SCA-9905

INCORPORATING CORE ANALYSIS DATA UNCERTAINTY IN ASSEST VALUE ASSESSMENT

Andre′ J. Bouchard and Matthew J. Fox
Conoco Inc.

ABSTRACT

This paper describes how uncertainty in core analysis parameters are integrated into the appraisal and development stages of a project's life-cycle using Decision and Risk Analysis techniques to focus data acquisition on the critical uncertainties influencing value. The process involves value-based decision-making using Monte Carlo techniques incorporating uncertainty in the factors controlling Net Present Value.

At the appraisal planning and execution stage the process largely involves analytical reservoir prediction techniques incorporating uncertainty in the fundamental parameters that control reservoir performance. For example, the technique can determine the significance of uncertainty in core analysis parameters such as capillary pressure, relative permeability, and residual oil saturation relative to other uncertainties influencing value. As a result, the value of data acquisition, including core analysis data, can be established early in the life cycle.

At the development planning stage a similar philosophy is adopted but more detailed analysis is performed when petrophysical and special core analysis data become available. For example, inter-well scale stochastic simulation of reservoir performance considering geologic body size, orientation, distribution, and permeability, relative permeability and residual oil saturation can be used to determine the factors controlling reservoir performance uncertainty. These factors can then be incorporated into an overall uncertainty assessment, including other variables such as costs and oil price, to identify the key uncertainties and the expected range of project value.

Examples are presented where core analysis data and its associated uncertainty had a significant impact on value assessment at the appraisal and development stages of the life cycle. The examples include waterflooding of a complex carbonate, a fractured oil reservoir under water injection, and an over-pressured mini-basin reservoir under primary depletion.

INTRODUCTION

At the exploration stage of an asset's life-cycle, investment decision-making in the presence of uncertainty has been practiced for many years using various methodologies. However, only in recent years has the petroleum industry moved towards consistently applying similar techniques in the process of making investment decisions at other stages of the asset life-cycle such as appraisal, development, and disposition. The increased level of competition for the world's petroleum resources and host government tax regimes that limit upside potential require more than ever that the critical uncertainties controlling asset value be identified and properly quantified prior to making an investment decision.

In order to accomplish this, asset-specific economic models must be constructed, integrating the uncertainties from all links of the value-chain: reservoir performance, development and operating costs, product prices, etc. This paper focuses on how uncertainty in core analysis parameters can be incorporated in asset value assessment. Cases are presented where uncertainty in core analysis parameters figured prominently in the decision making process.

METHODOLOGY

The methodology used to assess the impact of uncertainty in core analysis data on asset value and to drive core analysis data acquisition programs is based on Decision and Risk Analysis principles (1), or D&RA. D&RA is the process of identifying the critical uncertainties controlling asset value and quantifying the impact of these uncertainties on value.

Decision Criteria and Influencing Parameters. The first step in the D&RA process is to establish the decision criteria for investment. Typically, this is a combination of Net Present Value (NPV) and some measure of capital efficiency such as Internal Rate of Return (IRR) or Profitability Index (PI). For simplicity, in this paper the decision criterion is limited to NPV. Once the decision criteria have been established, an influence diagram is constructed to identify the parameters controlling the decision. The complexity of most problems requires that many influence diagrams be constructed, working from the highest level factors influencing value such as costs and revenue, to much more detailed diagrams dealing with, for example, recovery factor. Core analysis related parameters are explicitly included in the influence diagrams, their main influence being on oil-in-place, recovery factor and production rate. Figure 1 is a simplified Net Present Value influence diagram for an oil reservoir development highlighting the influence of core analysis related parameters. Implicitly, since Net Present Value is the result of discounted cash flows, the NPV influence diagrams are also the influence diagrams for other economic metrics of interest such as IRR and PI.

Economic Model Construction. The next step in the process is to build an NPV model for the asset incorporating the parameters identified by the influence diagrams. The model consists of three major components: reservoir performance prediction, cost estimation, and economics. The NPV model must be capable of probabilistic operation. The two alternative probabilistic approaches that can be used are the Monte Carlo or the Decision Tree(2) method. The former technique is preferred since the latter does not fully account for dependencies among parameters. An example of such a dependency is the relationship between residual oil saturation to water displacement versus initial water saturation magnitude.

At the pre-appraisal stage of the life-cycle it is frequently adequate to predict reservoir performance using analytical techniques. For example, pattern waterflood performance can be estimated using methods based on fractional flow such as Styles (3). At the post-appraisal and development stages of the life-cycle reservoir simulation in conjunction with geologic modeling is a more appropriate method to estimate reservoir performance. Analytical methods can easily be programmed into the NPV model. The results of reservoir simulation can be incorporated into the NPV model by developing response functions such as relationships between recovery factor, mobility ratio, heterogeneity and abandonment water-cut (4).

Parameterization. The next step in the process is to develop probability distribution functions to describe uncertainty in the model parameters. In the examples presented here, triangular distributions are used for most parameters. Triangular distribution functions are described by the minimum, most likely, and maximum value for the parameter. For core analysis parameters, these values can be derived from available core data or analogues. For example, in a pre-appraisal situation probabilistic analysis of the well logs from the discovery well can be used to define the mean water saturation (the most likely value) and the uncertainty in the mean at a 98 percent confidence level (subsequently used as the maximum and minimum values in the triangular distribution). Discrete distributions are used for parameters that cannot be described by a continuous function. Heterogeneity measures such as areal complexity relative to well spacing and tubing size are examples of parameters that discrete distributions are used for. Rectangular distributions are sometimes used when no value within the range is thought to be more likely than another value. An example of where a rectangular distribution is applied is in the case of oil price uncertainty.

Analysis of Results. The final step of the process is to identify the critical uncertainties controlling NPV. This can be done in several ways including rank correlation coefficients and tornado charting. The former method is more rigorous since all interdependencies among parameters are captured in the analysis. However, the results of that analysis are not as easy to interpret and communicate as those produced by the tornado method since the results are not in terms of NPV and the relative impact of upside and downside parameter values is obscured. The tornado charting method involves testing each parameter for its impact on NPV independent of the other parameters; therefore, some interdependencies may not be captured using this method. Ranking the parameters according to their contribution to the total variance identifies the critical uncertainties controlling NPV. The results of the tornado method are displayed on a horizontal bar graph. The size of the bar indicates the relative impact of uncertainty in the input parameters on NPV. In most cases the ranking of correlation coefficients and the tornado chart method identify the same critical uncertainties.

EXAMPLES

Following are three examples of where the methodology has been used to identify the impact of uncertainty in core analysis related data on Net Present Value. The results are presented in terms of percent change in NPV relative to either the base case or mean NPV. Note that in the tornado charts, most of the key uncertainty ranges (the bars of the tornado chart) are presented in terms of percent change from the base case value. The base case values for the key uncertainties can be found in Tables 1-3.

Waterflood of a Complex Carbonate. This reservoir is an unfractured carbonate grain stone mound composed of multiple coarsing upward geologic sequences. The asset was acquired from a previous operator who had drilled a number of delineation wells. The operator had attempted to core a number of wells, but recoveries were poor, recovering core only in the lower permeability zones. In addition, the log quality was also poor and this resulted in considerable uncertainty in water saturation. The reservoir was at a point where the decision to develop the asset was contingent on the reservoir performance prediction.

The reservoir development plan was to implement a pattern waterflood. The mobility ratio for this reservoir is unfavorable (M~3.0). This combined with the lack of core material led to questions about the magnitude and distribution of permeability in the reservoir since these impact, respectively, well rate and recovery factor. A sensitivity analysis was undertaken to understand the impact of these and other uncertainties on asset value and to aid in designing a data acquisition program. Reservoir simulation in combination with geologic modeling was used to predict reservoir performance. The key core analysis and development related parameters and ranges of uncertainty used for this example are shown in Table 1.

The critical uncertainties controlling 90% of the uncertainty in the NPV of this asset are shown in tornado diagram of Figure 2. For this example, a three-dollar swing in the price of oil controls 36 percent of the NPV uncertainty. Oil price uncertainty typically dominates most analyses. Uncertainties in water saturation, porosity and net thickness were obtained from probabilistic log calculations. Uncertainty in permeability was estimated from the limited amount of routine core analyses that had been performed. In the absence of laboratory data, the uncertainty in residual oil saturation was estimated from an in-house database.

Vertical heterogeneity uncertainty was characterized by a Dykstra-Parsons V-Factor (5) derived from core and log data. At this reservoir's mobility ratio, the degree of vertical heterogeneity as represented by V-Factor can have a significant impact on NPV as shown by the graph of Figure 3. This highlights the importance of correctly identifying the mean and the uncertainty in the mean of the input parameters. Only by performing value-based sensitivity analysis similar to that described above can the true impact of such uncertainties be understood.

Figure 4 is a graph comparing the NPV cumulative probability for two cases: one incorporating the uncertainty in all critical parameters, and the second limited to core analysis related parameters: specifically, porosity, water saturation, net thickness, permeability, vertical heterogeneity, and residual oil saturation. Comparing the ratio of the 80% confidence intervals for these two cases, approximately 51 percent of the total uncertainty in NPV is due to uncertainty in engineering parameters that core analysis data can influence. Core analyses is, of course, not the only means to resolve some of these uncertainties. For example, pressure transient analysis can provide large-scale permeability and connected volume estimates. Additionally, there is always a "residual" uncertainty in all parameters that is carried forward since it is not possible to have perfect knowledge of the reservoir.

The analysis described above was used to justify the acquisition of additional core and core analyses data including detailed permeability measurements, log parameters, capillary pressure data, and residual oil saturation measurements. The geologic and reservoir models were updated using the acquired data and new reservoir performance estimates were made. The project was approved for development and is pending implementation.

Fractured Oil Reservoir. This example involves a sandstone reservoir fractured by thrust faulting. The reservoir has high oil gravity and the viscosity is less than one centipoise at reservoir temperature and pressure. The reservoir is significantly under-saturated and under-pressured due to seal breach. Three exploration wells were drilled in the structure. Logs were run in each well producing reasonable quality porosity and net thickness information matching offset data. Water saturation determination was problematic because of the low resistivity contrast between the formation brine and the oil. No core was taken in the exploration wells because of drilling problems in the under-pressured environment. Several well tests were performed and suggested dense fracturing in certain parts of the reservoir. This led to the notion of water injection as means to maximize recovery from the reservoir, potentially taking advantage of oil recovery due to spontaneous water imbibition.

The asset was at the pre-appraisal stage of the life cycle and there was an opportunity to sell the asset prior to further investment in appraisal. In response to this, a reservoir engineering study was conducted with the goal of identifying the key uncertainties controlling asset value and determining the expected value and range of value for the asset. Reservoir performance was predicted using analytical methods calibrated to reservoir simulation. The main reservoir performance problem was the prediction of the matrix block transfer function. The key core analysis and development related parameters and ranges of uncertainty used for this example are shown in Table 2.

The parameters controlling 90% of the uncertainty in the NPV for this reservoir are shown in tornado diagram of Figure 5. Aside from oil price, the major uncertainty driving the value of this asset is wettability. It impacts NPV nearly +/-100% from the base case value, implying that uncertainty in wettability alone can cause the project to be economically viable or not. Since no wettability data were available for this reservoir, analogue data from an offset field was used in conjunction with an in-house database to develop the range of uncertainty in wettability. This range corresponds to an Amott-Harvey Wettability Index (6) of -0.20 to +0.20. In the reservoir performance model the impact of wettability is manifested in terms of its impact on the water displacing oil capillary pressure curve (i.e., the spontaneous imbibition component and the magnitude of the negative portion of the capillary pressure curve). The capillary pressure curve is also correlated to matrix permeability and porosity via the Leverett J-Function (7). Matrix permeability is also significant because it impacts the matrix to fracture transfer rate.

The range of fracture porosity used in the modeling was obtained from the well tests and analogues. Fracture porosity is not considered a core analysis related uncertainty and is best obtained from history matching reservoir performance.

The uncertainty functions for water saturation and net pay used in the analyses were derived from probabilistic log analysis. The range of matrix porosity used in the modeling was obtained from a database of offset wells from several analog reservoirs. This database provided much greater information concerning the lateral variability of porosity in the reservoir than the three exploration wells, and having confirmed the similarity of the log porosity to the database values, the mean and uncertainty in the mean from the database were used in the analyses. The database also provided estimates of matrix permeability. The range of residual oil saturation used in the analyses was obtained from an in-house database.

Well spacing appears on the tornado chart due to its impact on development cost. Well spacing is an issue for this reservoir because of the uncertainty in compartmentalization due to faulting and localized fracturing.

Figure 6 is a graph comparing the NPV cumulative probability for two cases: one incorporating the uncertainty in all critical parameters, and the second limited to the core analysis related parameters: specifically, water saturation, porosity, net thickness, wettability, and residual oil saturation. Comparing the ratio of the 80% confidence intervals for these two cases, approximately 67 percent of the total uncertainty in NPV is due to uncertainty in parameters that core analysis data can influence, the majority of the uncertainty being due to lack of knowledge concerning the wettability.

The importance and impact of wettability to this asset is demonstrated in Figure 7 where Amott-Harvey Wettability Index is plotted versus NPV. The non-linearity in the relationship is due to the relative contribution of the spontaneous imbibition recovery component versus the gravity drainage recovery component for the median matrix block height of this reservoir.

The foregoing analysis was used in a Value of Information exercise to determine whether or not to obtain core in an attempt to resolve the uncertainty in wettability prior to making a decision to offer the asset for sale. Ultimately, it was decided to undertake wettability measurements and these are still ongoing.

Over-Pressured Mini-Basin. This example is of an over-pressured turbidite sand reservoir prior to the drilling of an exploration well. Based on analogue fields, the sands were assumed to be unconsolidated to some degree. A finite aquifer was expected, the size of which would be a function of the oil accumulation size relative to the size of the basin. The oil was anticipated to be high gravity and under-saturated. The size of the prospect and the development cost environment dictated oil production by natural depletion. An evaluation to determine the critical uncertainties controlling the range of NPV if the prospect was a discovery was conducted prior to drilling the exploration well in order to justify the well and to evaluate data acquisition requirements. Specifically, the decision to be made was whether or not to side-track and core the exploration well should it result in a discovery. For this evaluation, reservoir performance was predicted using analytical methods calibrated to reservoir simulation. The key core analysis and development related parameters and ranges of uncertainty used for this example are shown in Table 3.

The analysis identified the critical uncertainties shown in the tornado diagram of Figure 8. Aside from oil price, the critical uncertainties controlling the majority of the uncertainty in NPV are pore-volume compressibility at initial pressure and oil-in-place. Unlike the two other examples described above, oil-in-place uncertainty was calculated outside of the asset model and treated as an input parameter rather than a calculation within the model. Oil-in-place uncertainty was calculated assuming exploration success treating hydrocarbon filled area, water saturation, porosity, and net thickness as uncertainties. These inputs along with permeability data were derived from analog data sets.

The range of pore-volume compressibility used in the analysis was derived from measurements on analog core and history matching of analog reservoirs. Because the reservoir is under-saturated, the pore-volume compressibility contributes significantly to the recovery factor. For this reservoir approximately 80% of the oil recovered is due to the energy supplied to the oil zone and the aquifer by pore-volume compressibility. The impact on NPV of the uncertainty in pore-volume compressibility alone is a +/- 50 percent change in the base case value.

Tubing head pressure appears on the tornado chart because it impacts abandonment pressure and this impacts reserves. Tubing head pressure and facilities cost are uncertain because at this stage of the life-cycle infrastructure design is only conceptual.

Figure 9 is a graph comparing the NPV cumulative probability for two cases: one incorporating the uncertainty in all critical parameters, and the second limited to the core analysis related parameters: specifically, pore-volume compressibility and permeability. Since oil-in-place was input directly in the model, uncertainty in water saturation, porosity and net thickness were not included in this calculation as was the case in the previous examples. Comparing the ratio of the 80% confidence intervals for these two cases, approximately 55 percent of the total uncertainty in NPV is due to uncertainty in parameters that core analysis data can influence, the majority of the uncertainty being due to uncertainty in pore-volume compressibility.

The foregoing analysis was used to justify side-track coring on the exploration well in the event of a discovery.

IMPERFECT INFORMATION

The above examples are not meant to imply that all of the uncertainty in core analysis related engineering parameters is resolved by obtaining core and making measurements. Core analysis data are imperfect information due to the uncertainty in laboratory procedures and the small volume of the reservoir that core represents. The impact that cores analysis data acquisition can have on asset value must be assessed by including the aspect of imperfect information in the Value of Information calculation.

CONCLUSIONS

1.) A methodology has been proposed that can be used to assess the impact of uncertainty in core analysis data in the context of the other uncertainties impacting asset value.

2.) The proposed methodology is based on integrating uncertainty in core analysis related engineering parameters into asset economic models such that the impact of core analysis data on Net Present Value can be assessed.

3.) Examples of where the methodology has been used to identify the impact of uncertainty in core analysis related data on Net Present Value have been presented.

4.) Core analysis data have been shown to have a significant impact on asset value for a wide range of reservoir problems.

REFERENCES

1. Brown, R. V., Kahr, A. S., and Peterson, C., Decision Analysis: An Overview, Holt, Rinehart and Winston, 1974, 3-5.

2. Freund, J. E., *Introduction to Probability*, Dover Publications Inc., 1973, 155-156.

3. Stiles, W. E., "Use of Permeability Distribution in Waterflood Calculations," *Trans*., AIME (1949) **186**, 9-13.

4. Jones, A. D. W., Al-Qabandi, S., Reddick, C. E., and Andersen, S. A., "Rapid Assessment of Pattern Waterflood Uncertainty in a Giant Oil Reservoir," SPE 38890.

5. Dykstra, H. and Parsons, R. L., "The Prediction of Oil Recovery by Water Flood," *Secondary Recovery of Oil in the United States*, 2nd ed., API (1950) 160-174.

6. Anderson, W. G., "Wettability Literature Survey—Part 2: Wettability Measurement," *Journal of Petroleum Technology*, Nov., 1986, page 1246-1262.

7. Leverett, M. C., "Capillary Behavior in Porous Solids," *Trans.*, AIME (1941) **142**, 152-169.

ACKNOWLEDGEMENTS

The authors thank the management of Conoco for permission to publish this paper and Jeff Jurinak, Frank Koskimaki and Chad Huffman for reviewing the manuscript.

Figure 1

Simplified Influence Diagram Showing Realtionship of Core Analysis Parameters to NPV

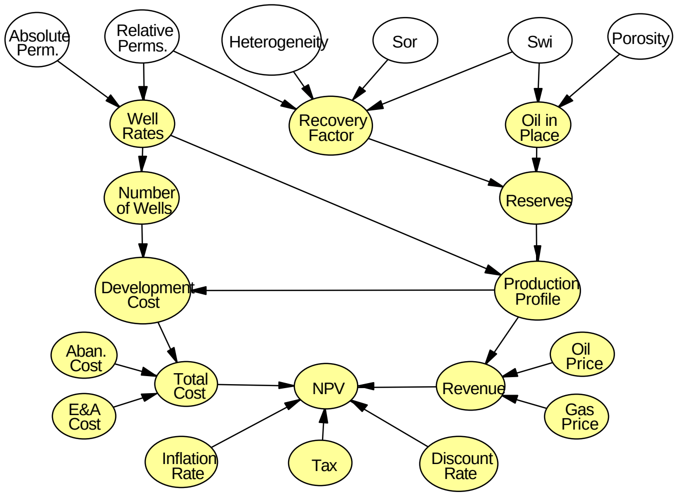

Figure 2
Waterflood Example:
Critical Uncertainties Controlling 90% of NPV Uncertainty
(Percent Change from Base Case NPV)

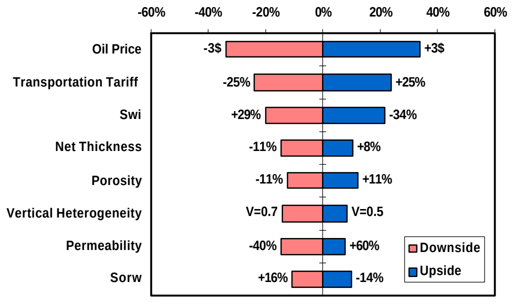

Figure 3
Waterflood Example:
Impact of Vertical Heterogeneity on NPV

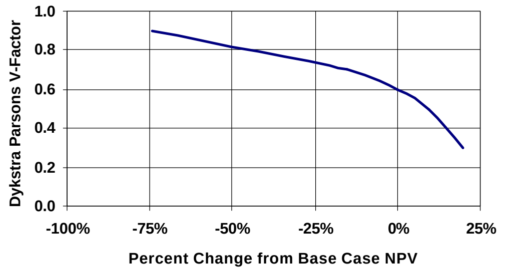

Figure 4
Waterflood Example:
Impact of Uncertainty in Core Analysis Related
Parmeters Relative to All Parameters

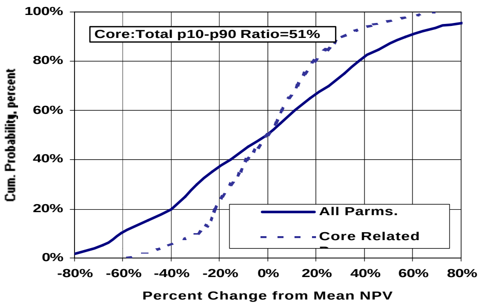

Figure 5
Fractured Oil Reservoir Example:
Critical Uncertainties Controlling 90% of Uncertainty in NPV
(Percent Change from Base Case NPV)

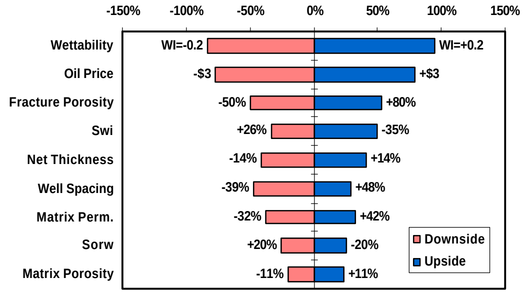

Figure 6
Fractured Oil Reservoir Example:
Impact of Uncertainty in Core Analysis Related
Parmeters Relative to All Parameters

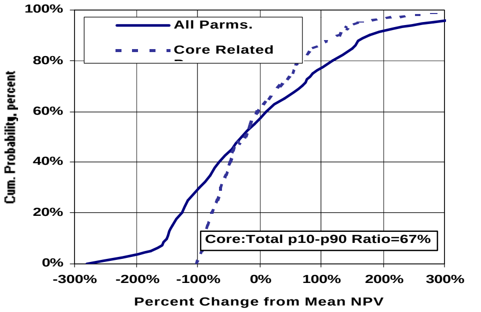

Figure 7
Fractured Oil Reservoir Example:
Impact of Wettability on NPV

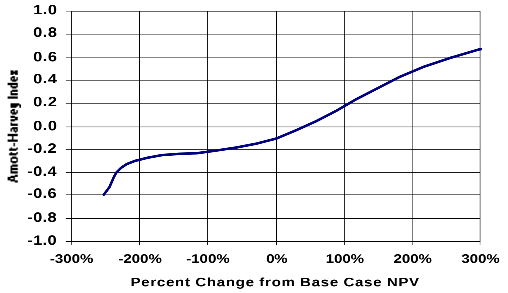

Figure 8
Overpressured Mini-Basin Example:
Critical Uncertainties Controlling 90% of Uncertainty in NPV
(Percent Change from Base Case NPV)

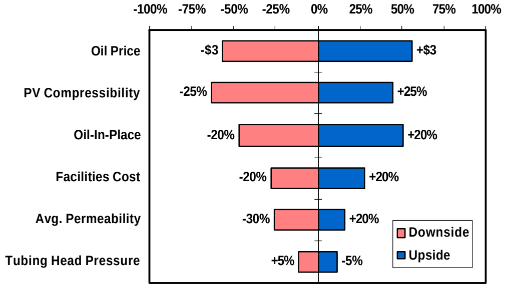

Figure 9
Overpressured Mini-Basin Example:
Impact of Uncertainty in Core Analysis Related
Parmeters Relative to All Parameters

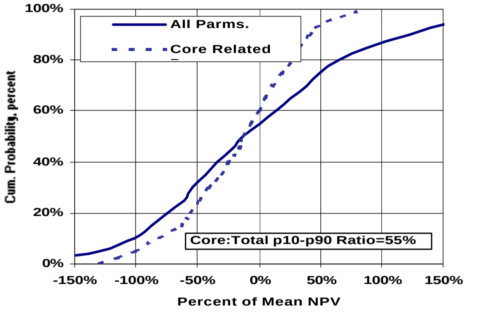

Table 1
Waterflood Example
Key Inputs and Ranges of Uncertainty

	Minimum	Most Likely	Maximum	
Core Analysis Related Inputs				
V-Factor	0.5	0.6	0.7	
Porosity	0.14	0.17	0.20	**frav. GRV**
Perm (Kair)	67	137	256	**md**
Swi	0.14	0.26	0.37	**frac. PV**
Ko@Swi/Kair	0.55	0.72	0.80	**fraction**
Krw@Sorw/Ko@Swi	0.20	0.35	0.50	**fraction**
Sorw	0.22	0.28	0.36	**frac. PV**
Net Thickness	95	123	137	**feet**
Development Related Inputs				
Well Spacing	92	143	206	**acres**
Well Cost		Base +/- 20%		
Facilities Cost		Base +/- 25%		
OPEX		Base +/-10%		
Tranportation Tariff		Base +/- 25%		
Oil Price		Base +/-$3		

Table 2
Fractured Oil Reservoir Example
Key Inputs and Ranges of Uncertainty

	Minimum	Most Likely	Maximum	
Core Analysis Related Inputs				
Wettability	-0.20	0.00	0.20	**Amott-Harvey**
Fracture Porosity	0.001	0.005	0.01	**frac. GRV**
Matrix Porosity	0.08	0.10	0.12	**frav. GRV**
Matrix Perm (Kair)	0.67	1.13	1.76	**md**
Swi	0.15	0.30	0.40	**frac. PV**
Ko@Swi/Kair	0.42	0.55	0.70	**fraction**
Krw@Sorw/Ko@Swi	0.09	0.18	0.29	**fraction**
Sorw	0.21	0.29	0.37	**frac. PV**
Net Thickness	78	95	113	**feet**
Matrix Block Height	5	10	15	**feet**
Development Related Inputs				
Well Spacing	150	300	500	**acres**
Well Cost		Base +/- 20%		
Facilities Cost		Base +/- 30%		
OPEX		Base +/- 11%		
Oil Price		Base +/-$3		

Table 3
OverPressure Mini-Basin Example
Key Inputs and Ranges of Uncertainty

	Minimum	Most Likely	Maximum	
Core Analysis Related Inputs				
Pore Volume Compressibility	10	20	30	**vol/vol/psi**
Porosity	0.22	0.26	0.29	**frav. GRV**
Perm (Kair)	173	280	367	**md**
Swi	0.26	0.29	0.35	**frac. PV**
Ko@Swi/Kair	0.70	0.85	0.95	**fraction**
Krw@Sorw/Ko@Swi	0.45	0.55	0.65	**fraction**
Sorw	0.14	0.25	0.33	**frac. PV**
Development Related Inputs				
Well Spacing	206	349	464	**acres**
Tubing Head Pressure	1100	1250	1400	**psia**
Well Cost		Base +29%; -14%		
Facilities Cost		Base +/- 30%		
OPEX		Base +60%; -40%		
Oil Price		Base +/-$3		