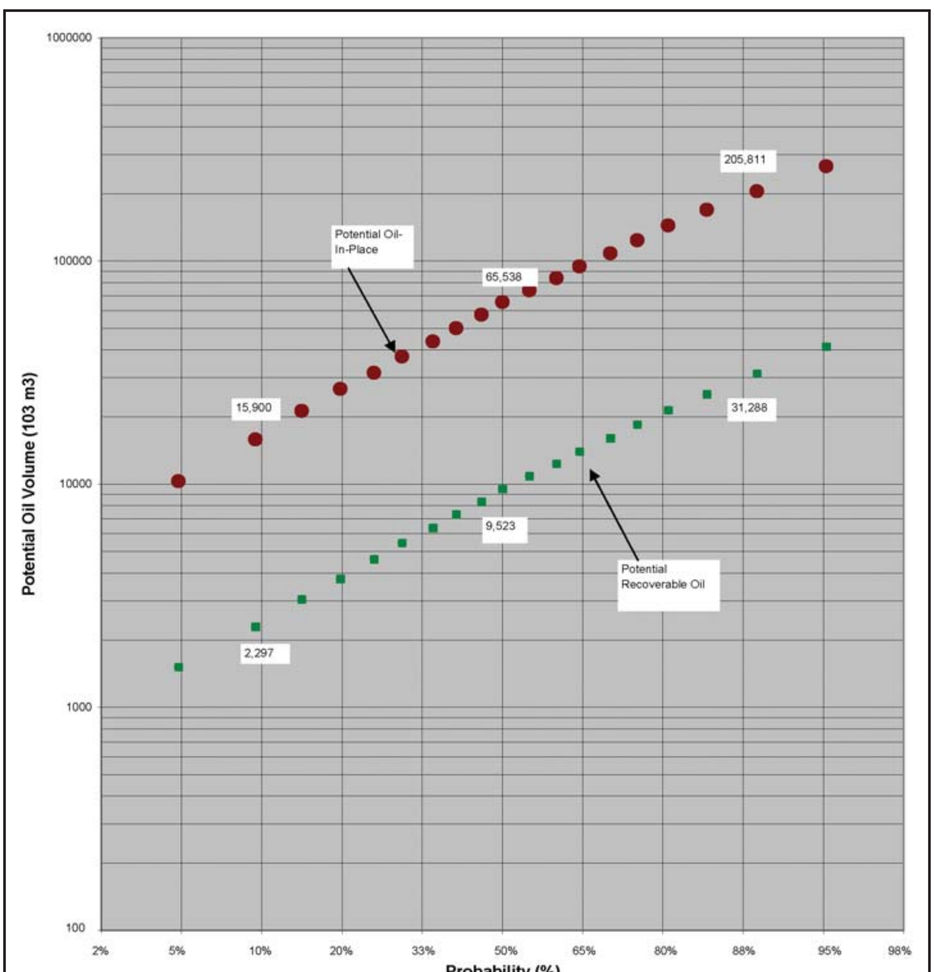

Figure 2. Probability Chart, Oil Exploration Prospect.

Currently, there is no good basis from which to estimate the residual water saturation in the gas-bearing sands. The best value for good-quality sands would be 15% Sw. An average water saturation value for the "dirty" fine-grained sands might be about 40% but could be as high as 60% (the maximum value for fine-grained sand).

Well test data indicates that the deposit contains a sweet, 0.7 gravity gas. Two pressure buildup tests indicate a reservoir pressure of 3,448 and 4,138 kPa(abs) for an arithmetic average of 3,793 kPa(abs). Reservoir temperature is estimated at 38°C. The gas deviation factor (Z) at initial reservoir conditions is estimated to be about 0.9.

Sand permeability is expected to vary considerably between individual sands with a range of 3 to 30 mD. Based on experience and reservoir engineering principles, gas recovery from volumetric expansion of a reservoir at shallow depth is generally in the order of 70 to 85%. Due to the limited areal extent of the sands, the most likely value is estimated at 75%

The following table summarizes the input parameters that were used to develop the volumetric estimates of gas-in-place and recoverable gas for the development prospect:

$$OGIP=A*h*\Phi*(1-S_W)*\frac{(T_s*P_i)}{(P_s*T_f*Z)}$$

Parameter	Min	Most Likely	Max
Area (ha)	600	1000	1600
Net Pay m	12	21	46
Porosity	8%	12%	18%
Water Saturation%	15%	40%	60%
Reservoir Pressure kPa(a)	3448	3793	4138
Recovery Factor	70%	75%	85%
Reservoir Temperature °C		38	
Gas Deviation Factor Z		0.9	

Once 3-point estimates have been developed, Monte Carlo simulation can be used to calculate the gas-in-place and recoverable gas volumes. Monte Carlo simulation consists of randomly selecting values for each input parameter and calculating a gas-in-place and recoverable gas volume. Many iterations (in this case 10,000) creates gas-in-place and recoverable gas distributions.

From the simulation, Geologist A's gas development prospect has an 80% probability of containing between 380 and 1,624 $10^6 m^3$ of gas-in-place. Based on the technical input,

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there is an 80% chance that the recoverable gas volume is between 285 and 1,219 $10^6 m^3$ of gas. The mathematical significance of the P50 value is that it is the number that splits the distribution into 2 equal halves.

An obvious question is why can't we simply multiply all the minimum input parameter values to determine the minimum gas volume and all the maximum values for the maximum volume? Doing so yields the following values:

	Min	Most Likely	Max
Gas-in-Place $10^6 m^3$	171	582	4,565
Recoverable Gas $10^6 m^3$	120	437	3,880

	P90 $10^6 m^3$	P90 $10^6 m^3$	P90 $10^6 m^3$
Gas-in-Place	380	808	1624
Recoverable Gas	285	607	1219

As can be seen, the minimum values are much less than the P90 values calculated previously and the maximum values are much greater. Even a calculation using the most likely values doesn't match the P50 values very well. From inspection of the probability graph (Figure 1) the chances of recovering more than 120 $10^6 m^3$ of gas are greater than 98% (100-2%). At the other end of the scale, there is less than a 2% chance of producing 3,880 $10^6 m^3$ from the prospect (the probability value corresponding to 3,880 $10^6 m^3$ is well off the scale).

The reason for the large discrepancies is because the error in the product of multiplication successively increases with each multiplication, unlike addition. To illustrate, if the estimated value for each input parameter is out by 17%, the sum of addition will also be out by 17%. Not so with multiplication:

	-17% Error	Correct	+17% Error	Alternating
A	5	6	7	7
h	5	6	7	5
Φ	5	6	7	7
1-Sw	5	6	7	5
Addition	20	24	28	24
Error	83%		117%	100%
Multiplication	625	1296	2401	1225
Error	48%		185%	95%

Even alternating from a conservative to an optimistic estimate doesn't completely cancel out the errors when multiplying.

In this article we have outlined the rationale for Monte Carlo Simulation. Geologist A's development prospect was used as an example. In next month's article, we will present Geologist B's exploration prospect and then compare the two Monte Carlo Simulation outcomes, clearly showing how Monte Carlo can be used to determine economic viability and therefore aid in business decisions!

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

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Temperature increase, due to changes in various climate drivers, is one of the easiest variables to model. Large-scale climate trends can be modelled with a fair degree of certainty although regional trends are not as readily simulated due, in large part, to computational limitations. A very good fit with historical data has been achieved from models incorporating both man made and natural climate drivers (see Weaver in Coward and Weaver, 2004). The current warming over the last 50 years, based on these models, is attributed predominantly to the enhanced greenhouse effect from anthropogenic sources, while changes in solar radiation accounts for a portion of the warming. Warming in the first half of the 20th century is attributed largely to increased solar output while the mid-century cooling is attributed to sulphur emissions due to burning of coal (Dessler and Parson, 2006).

I maintain that our duty to society is to provide unbiased information that accurately reflects the state of scientific knowledge at this time. The position paper fails to achieve this by presenting a highly selective reading of the current state of knowledge both of current climate change and of paleo-climates. In addition, the findings of the atmospheric science community are discredited or presented as being highly uncertain. This judgement is not backed up by refereed articles nor is it a judgement by people engaged in the research. If we as a scientific organization wish to challenge the research of thousands of scientists then we must be able to present independent research to back our statements and be willing to have them critically scrutinized by the entire scientific community. Although we may not like the findings of the atmospheric science community, casting aspersion upon their conclusions reduces us to the status of an advocacy group for our industry as opposed to a scientific organization.

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