WHAT YOU SHOULD KNOW ABOUT EVALUATING SIMULATION RESULTS-PART 1

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Currently, Mike is president of Applied Reservoir Engineering & Evaluation Ltd. (ARE) where he manages economic evaluations, general reservoir engineering and reservoir simulation studies.

He has been active within the technical societies in Calgary. A past technical program chairman for The Petroleum Society's Annual Technical Meeting, he was responsible for newsletter advertising (SPE) for two years, and currently serves on the National Board of the Petroleum Society. He has written eight technical papers and has been invited to make a number of industry presentations. The substance of this article was presented at the Petroleum Society's Calgary Technical Luncheon on September 23rd, 1996.

Introduction

Evaluation and exploitation engineers are often provided with a numerical simulation study as part of the technical support for an economic evaluation of an oil and gas property. Simulation involves many specialized techniques which many people may not be familiar with. Based on experience in a corporate reserves group, exploitation and as a simulation engineer, a procedure has been developed which will aid in assessing the applicability of simulation results to an economic evaluation. The procedure consists of:

1. consistency checks;
2. identifying the critical issues;
3. evaluating the simulation technique; and,
4. report review.

Some of the more common techniques, which are unique to numerical modelling are explained. Simulation has some potential limitations. Those most likely to affect an evaluation are highlighted.

This procedure has proven to be time effective. Simulation results may complement the evaluation process, however, they cannot replace an experienced evaluations engineer's judgement. In the majority of cases the evaluation engineer will have to make some adjustment to the "reserves" predicted in a simulation report. In particular, risk and economic limits must be assessed in a financial reserves evaluation.

This article has been split into two parts. Part 1 covers the Introduction, Consistency Checks and Identifying the Critical Issues. Part 2 covers Evaluating the Simulation Technique, Report Review, and Conclusions.

Objectives

The basic objectives of a simulation engineer and an evaluations engineer are normally completely different:

1. A typical simulation study objective is to identify the single best method of depleting a pool. A unique recovery factor, representing the simulation engineer's "best estimate," will be assigned to different production scenarios. The highest recovery factor indicates the best methodology to be implemented. Such a study has been instituted for technical reasons and will often be used to justify projects and/or for government submissions. The results are primarily comparative in nature. The results of such a study may or may not include economic considerations.
2. The evaluations engineer seeks to establish a dollar value for a property. Economic limits must be incorporated into every estimate. He must also categorize uncertainty by assigning proven, probable and possible reserves. A single value must be determined for each category.

This difference in objectives can result in the simulation engineer and the evaluations engineer having completely different concepts of reserve definitions. Unfortunately many of the different parties have historically used the same term—proven reserves. There were, however, significant differences in the wording between those defined by technical societies, governments and those required for financial reporting. Several years ago one of the most common technical definitions involved "neither pessimism or optimism." To eliminate confusion, the technical definition has now been replaced by the financial definitions ("reasonable certainty"). Nevertheless one will likely encounter a report with "technical proven reserves" which really represents proven reserves plus some portion of probable reserves.

In summary, it will be necessary, in the majority of situations, to adjust the recoveries and reserves from a simulation report to meet financial purposes. Furthermore, the evaluations engineer will likely have to articulately explain these differences.

Basic Concept

Without resorting to mathematics, a numerical model consists of a series of blocks linked together by an interblock transport equation. Each individual block is one dimensional. Internal flow is therefore instantaneous. The material balance is derived from an assumed PVT behaviour (usually black oil) and the properties of the block. These properties are, in turn, determined by geological input of porosity and net pay. Interblock transport is linked via the input permeability and Darcy's law.

A reservoir simulator has an advantage over analytical solutions since it allows complex patterns of flow and reservoir properties to be put together. Since flow only occurs between blocks, the size of the blocks must be smaller than the modelled flow pattern.

Background

Most simulation studies follow a similar format and basic procedure. The major components are described as follows:

1. *Data Gathering:* A reservoir simulation involves a considerable amount of data input. In the first stage all data is screened for quality. For most simulations, lab data is not available for all of the input. Correlations or data from offsetting or analogous pools must be used. Geological maps of porosity, net pay and permeability must be developed and translated into the grid format.
2. *Initialization:* In this stage preliminary calculations are made for running the simulator. Grid block water saturations are calculated based on capillary pressure data. The importance of water saturations is indirect; the correct determination of original oil in place (OOIP) is the main objective. Most programs feature data checking routines at this stage.
3. *History Match:* The numerical model is run through time with the base product production (oil or gas) specified in the model input. The idea is then to match the rest of the production behaviour, such as the GOR, water production, or condensate rates, to the actual behaviour which has occurred in the reservoir. History matching normally consumes roughly one third of total study time, making it the largest single component.
4. *Tuning Phase:* In order to make predictions, the kh, or bottomhole pressure, of all wells must be adjusted to match actual production performance. This involves a series of trial and error runs to obtain the correct values.
5. *Predictive Stage:* At the end of the tuning phase the model is usually terminated with a "restart." This input data file contains all of the information necessary to continue a simulation at a later time. Several different production scenarios or alternatives are run from the same time step and compared. With different runs, various injector patterns, changes in rates and producer-injector locations can be studied.
6. *Report:* The assumptions on which a simulation is based should be outlined. Simulation also generates an enormous amount of paper output. It takes considerable time and ingenuity to reduce this data to a form which can be understood from a common sense perspective.

Most simulation reports are written as a variation on the above outline. With this background, the evaluation engineer may proceed to assess a simulation report.

Consistency Checks

The first step is to apply some relatively simple consistency tests. In many cases these plots or cross-checks may be included directly in the report, and all that is required is to review them and note exceptions.

History Match and Main Prediction on the Same Plot

The majority of simulation engineers prefer linear rate vs. time plots over semilog rate vs. time plots. Evaluations engineers almost always prefer the latter, since they commonly use decline analysis. In order for one's experience base to have its full impact, the results of the study should be plotted in the format to which one is accustomed.

The predictive phase and the history match phase of a study are usually performed at different times and using a separate computer run. Very often the history match plot and the prediction are not plotted together. A combined plot can be very informative.

The use of such plots has enabled the author to present reserves to clients in a readily comprehended manner. In one such case, our critique of a simulation caused a client to rethink his approach to optimizing production. The client has subsequently achieved highly successful results with a different and less costly optimization program.

Problems Observed

Specific problems which the author has observed include:

1. Unrealistic production forecasts. In one case that the author reviewed, modelling predicted production response in a re-implemented waterflood which exceeded the original (successful) waterflood peak production.
2. Simulations which have not been properly tuned. The initial production in one case was too high—which led to optimistic recovery predictions.
3. Projected profiles which, when compared to offset projects, showed different production responses. This indicated that critical reservoir mechanisms had not been accounted for.

Repeat the Same Procedure on an Individual Well Basis

As in the above section, plotting the prediction and history match on consistent plots for individual wells is recommended. Items to watch for include:

1. Tuning of individual wells. Although the overall pool performance may match, the author has seen simulations where the best wells had 25% production jumps. (At the expense of minor producers). The resultant prediction was skewed optimistically.
2. Systematic trends in mismatches. For example, an active water leg will result in wells watering out in relation to their dip position.
3. How boundaries have been handled. If the model is not a closed system, such as a window study or where only a part of the reservoir has been modelled, there will likely be a buffer area which is extremely difficult to match.

Scoring System

Almost every numerical modelling study has a history match. Surprisingly, in all of the literature that the author has reviewed, there have been no firm guidelines to determine an adequate history match. This is probably because conceptual implementation is as important as the quality of matches on individual wells.

Assuming, for the time being, that the study has been properly designed; it is rare for all of the wells in an areal simulation to match historical data perfectly.

The degree to which individual wells match can vary considerably. For this reason, it can be difficult to decide if the match is satisfactory overall. The following approach is suggested:

1. Make a list of all of the wells. Then assign each well a score from one to ten for:
   i. overall history match quality
   ii. the importance of the well to the pool.
2. Multiply factor a times b and sum the products for all of the wells. Divide by the sum of the b factors. This can be done very easily using a spreadsheet.

The author does not have a standard numerical threshold. However, after using this method, the author has been able to draw conclusions regarding the overall history match quality.

Perform Simple Numerical Checks

The following checks have proven to be quite useful in the past:

1. Match Original-oil-in-place (OOIP) derived from the model to those calculated by volumetrics and material balance. Note that the OOIP will often change in history matching. Are the changes reasonable?
2. What Percentage of OOIP (and original-gas-in-place) has been produced. Does the model match the actual production which has occurred?
3. Calculate the recovery factors for all subsidiary products. Are these numbers reasonable?

4. Check the water saturations in the model vs. the results from log analysis.

Example Problems

These checks, and any others which one may think are appropriate, will identify a number of potential errors. Some examples observed include:

1. Sensitivity cases can get mixed up. One such error found by the author involved a gas injection sensitivity result which got mixed in with a waterflood sensitivity. This was found by checking the solution gas recovery as a percentage of OGIP. Simulators create enormous amounts of output; clerical errors are inevitable.
2. Changes to the OOIP in history matching may have been excessive. In one review a 40% increase had been made in the downdip portion of the reservoir. Subsequent analysis indicated that this could have been best represented by an active aquifer.
3. Check metric conversions. The built in metric conversions within a simulator often use slightly different conversion factors. In rare instances, there may be a mistake in the numerical model. More commonly, a model will be run in Imperial units and the final results will have been converted manually for the report.

After completing all of the above checks, the overall purpose of the simulation should be examined, before evaluating simulation technique and proceeding to detailed review of the report.

Identifying Critical Issues

Examples

A number of different situations exist where an evaluations specialist will likely encounter a simulation:

1. Probably the most common situation which one will encounter concerns a property that has been on primary production, that an operating company has decided to waterflood. They are looking for waterflood reserves based on the results of a simulation.
2. Another common situation involves a recently drilled well, in a new field, which has either a gas or water contact in close proximity to the completed interval. A simulation has been provided to support a recovery factor as well as GOR or watercut trends.
3. An operating company has a mature field which they have modelled to optimize production. Small increases in overall recovery factor may represent major increases in remaining reserves. Often it is hard to distinguish incremental reserves from production acceleration.
4. A large gas field has been developed which exhibits retrograde liquid condensation. A study has been used to determine what ngl and gas recovery will be.
5. A large miscible flood has been installed. The operating company has performed a simulation. Since limited production history exists, a simulation is often the best method of engineering analysis available to estimate recovery.

The nature of numerical models introduces some modelling requirements which are necessary to achieve these objectives. The following attempts to present some of the techniques of reservoir simulation and how these specific requirements arise.

Simulation Grids

Ideally a very fine grid could always be used. However, as the dimensions of a grid increase, the amount of calculation time increases very rapidly. Determining the amount of work varies depending on the mathematical implementation used in the simulator. In very general terms, for a common direct matrix solver implementation and a square two dimensional grid ($n * n$), the amount of computer time increases to the fourth power of the grid dimension (n^4). With layers, the amount of time increases by the cube of the number of layers. A large grid can exceed the capacities of a supercomputer for a large reservoir. Constructing a model usually involves some compromises.

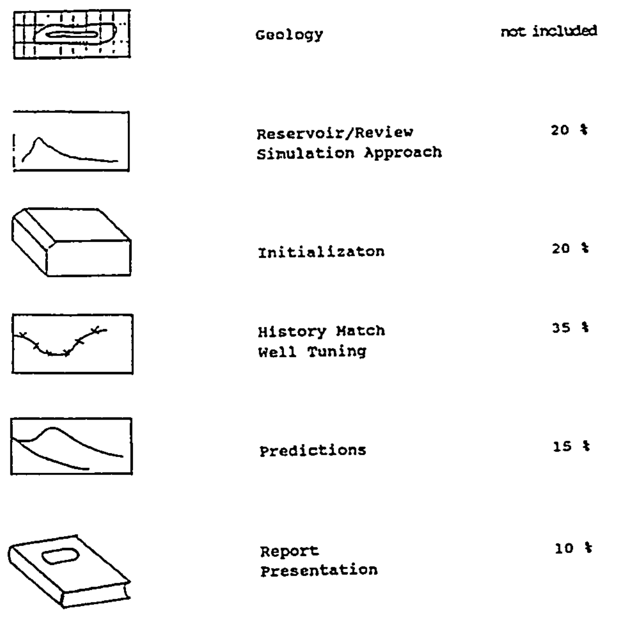

FIGURE 1

Handling Wells

Immediately surrounding a well there is a very strong flow concentration, which must be taken into account. Inflow into a well is handled by a steady state analytical equation which assumes radial flow. This equation has been modified to relate the grid block pressure and wellbore pressure to well performance. Recall that the usual textbook analytical inflow equation is related to the average reservoir pressure at infinite distance. Allowance can be made for directional permeability and rectangular grid blocks. The geometry for this situation is shown in Figure 1. Any deviation from this situation will not be accurately represented.

One of the most common deviations is a partial completion. It is the usual practice to capture this error with a skin factor similar to that developed by Brons and Marting. This usually works satisfactorily.

This will not work whenever a fluid contact exists, as shown in Figure 2. In this situation a fine grid is necessary to model the variation in fluid saturations, pressures and flow pattern. This has led to the development of coning models which typically utilize radial grids. These models are usually formulated more rigorously mathematically to handle higher grid block throughputs. This works very well for single well studies.

From the above discussion, the reader should have the impression that handling a well could require a very large number of blocks be built into the model. Once again, the capacity of a computer can be exceeded. For an areal model which has multiple wells and fluid contacts, more sophisticated techniques have been developed to keep grids to reasonable dimensions:

1. A separate detailed coning study will be performed to determine well behaviour. Provided the saturations change in one direction consistently, the radial inflow equation may be fooled with a "well pseudo relative permeability curve." Each well may be assigned a water-oil and/or gas-oil relative permeability that is different from the laboratory rock relative permeability. The proportion of oil, gas, and water produced as a result of coning can be accurately replicated this way.
2. An analytical equation may sometimes be used to calculate the proportion of water or gas resulting from coning. This involves some custom modifications to the simulator. There are a number of different correlations which can be used. Ordinarily history match tuning to the equation will be required to get good results.
3. A special areal model can be developed which has a special

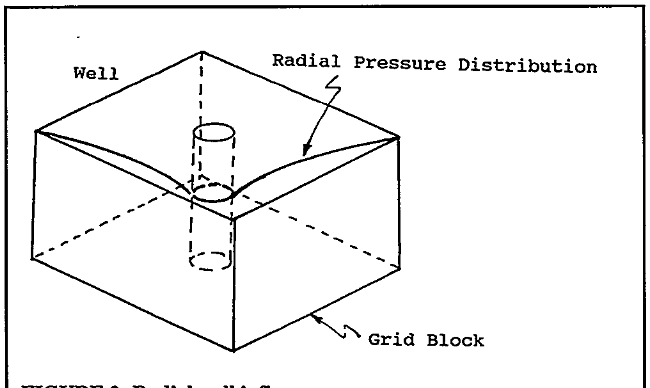

FIGURE 2: Radial well inflow.

coning model routine built in (i.e., a simulator within a simulator). This requires a custom model.

4. Recently models have been built which allow subgrids or grid refinement. This effectively handles the coning phenomena. The number of local grid refinements allowed in a model may be limited. Therefore, in large studies, the older techniques described previously will still be used.

Pseudo Relative Permeability

The petroleum literature describes many pseudo properties (pressures, times, permeabilities etc.) which rarely indicate the true purpose or nature of the concept. "Pseudo Relative Permeability is no exception. In the author's opinion the single most misunderstood aspect of simulation is relative permeability. Pseudo relative permeability has a number of distinct purposes in simulation. The best way to explain them is from a historical perspective.

Vertical Equilibrium

The first use was envisaged by Coats. It can be used in thick reservoirs, where the capillary pressure transition zone is thin (e.g., a sharp gas-oil contact) in relation to the total zone. The implicit assumption is that gravity forces are much stronger than lateral forces. Thus there are always two sharp and distinct phases in a grid block. This technique can allow the representation of a thick reservoir with a single layer areal model. Reducing a multi-layer problem to a single layer can result in significant economic savings, or even allow simulation of a large field, which could not be solved any other way. This is also known as VE—for Vertical Equilibrium.

The resultant "fudged" relative permeabilities look like two straight lines such as depicted in Figure 3. Some degree of vertical equilibrium is common. This can be demonstrated by running sensitivities on a five spot waterflood pattern that has good reservoir properties, moderate thickness, and relatively low production/injection rates. The author has overheard engineers say, sarcastically, that they could use simple straight line relative permeabilities and get decent results from a simulator. Their results were likely an accurate representation of the physics in the reservoir.

Hearn Type Relative Permeabilities

It has been long recognized that the effectiveness of waterfloods is strongly affected by layering in the reservoir. In a layered reservoir, the displacing fluid will move more quickly through the most permeable layers. This causes a more rapid and more gradual breakthrough of the displacing fluid. In classical reservoir engineering this has been accounted for via techniques developed by Stiles and Dykstra-Parsons.

The second pseudo relative permeability technique envisaged was developed by C. L. Hearn, to account for layering. This calculation assumes piston like displacement in the reservoir and no vertical communication. This is therefore at the opposite end of the spectrum from VE. Although there are "errors" in this method, the loss in accuracy can be insignificant when compared to correctly accounting for layering. Typical curves are shown in Figure 4. These curves accelerate water breakthrough.

Combination Relative Permeabilities

Some time after the above two techniques had been developed it was realized that various combinations of capillary pressure transition zones, layering, reservoir thicknesses, and the extremes of horizontal vs. vertical velocities could be accounted for. These curves can be derived both analytically and via cross-sectional modelling. An excellent explanation of the analytical methods may be found in Dake's Fundamentals of Reservoir Engineering [Reference (4)].

Dynamic Pseudo Relative Permeability

The first dynamic method was developed by Smith, Mattax and Jacks. It requires that a cross-sectional model of the reservoir be made. Special computer utilities have been developed which average the relative permeability of each phase, for each column of grid block layers contained within a cross-section. The average relative permeability is then plotted against the average water saturation for each grid block layer column. The resultant curve is a dynamic "pseudo relative permeability curve." These curves will need to be used in conjunction with appropriate "pseudo well relative permeabilities." A single layer cross-section, utilizing these both types of pseudo curves, can easily duplicate the results of a multi-layer cross-sectional run to within a few per cent.

A second dynamic method has also been developed by Kyte and Berry. They averaged saturations and relative permeabilities from laterally adjoining grid blocks to make larger grid blocks. This has the additional potential of controlling dispersion (which is discussed later in this article).

Relative permeability curves used in simulation represent the effects of: transition zone thickness, layering, vertical/horizontal permeability and production rates; in addition to the fundamental property of the rock (determined by laboratory experiment).

Any areal simulation really involves, to some degree, a "pseudo relative permeability." To the uninitiated the use of pseudo rel-

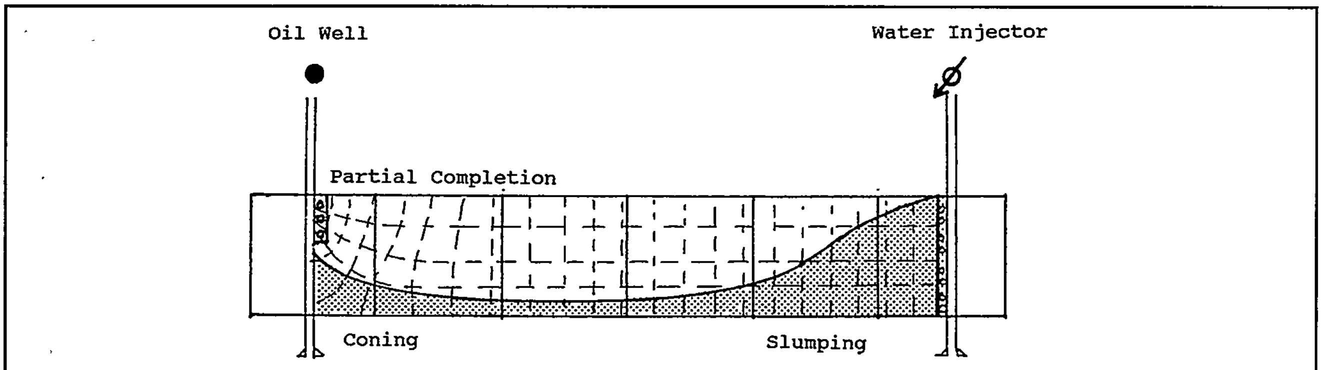

FIGURE 3: Deviations from radial flow patterns caused by multiple saturations and completion.

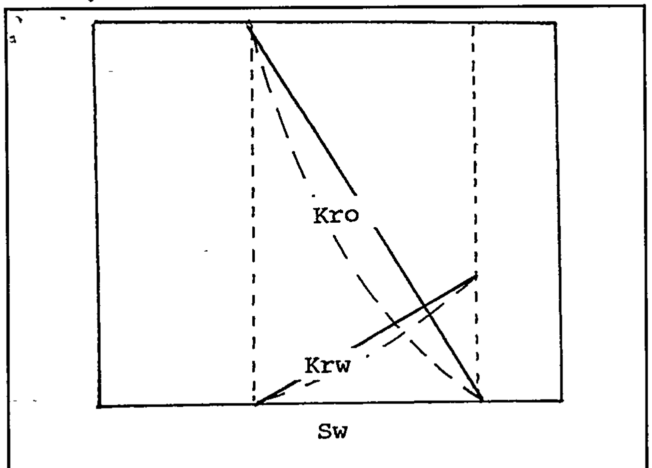

FIGURE 4: Vertical equilibrium (VE) pseudo relative permabilitycurve.

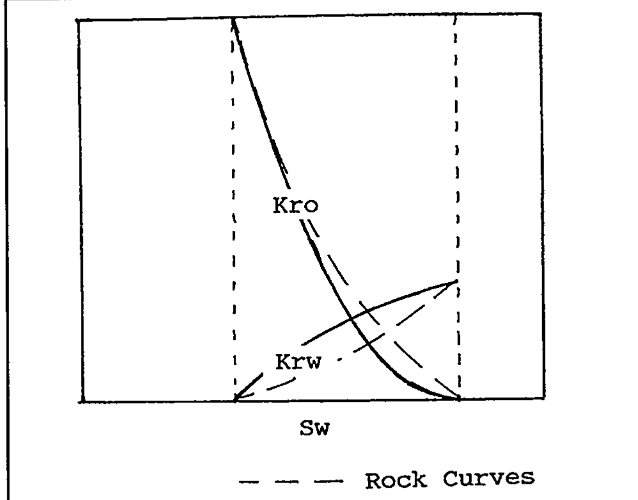

FIGURE 5: Hearn type pseudo relative permeability curve.

ative permeability, which results from history matching, appears to be "gross modification of lab data." The above is intended to provide enough background to understand the basic concepts. A summary of the various techniques and where they should be used is presented in Figure 5. The use of these curves is an economic necessity.

Model Design

Using the concepts developed above, the evaluations engineer should check what he considers to be the most important issues. Some examples might be:

1. For the waterflood, implemented after a period of primary production, one of the most critical aspects of model design is characterizing layering or heterogeneity. This can be done either with detailed layering built into a model or via "pseudo relative permeability curves."
2. For a well drilled into a pool with a water or gas contact, the critical modelling issue will likely be accounting properly for near wellbore effects. This would usually involve a detailed coning study, defining layers, covering the correct range of production rates and including the effects of hysteresis.
3. For a mature field optimization study the most critical aspect of the study would likely be how to build a balanced model. This could require preliminary coning and cross-sectional studies which must be later integrated into an areal model. Integration is the major issue.
4. For a retrograde gas condensate reservoir will likely require a compositional simulator. Proper PVT characterization will comprise a major portion of the study.
5. For a miscible flood a number of critical issues are possible. The same simulator may not address all of the issues effectively. If miscibility is the critical issue a compositional simulator is in order. If maximizing sweep efficiency is the critical concern, then a pseudo miscible simulator is probably the most effective solution.

Note that other factors, such as well spacing, laboratory relative permeability, PVT properties, injectivity and timing of wells are still important.

Any numerical model, depending on its design, will take into account various factors in varying degrees. Tradeoffs are almost always required in the design of a model. A study may have been designed to address a specific isolated objective. The objectives that the simulation engineer has designed his model around, and one's perception of the critical issues must coincide. Otherwise, although the simulation may have met its objectives, it may not be of direct use in the broader reserves picture.

Conclusion

This concludes Part 1. In Part 2, steps are outlined to check how these critical issues have been handled in Evaluating the Simulation Technique. This includes the implementation of grids, wells, pseudo relative permeability curves, numerical errors and layering/heterogeneity. Report Review is then discussed and Conclusions presented.

EDITOR'S NOTE: Part 2 will be published in our newly planned August issue. Watch for it!

News Briefs
Continued from page 18

mud technology and was drilled at a 100 degree angle to vertical. Windsor has substantially increased proved producing and proved undeveloped reserves with the completion of these last two wells. This is the third successful completion of the 19-well 1997 development program, that will further develop the Miley A sand and confirm the B&C sands.

Sproule Opens Denver Office

J. Glenn Robinson, president of Sproule Associates Limited—a well known international geological and petroleum engineering consulting firm located in Calgary—recently announced the formation of Sproule Associates Inc. The new company joins Spoule International Limited as the second, wholly owned subsidiary of the Calgary company.

Opening its office in March 1997, located in downtown Denver, Colorado, the office is managed by Leslie S. O'Connor, who has over 18 years of geological, reservoir engineering, and evaluation experience with various oil and consulting companies in Denver. With over 45 years in operation, Sproule is one of the leading evaluation companies in the oil and gas industry. They have thousands of clients in Canada, the U.S., and around the world, and are always looking for international opportunities. With the large number of U.S. clients using their services, and with Leslie's qualifications, it was an opportunity ready-made for them.

Sproule specializes in economic evaluations of oil and natural gas reserves for companies, financial organizations, and government agencies involved in the petroleum industry. Projects involve leading-edge technology related to reservoir characterization, 3-D seismic, horizontal drilling and thermal recovery processes. The company is also well known for the courses they offer: Evaluation of Canadian Oil and Gas Properties and Application of Risk analysis to Decision-Making for Oil and Gas Producers.