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## **Successful Drilling of an Underbalanced Horizontal Well in the Rigel Halfway Pool - Laboratory Screening and Field Results**

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### **Abstract**

The Middle Triassic Halfway formation in northeastern British Columbia is a high quality, well sorted quartzose sublitharenite. Past drilling operations using conventional overbalanced technology in the reservoir had indicated significant formation damage occurred due to a combination of mechanical and chemical formation damage effects associated with the loss of drilling fluid to the formation. A series of compatibility and special core analysis tests were conducted to refine an underbalanced drilling procedure with natural gas for a 300 m long horizontal well in the formation using a natural gas-mist hydrocarbon system at a 1400 kPa underbalance pressure level. The well was drilled successfully and flowed at peak rates of up to 1100 m<sup>3</sup>/day (almost 7000 bbl/day) of oil and 340,000 m<sup>3</sup>/day (12,000,000 scf/day) of gas during the underbalanced drilling operation. Post test pressure transient and interference tests indicated an in-situ permeability of 150 mD with zero skin factor indicating that the well had been drilled successfully in an undamaged fashion. The well has currently produced close to 13,000 m<sup>3</sup> of oil (80,000 bbl) and over 11,000,000 m<sup>3</sup> (400 MMscf) of gas with initial AOF potential of approximately 520 m<sup>3</sup>/day (3300 bbl/day).

### **Introduction**

The Middle Triassic Halfway formation of the Rigel field located in northeastern British Columbia is part of a regressive sequence, bounded stratigraphically below by silts and shales

of the offshore Doig formation and above by continental hypersaline anhydrites, dolomites, silts and shales of the Charlie Lake formation. The formation exhibits a regional southeasterly dip with an average depth of 1266 meters.

The pronounced north-south orientation of the pool is thought to be influenced by rejuvenation of deep-seated faults. Although not visible on seismic traces, small scale reactivation may have controlled the axis of deposition and subsequently aided in the preservation of reservoir facies.

The Rigel Halfway C pool is fine-grained, well-sorted quartzose sublitharenite with patchy calcite cementation. It is interpreted as a cross-cutting tidal channel fill deposit, juxtaposed against tight sands and shales of the Halfway barrier-bar system. Using a permeability cutoff to oil of 1.0 mD, a porosity cutoff of 8% was determined for two wells including C-20-L (from which experimental sample selections were taken). Based on these cutoffs, net pay of the reservoir ranges from approximately 1.1 meters to 7.8 meters. Rock quality of the formation is characterized by an average permeability to air of approximately 100 mD, with core sample permeabilities increasing from 25 to 85 mD in the upper interval (1263 to 1266 meters) to 100 to 900 mD in the lower interval (1266 to 1270 meters). Porosity over the entire interval increases with depth from 15% to 25%, and original oil in place for the pool is estimated to be 1.6 x 10<sup>6</sup> m<sup>3</sup>.

### **Drilling Strategy**

Utilizing drilling and production experience gained through other wells in the area, Samedan Oil of Canada set out to drill a horizontal well (3-33). The objective of drilling the 3-33 well was to target the recoverable oil by drilling a non-damaged horizontal well with high deliverability for the least drawdown and GOR performance. Experience with the C Pool indicated that formation damage had occurred when drilling previous wells, and that damage was severe enough to prevent water injection for a waterflood, even after perforating the injector. A fracture job established excellent injectivity leading

to the conclusion that to achieve a successful well, determining the best method of preventing formation damage caused by the drilling process was necessary.

Reviewing the performance of wells in the Rigel area and researching the success of other horizontal wells drilled in western Canada suggested that damage from the drilling process contributes to less than expected production performance. The damage was primarily due to two main processes: 1) selection of inappropriate drilling fluids, and 2) physical damage caused by not being able to remove drilling solids from around the wellbore. It was determined that the best way to prevent these processes from occurring would be to drill the well underbalanced with a gas/liquid system. Providing the right system is utilized, and underbalanced pressure is maintained<sup>1,2</sup>, little or no rock/fluid or fluid/fluid sensitivity should occur, and solids invasion would not be a concern. Samedan undertook a study jointly with Hycal Energy Research Laboratories to investigate these phenomena with respect to the Halfway sand at Rigel. With these parameters in mind, two hydrocarbon-based fluids were selected for testing (one viscosified and the other unviscosified). Resourcing an economic and sufficient supply of gas to maintain underbalanced pressure supported utilization of sweet natural gas already being produced by other Samedan wells in close proximity. With fluids and method of drilling determined, the next phase was to evaluate the performance of both systems in the laboratory to optimize well performance.

### Coreflow Experimentation

**Sample Selection, Screening and Preparation.** Proper selection of test samples is essential for any coreflow experiment. For this study, a selection of small plugs with a maximum diameter of 3.81 cm were drilled from unpreserved full diameter core from well C-20-L/94-A-9 and re-analyzed for routine air permeability and porosity. From this analysis two test samples were selected based on:

- good lithological representation of the zone of interest. The samples were homogeneous quartzose litharenites and exhibited no microfractures or other small-scale heterogeneities;
- permeability and porosity of each sample was comparable to the overall quality of the target zone of the reservoir; and
- both samples were similar in quality to each other (to be discussed later).

**Laboratory Tests.** In certain drilling operations where it is not known whether to use an oil-based or water-based fluid, or different methods of drilling are under consideration (ex. overbalanced versus underbalanced etc.), a suite of preliminary coreflow tests is useful for narrowing down the selection of test fluids without conducting extensive and expensive

experiments with whole mud systems. The Rigel study was somewhat unique in that prior selection of only two mud systems had been made, and it was known that the well was to be drilled underbalanced. The purpose of the study, therefore, was to determine which of the two mud systems would perform more favourably in an underbalanced fashion, thus negating the need for preliminary formation damage mechanism identification through various intermediary coreflow tests. Determination of rock wettability and fluid compatibility was conducted to ensure that obvious problems would not be encountered through the use of the oil-based product.

The use of water-based (Gel Chem or Polymer) fluids was discounted at the outset due to greater potential for formation damage caused by phase trapping of the water within the porous media either through spontaneous imbibition or filtrate loss during overbalanced pulses that may be encountered or required (ex. bit trips, well control etc.), and due to poor productivity observed in previous wells exposed to aqueous-based fluids in the past. It was felt that oil-based fluids in an underbalanced mode would eliminate much of the potential for damage to occur, and so this would be the most logical place to start the experimental program. As with most underbalanced operations, maintaining underbalance pressure while drilling the well could only be achieved by co-injecting the drilling fluid with gas or another density-reducing product. Since natural gas was available for this operation, the coreflow tests simulated the same process using methane displaced into the drilling fluid at a specified rate.

**Fluid/Fluid Compatibility.** Preliminary work was conducted to determine whether solids would be precipitated during mixture of the hydrocarbon drilling fluid and native crude oil since appreciable precipitation of solids could cause significant formation damage from solids entrainment in the event of fluid loss during drilling. If no incompatibility is observed between the two fluids, the drilling fluid can then be used in a coreflow experiment.

### Coreflow Experimental Procedure

**Core Restoration.** Test cores were originally in an unpreserved state, and therefore required a reconditioning procedure to restore rock wettability and saturation. The cores were mounted at reservoir conditions of temperature and net overburden pressure, and a two week restoration phase ensued. Although the common practice is to conduct the restoration phase over a six to seven week period, time constraints required abbreviation of this procedure. Because of this fact, the wettability was measured to evaluate whether the restoration phase had been successful.

Initial displacement with formation brine established a water-wet condition which is a likely possibility for this type of rock.

followed by approximately ten days of discontinuous displacement with native crude oil. During the oil displacement, if the rock has a tendency to be more neutral or oil-wet, the transition can occur.

**Contact Angle Measurement.** Previous analysis on the Halfway rock indicated that wettability of the formation was neutral (neither oil- or water-wet), and it was essential that this wettability be restored in the test samples. The possibility of utilizing a surfactant to prevent solids build-up in downhole tubulars also required investigation of how much the reservoir wettability would be altered by the surfactant. Two contact angles were measured on a post-restoration cores (one soaked in drilling fluid with surfactant added).

**Underbalance Drilling Fluid Tests.** Two underbalanced drilling fluid tests were conducted on separate core samples using the two mud systems previously described. Test #1 utilized a core exhibiting an initial permeability to air of 231 mD and porosity of 19.4%, and test #2 was conducted on a core with an air permeability of 293 mD and porosity of 19.4%.

For both tests, initial permeability to native crude oil was measured to establish a baseline permeability to undamaged rock, followed by the underbalanced drilling fluid exposure. For this procedure, methane gas was injected into hydrocarbon drilling fluid in a 5:1 ratio (gas to oil) and the mixture was circulated past the sandface of the core. To simulate underbalanced conditions expected in the field, native crude oil was continuously displaced through the core toward the sandface at 700 kPa above the drilling fluid circulation pressure. Following this phase a regain permeability was measured to determine the effect of the drilling fluid on permeability.

As with many underbalanced drilling operations, maintenance of a true underbalanced pressure is not always possible. Among many possibilities, this can be due to pressure spikes encountered as joints are made up or as the tubulars are being tripped, loss of fluid can occur if zones of low pressure are penetrated (less likely in a horizontal application), and if well control is required to prevent a kick for example, overbalance pressure may be required.

To simulate the possibility of losing underbalance pressure at any time during the drilling or completions operation, each test sample was subjected to an overbalance pulse of the same drilling fluid system. This was followed by regain permeability measurement to observe any damage caused by fluid invasion during the overbalance pulse. The mechanical entrainment of drill solids, which were included in the mud system being circulated, would likely comprise the major portion of any damage observed in this particular situation.

## Experimental Results

**Contact Angles.** Results of the contact angles measured on restored rock and restored rock soaked in an oil/surfactant mixture clearly showed that the oil/core interface angle on the restored sample was 90° or neutrally wet. The contact angle on the second sample soaked in drilling fluid with surfactant indicated that as expected, the surfactant caused the wettability of the rock to change to strongly oil-wet.

Therefore, it was concluded that it would be unwise to utilize the surfactant as it may increase propensity for premature water breakthrough and reduce oil permeability in the near wellbore region due to an adverse alteration in relative permeability.

**Compatibility Tests.** Fluid-fluid compatibility tests indicated that the produced crude oil and oil-based mud system were compatible in all ratios at reservoir temperature condition.

**Coreflow Test #1 - Viscosified Hydrocarbon with Methane Co-injection.** Initial effective permeability to oil was 71 mD, and following underbalanced exposure to the drilling fluid, the permeability decreased by 67%. Subsequent exposure at overbalance pressure caused an additional 21% loss in permeability for a final decrease of 88%. Damage to the core during the underbalance phase was believed to be due to adherence of the viscosified oil and microfines to the sandface of the core, and invasion of this same material during the overbalanced pulse caused further impairment. Post-test petrographic analysis of the core revealed that some pores and pore throats throughout the entire length of the core were occluded by fines coated in oil as well as "mud oil" which was believed to be the viscosified hydrocarbon.

**Coreflow Test #2 - Unviscosified Hydrocarbon with Methane Co-injection.** Initial effective permeability to oil was 41.7 mD and there was no reduction in this value following underbalanced exposure to the drilling fluid. However, the overbalance pulse with the same fluid did cause a 57% reduction from the baseline permeability. Impairment in this core was due to invasion of drilling microfines which became entrained in the porous media during the overbalance pulse. Post-test petrography indicated that oil-coated fines occluded some pores and pore throats, with a similar "mud oil" coating on some pores contributing to the impairment.

## Study Conclusions

Results of the study clearly indicated that when the Halfway sand was exposed to water-based and certain oil-based muds, irreversible reductions in permeability were effected. As well, when crushed reservoir rock was worked into the core face, the resulting mechanical damage was significant.

Although the unviscosified drilling fluid was recommended for use (with natural gas co-injection) over the viscosified version, it was stressed that this was only if underbalance pressure could be maintained in order to prevent formation damage. Using a surfactant in the drilling fluid to prevent solids build-up in the wellbore was discouraged since altering the wettability of the formation to a more oil-wet condition could have a significant and negative impact on the production performance of the well.

The study concluded that not enough confidence could be gained through using a conventional gas/hydrocarbon mud system as damage would be severe if the underbalanced condition was compromised. It was felt that in order to maintain production as high as possible with the lowest gas/oil ratio, up to the allowable, an undamaged horizontal wellbore would be required. The only drilling process that was left if oil and water-based drilling fluids were eliminated was to drill the well underbalanced with gas. Investigations into the use of gas as a drilling fluid led to the conclusion that the effects of drilling fines on the formation could be negated if the fines are removed before they have a chance to become mechanically crushed in the wellbore. Also, a condition of 100% underbalance would be much easier to continuously maintain using a gas-based system.

### Drilling Operation

With the laboratory work completed, and the decision made to utilize gas as the drilling fluid, it was then necessary to determine which gas to use and flow rates of the gas to provide adequate hole cleaning ability. Although nitrogen is typically the gas of choice, consultation with suppliers raised two problems: 1) the proximity of Rigel centres of production of nitrogen, and 2) the quantities of nitrogen necessary to maintain 1400 kPa underbalance pressure at all times. The logistics and costs strongly supported utilization of sweet natural gas readily available to Samedan through facilities within 200 meters of the target well 3-33, thus natural gas was selected as the drilling fluid of choice with a very small amount of the compatible hydrocarbon fluid, used in the previous lab tests, added in mist form for lubrication purposes.

Approval was received from the B.C. Ministry to use natural gas, and a pressurized surface control and flare system was installed on location since sour gas could not be vented directly to atmosphere. With personnel safety as a prime concern, a state-of-the-art Williams rotary head directed the well effluent to the pressurized and contained separation equipment from which gas returns from the wellbore were flared in a 30 meter stack.

A medium "kick-off" radius was selected for the build-up section of the horizontal well and 178 mm pipe was set in a horizontal mode 100 meters west of well centre. This offset

enabled drilling out of the intermediate section and commencing circulation to natural gas prior to drilling the Halfway. The Halfway zone was penetrated with natural gas rates of  $114 \times 10^3 \text{ m}^3/\text{day}$  of gas down the 101 mm drill pipe with 100% returns. Immediately upon penetrating the Halfway, oil influx into the wellbore commenced at a rate of  $600 \text{ m}^3/\text{day}$  of sour oil. Cuttings were transported to surface at a high velocity such that they were virtually unworked by mechanical action.

Drilling proceeded in a westerly direction for approximately 300 meters in an underbalanced condition with a single bit, and during this time the total gas injection rate increased to  $170 \times 10^3 \text{ m}^3/\text{day}$ . Total withdrawal from the well reached peak rates of up to  $1100 \text{ m}^3/\text{day}$  of sour oil and  $340 \times 10^3 \text{ m}^3/\text{day}$  of total gas. Bottom hole pressure was monitored throughout the drilling operation, and the well continued to flow underbalanced during the entire time. This was in part attributable to reducing joint connection time by using double joints in a top drive rig.

As drilling proceeded it was felt that influx rates were approaching the maximum well potential. The well was drilled by utilizing a motor and rotating the drill pipe, and when trajectory corrections were required rotation ceased. This method enhanced cuttings transport which increased the penetration rate ten-fold over conventional overbalanced operations in the Halfway in the past. When the bit was scrubbed and the angle could not be maintained, the decision was made to remove the drill string and cease operations as it was felt that flow rates were acceptable and well productivity may be jeopardized by a kill and tripping operation to install a new bit. The well was self-killed (with clean produced oil) and left with a series of plugs in place while rigging out.

### Well Test Results

The horizontal well was brought on stream flowing 100% oil and gas (no water) through a separator. Two tests were conducted simultaneously on the horizontal well:

- 1 Test #1 was a conventional flow and build-up test on the horizontal well where quartz gauges were set in the vertical section of the hole just at the point of kick-off. The in-situ permeability to oil, as determined by an analytical horizontal model suggests that the horizontal permeability parallel to the well axis is 150 mD, perpendicular is 120 mD and the vertical permeability is 40 mD (these permeabilities are reduced from virgin conditions as this reservoir was already partially depleted). The skin factor determined from this analysis was +/- 0.25, or essentially zero skin, indicating that the drilling process had not damaged the wellbore and hence the objective of minimal damage was achieved.

2. The second test was an interference test run between the horizontal well and a vertical well approximately 200 meters away. Results of this test confirmed the magnitude of horizontal permeability in the reservoir validating the interpretation of the horizontal well test. The 3-33 horizontal well has since produced approximately 80,000 bbl of oil and 400 MMscf of gas. The initial well productivity determined from the build-up test was approximately 530 m<sup>3</sup>/day under AOF conditions. It is believed that with the wellbore in its undamaged state, and with the permeability associated with this reservoir, that Samedan achieved very good separation of oil and gas and hence a relatively low producing GOR at high oil rates.

## Conclusions

A successful underbalanced well was drilled in the Halfway Formation in the Rigel "C" pool using a natural gas-hydrocarbon mist system. Lab test studies indicated the importance of underbalanced condition maintenance to obtain a zero skin condition. The well flowed at rates of up to 1100 m<sup>3</sup>/day (7000 bbl/day) during the drilling process with post-test PTA work showing zero skin, indicating that the objective of zero invasive formation damage appeared to have been achieved.

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