Optimization of Gas Utilization to Improve Recovery at Hibernia
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Abstract
The Hibernia oil field is located in the North Atlantic Ocean over 300 km from St. John’s, Newfoundland. The field consists of numerous fault blocks undergoing conventional gas or water injection. The gas injection process is proving to be very efficient providing high recoveries in individual blocks. Expansion of gas injection through conventional development or EOR may potentially provide significant benefits if optimized correctly under a limited gas supply. The need to understand the relative benefits of gas injection into one block versus another has increased and necessitated a full gas utilization study. One EOR option being considered is water-alternating-gas (WAG) injection in some blocks.

The objective of the study is to establish a field-wide improved recovery plan based on integrated laboratory, reservoir simulation, pilot, gas supply, and infrastructure studies. This paper will describe the integrated study plan and current progress.

The Gas Utilization Optimization Project entails three broad phases: 1) Study Phase; 2) WAG Pilot Execution; and 3) Field-Wide EOR Development. The primary focus at this point is the Study Phase, which will include laboratory studies, reservoir simulation studies, pilot engineering studies, and gas supply and infrastructure assessment.

The laboratory studies are being performed to develop a better understanding of PVT, EOR, and SCAL as it applies to the WAG pilot and field-wide development. The reservoir simulation studies provide a basis for the design of the EOR pilot and the field-wide development plan. Pilot engineering must be performed to ensure the pilot will provide the information necessary to make business decisions on future development. Assessing gas supply and infrastructure is essential to understanding gas availability, value, and opportunities for enhancement. This phase is particularly important for remote locations where external gas supplies are limited.

This study provides a template for obtaining and integrating information and data necessary to design, evaluate, and implement a gas injection project for improved oil recovery.

Field Background
Located over 300 km southeast of St. John’s, Newfoundland (Figure 1), the initial discovery well for the Hibernia field was drilled in 1979 and delineated by nine additional wells over the next five years. The Hibernia reservoir is highly faulted and consists of multiple, stacked fluvial channels and sand bars. A gravity based structure (GBS) with 64 well slots was constructed from 1990 to 1997 at a cost of over $4G (US). Two on-platform drilling rigs were initially operated simultaneously on the GBS, but now only a single active rig crew is present and moves between rigs as needed.

The development includes two main reservoirs, the Hibernia and the Ben Nevis Avalon (BNA) (Figure 2). The expected ultimate recovery in the initial development plan was roughly 600 MB. Through continued optimization, exploration, and expansion, the field has produced in excess of 800 MB with significant remaining reserves. The original facilities were designed for 150 kBD, however debottlenecking enabled test rates of 230 kBD to be achieved. The plateau rate was originally expected to be about 135 kBD, but the actual plateau rate was over 200 kBD. Figure 3 provides a comparison of historical and forecast production rates for Hibernia.
To date, the majority of the Hibernia reservoir fault blocks have been developed and remaining drilling targets include smaller blocks and infill well opportunities. Development is progressing on BNA and Hibernia South Extension. Other remaining opportunities under evaluation include minor reservoirs such as the Catalina, Cape Island and Jeanne d’Arc formations.

Thus far, 70 total development wells have been drilled and 61 slots are in use. On the order of 50 additional wells are anticipated through a combination of adding subsea wells as well as slot reclaims. There is no gas export and the field currently operates with gas injection into northern fault blocks with gas caps and water injection into southern blocks (Figure 4). The field is currently gas compression, water injection, water production, and slot constrained. Current reservoir management strategies optimize the incremental rate with existing injectors. Significant EOR potential may exist which necessitates evaluation of these opportunities to enable additional recovery.

**Optimization Project Objectives and Plans**

EOR projects typically require a large amount of capital investment and operating expense, besides having low incremental production over a long period of time. In addition, uncertainties in technical data could impact the EOR process assessment. Hibernia has the further complicating factor of a limited gas supply. It is imperative that a disciplined process is used for EOR evaluation to ensure technical uncertainties and risks are appropriately identified and managed to support investment decisions. The assessment requires a full spectrum of technology including specialized laboratory data acquisition and mechanistic reservoir simulation.

The need to evaluate the remaining oil recovery potential for gas injection and establishing a proactive strategy for gas sales at Hibernia led to identifying the following objectives:

- Investigate the potential for EOR in the Hibernia water flood and gas flood
- Implement an EOR pilot scheme to demonstrate the benefits and reduce risk
- Establish a field-wide EOR Development Plan
- Investigate gas commercialization including regional solutions
- Meet R&D obligations

The plan for meeting these objectives has been broken into three phases: 1) Study Phase, 2) Pilot Execution, and 3) Field-Wide EOR Development. The project is currently in the study phase and is the primary focus of the remaining discussion. Pilot Execution and Field-Wide EOR Development are discussed briefly for completeness. Integrating all aspects of the study scope requires coordinating efforts and studies from several different sources. Figure 5 shows how results from studies being performed by Memorial University of Newfoundland (MUN), Hibernia Management and Development Company (HMDC), and other contractors all feed into developing a field-wide EOR plan for Hibernia.

**Study Phase**

The study phase provides the technical foundation for pilot execution and field-wide development. The study phase of the project entails laboratory studies, reservoir simulation studies, pilot engineering studies, and gas supply & infrastructure studies.

**Pilot Execution**

The planning for the pilot phase has been underway since 2009 and once executed will provide data to calibrate models to field performance. This step is essential for to address key uncertainties and will deliver a basis for field-wide implementation.

**Field-Wide EOR Development**

Once studies have been performed and pilot performance is incorporated, an operating strategy for field-wide EOR development will be implemented. The field-wide implementation will optimize the gas utilization for the entire field to achieve maximum benefits for the stakeholders.

**Study Phase**

Ordinarily, an EOR study phase would include screening to determine suitable EOR processes for the given fluids and reservoir properties and prioritizing field targets based on ranking criteria such as field maturity, resource size, operational aspects, and technical knowledge of the reservoirs. This process has been streamlined and focused for Hibernia due to the isolated location, limited availability of injectants, and the need to meet the local R&D obligations. Both screening calculations and field experience with gas injection in the northern fault blocks suggest that the hydrocarbon gas currently injected has potential for additional recovery through water-alternating-gas (WAG) injection in blocks currently undergoing waterflood. The challenge is determining if and when those benefits will exceed the benefits currently being achieved with
current gas injection strategy and where that gas will achieve the greatest economic benefit in the field.

Laboratory studies and reservoir simulation studies will acquire the data and investigate the implications of that data on modeling and evaluating the expected performance of the WAG injection in the field. Pilot engineering studies are needed to ensure that the pilot project can be executed and will provide the data necessary to evaluate and optimize field performance prior to field-wide implementation. Gas supply and infrastructure studies will assess a wide range of technical aspects necessary to ensure an appropriate reservoir engineering basis and that operational and maintenance considerations are fully addressed.

**Laboratory Studies**

A full range of laboratory studies is in progress to characterize the reservoir fluids, determine miscibility conditions, characterize EOR mechanisms, determine rock properties, and measure incremental recovery from gas injection. Basic PVT and swelling tests were performed to develop an equation of state fluid characterization that will accurately model the fluids under consideration for EOR. Slim tube tests were conducted to determine Minimum Miscibility Pressure (MMP) of the WAG system. Three-phase relative permeability measurements are being made to provide input for reservoir simulation of the WAG process. New laboratory capabilities are being developed to perform reservoir condition core flood studies to measure incremental recovery from gas injection. While MMP information can be obtained from slim tube measurements, reservoir-condition coreflood studies are essential for a better understanding of pressure sensitivity, residual oil saturation, and solvent mobility. Because “miscible” processes are often a mixture of miscible and low interfacial tension (IFT), near-miscible processes, understanding displacement mechanisms at near-miscible conditions can help us better simulation field-scale miscible processes.3

The first step of the laboratory studies phase is to define miscible conditions in the waterflood area and provide more accurate input data for modeling WAG injection. Extensive PVT measurements have been performed on Hibernia fluids from the different blocks and provide a good foundation for a general understanding of the fluid system and phase behavior. Swelling tests and slim tube studies have also been performed on fluids at Hibernia; however, these tests primarily targeted the current gas injection region of the field and not the target area for the WAG pilot. The target fluids are somewhat deeper and more undersaturated than the fluids with swelling test and slim tube data, so new swelling tests and slim tube measurements were performed on oil samples from the target area. To complete the data set, a complete PVT study including detailed compositional analyses using both C36+ gas chromatography and true boiling distillation was performed.

All of these data are in turn used to develop an equation of state fluid characterization. A volume translated Peng-Robinson4 equation of state was selected for use in reservoir simulation. An initial fluid characterization was developed by tuning plus fraction critical properties to match basic PVT data from constant composition expansion, differential liberation, and flash data measured on a fluid sample from the B16-59 well. That fluid characterization was in turn used to predict swelling test data measured after the basic PVT data. The initial fluid characterization was reasonably accurate predicting bubble point pressures and other properties up to about 60% injection gas, but failed to predict the dew point pressures at 70% injection gas and above. The fluid characterization was then retuned to match all the basic PVT data as well as saturation pressures over the entire range of injected gas content as shown in Figure 6. This EOS fluid characterization will be used for future compositional simulation of remaining experiments and field-scale compositional WAG models. The characterization can also be used to simulate the impact of different operating conditions, estimate recovery sensitivity to different injection gas compositions, and evaluate the need for additional experimental data.

Special Core Analysis Lab (SCAL) data are being obtained through experiments being performed in-house to understand the flow characteristics of the three phases (water, oil, gas) during the WAG process. The objective of the SCAL study is to provide the most representative three-phase relative permeability curves (oil/water/gas) for the WAG pilot and full-field studies and to investigate WAG three-phase hysteresis effects in order to assist in the estimation of recovery efficiency. Prior lab studies performed in-house for the Hibernia Q-block to experimentally obtain the two-phase relative permeability curves for the water flood and the gas flood field programs indicated good reservoir quality quartz-cemented oil-wet sandstones with permeability in the 1200-2000 mD range. Historically, various models such as those by Stone5,6 have been used to convert lab-derived two-phase relative permeability data such as gas-oil and oil-water relative permeability curves into three phase ternary displacement data. The use of these models to extend two-phase relative permeability data into three-phase behavior does not always yield the correct results7,8,9 and it is important to obtain true three-phase displacement functions to reduce the uncertainty in simulation models and the risk in project investment. Even though the Stone-type models were derived for water-wet systems, in the end, these are a way of doing mathematical interpolation that may still work well under conditions that violate Stone’s original assumption of water-wet rock. However, unless there is experimental data, there is no way of knowing if the models correctly represent field conditions. Experimental calibration of Stone-type models is especially important when the three-phase region comprises a significant volume of the reservoir, which is likely to be the case in a WAG process.
The displacement functions (relative permeability as a function of phase saturation) are developed by performing experiments that replicate true reservoir conditions in the lab, i.e., true reservoir pore pressure, field overburden pressure, reservoir temperature, and use of reservoir fluids and reservoir core samples that have been restored to the field wettability conditions. The restoration process is challenging for carbonate reservoirs, but works well for good quality sandstone reservoirs. It was agreed that a WAG SCAL study would provide additional value beyond our understanding from the double displacement tests (gasflood following a waterflood) performed for the Hibernia Q block in earlier studies, as hysteresis in WAG may lead to results differing from a simple double displacement process. While the general best practices for advanced core analysis are described in Meissner et al. 10, the specific approach in obtaining the three-phase relative permeability involves creating similar saturation conditions within the experimental core sample as expected in the reservoir during the WAG process. The three-phase steady-state relative permeability trajectories start from two-phase oil-water imbibition steady state points, and finish with two-phase imbibition gas-water with near-residual oil saturation. As shown in Figure 7, starting from a two-phase oil-water imbibition steady state condition, gas is introduced as the third phase to obtain a three-phase steady state. This steady state is followed by water injection followed by gas injection to best match a WAG-type process. Each trajectory ends with a final unsteady-state waterflood to residual oil and gas saturations. The process is repeated to obtain additional trajectories starting from different initial oil-brine saturation steady state conditions, thus resulting in ternary diagrams such as the one shown in Figure 7.

The SCAL and PVT data are being used along with results from slim tube and double displacement coreflooding studies to determine the effect of gas-phase composition and WAG operating parameter optimization. Normally, these types of studies would be performed at ExxonMobil’s Upstream Research Company in Houston, TX, as per previous studies by Shyeh-Yung and Stern 11,12. In this case, the studies will be performed at Memorial University of Newfoundland (Memorial). The collaborative research and development project with Memorial not only helps HMDC meet its R&D obligations but is creating a new world-class Hibernia EOR Lab through its investment in the laboratory, equipment, and research. The Hibernia EOR Lab is in the process of being constructed and will house a variety of equipment to investigate miscible and immiscible phase behavior for enhanced oil recovery at the pore and core scale along with analytical instruments to determine fluid and rock properties for operating conditions up to 69MPa and 160°C. The MMP Coreflooding apparatus, shown in Figure 8, will be used to perform slim tube and coreflooding experiments to confirm optimal displacement efficiency as a function of enrichment, injection pressure, WAG ratio etc. using field specific fluid and rock samples.

Optimal WAG recovery is a function of phase behavior, WAG operating conditions, and reservoir properties 3,11-12. The goal of the laboratory studies is to selectively examine recovery at the pore and core scale using a series of visualization, coreflooding, miscibility (slim tube) experiments, along with simulation studies to infer optimal operating strategies. Laboratory studies will confirm recovery results as a function of oil and gas composition and reservoir properties in order to better plan field wide implementation strategies. Going forward to potential field wide implementation, it will be necessary to benchmark the phase behavior and displacement mechanisms as a function of oil and gas composition and reservoir properties. Finite changes in composition based on block to block variability coupled with changes in gas composition based on supply source and timing will impact pore level miscibility and microscopic recovery efficiency. The effects of fluids’ composition, injection pressure, mode of operation (constant injection pressure versus constant flow rate), number of WAG cycles and WAG ratio on incremental oil recovery are parameters of interest for visualization and double displacement tests.

Reservoir Simulation Studies
The simulation studies are being conducted using ExxonMobil’s reservoir simulation system, EMpower®. The studies range from core-scale models to field-scale models and will be critical to the ultimate decision for field-wide EOR implementation. It is critical to accurately represent all of the laboratory studies in order to compare the different development plans. Ultimately, being able to match the pilot performance will be a key step in gaining confidence in the model results.

The starting point for the WAG analysis is a black oil simulation model built from the current geologic interpretation. The model had been history matched relatively recently and did a good job of matching the water flood performance. The water flood has over 15 years of production history and many of the blocks are producing at greater than 80% water cut so the water flood displacement is well understood. Two key changes were required to be able to use the model to analyze WAG – conversion to compositional fluid modeling and three-phase relative permeability. Previous sensitivities had not adjusted for either of these factors and were believed to be optimistic. The potential pilot blocks were converted into separate sector models to conserve run time and facilitate the WAG analysis. While there is a minor amount of communication between the fault blocks, historical analysis has shown this to have minimal impact on model predictions.

Initial compositional simulation studies were conducted using the available fluid data. An equation of state was matched to the PVT measurements of the selected block in conjunction with the swelling tests from the gas flood area. The objective was to get an initial fluid representation for sensitivity analysis and to update the equation of state once the new laboratory studies were complete. The compositional model used 13 components with the components above C6 lumped into three fractions. A core-scale simulation model was used to model the slim tube study and the ExxonMobil fluid properties
software, ProTherm®, was used to match the PVT measurements and swelling tests. The Hibernia field data indicates a compositional gradient with depth. This was accounted for in the black oil model by using gravity segregation to account for the changing composition with depth and initializing the model with a saturation pressure vs. depth trend based on the measured data. In the compositional model, the initial compositions were input vs. depth based on the measured data. When run through the historical period, there was good alignment of the compositional model with the black oil model results and no additional history matching was required. This provided a good quality check on the validity of the black oil modeling that was being used to model the rest of the water flood.

The initial compositional simulation studies also incorporated high-quality, steady-state two-phase water-oil and oil-gas relative permeability data that are available for the Hibernia reservoir. History matching of the water flood and gas flood has shown the two-phase data to be a good representation of the fluid displacement. Results from a Hibernia double displacement experiment were also available. The objective of the experiment was to determine whether injection of gas following waterflooding would yield additional oil recovery. A post-waterflood condition was first established and then gas was injected to displace the remaining oil. The relative contributions of all three phases were recorded as a function of time. The double displacement experiment was unsteady state in nature, and three-phase relative permeability data was derived based on Johnson, Bossler, and Naumann (JBN) analysis. As expected, the three-phase relative permeability data were path-dependent and very different from the two-phase situations.

It is common practice in reservoir simulation to rely on two phase relative permeability tables with an interpolation model to estimate relative permeability under the three phase flow conditions. In EMpower®, the Fayers and Matthews modification to Stone’s model is used to represent the three-phase relative permeability. In order to ensure the simulation model accurately represented the three-phase behavior, the double displacement study was modeled in EMpower®. A 1-D model was built to the specifications of the core study with all core and fluid properties aligned with the report. Some modifications were required to the derived two-phase relative permeability tables in order to replicate the three-phase results. The additional planned SCAL data discussed above will measure the three-phase steady-state relative permeability versus saturation and will be incorporated into the simulation models once it is complete in order to reduce uncertainty. The incorporation of the new data may require consideration and use of other three-phase relative permeability models to accurately represent the flow processes.

With the updated fluid and displacement data, the fault block sector models as shown in Figure 9 were used to run sensitivities on the pilot performance. The incremental benefits were reduced as compared to prior analysis using black oil and un-modified two-phase relative permeability. Three different fault block models were constructed in order to test the range of potential WAG benefits and help choose the pilot block. Griding sensitivity studies were conducted given that the base models used 100m x 100m areal grid size, which was believed to be large for a WAG analysis. Models with 50m and 25m areal grids were tested and differences of results were observed. The coarse scale models were optimistic in the incremental recovery for WAG but were beneficial from a run time perspective. Given the high number of sensitivity cases planned for the pilot optimization, the majority of the sensitivity cases were run using the coarse scale model (100m x 100m) with key cases run on the medium scale model (50m x 50m).

The pilot sector model will continue to be refined as additional data become available. Following pilot implementation, being able to replicate the performance in the simulation model is critical to gaining the credibility required in the tool to be able to use it for field wide decision making. Additional sector modeling work will also be completed on the gas flood area, investigating the potential for EOR in the gas flood. Potential benefits in the gas flood include improved recovery of cellar oil while freeing up gas to be used in the water flood.

Field-scale modeling will be required in order to assess potential changes to the field-wide development plan. Critical within this study will be an understanding of the available gas supply and an ability to compare the relative value of the gas within the different areas of the field. A flood management tool will be required which has the ability to simultaneously optimize gas injection, water injection, WAG injection, and gas lift. It is impractical to utilize a full field compositional simulation model for this purpose, but the results of the sector simulation models will be leveraged in the flood management tool.

Pilot Engineering Studies
The key objective of the WAG pilot is to better understand the potential risks and benefits while minimizing capital exposure. The pilot will allow HMDC to collect production data to calibrate reservoir simulation models and will provide proof of concept of the operating conditions/facility modifications.

A preliminary screening of the Hibernia reservoir fault blocks was used to identify candidate blocks for the WAG pilot. Ideal pilot candidates had the following attributes:

- significant EUR potential from WAG;
• short time to observe WAG response;
• relatively isolated block to ensure conclusive results from pilot; and
• mature block development with limited risks to future volumes.

Based on the preliminary screening, a specific fault block was chosen as the most likely WAG candidate. This block was used to test a variety of sensitivities in order to establish the optimum operating parameters for the WAG pilot. The sensitivities tested included operating pressures, length of WAG cycles, total length of WAG injection, water/gas injection rates and ratios, profile control, and completion intervals.

Initial analysis of the operating conditions of the injector during water and gas injection cycles identified hydrate formation and corrosion as potential risks posed by WAG injection. Further modeling is planned to better quantify these risks and identify any facility and/or well modifications necessary to mitigate against them. Other considerations currently being assessed include optimizing currently installed facilities and minimizing the footprint of any additional equipment, such as piping and tie-ins, required for the WAG pilot.

Gas Supply and Infrastructure Studies
The existing gasflood in Hibernia currently utilizes all available gas from the field. Field-wide application of gas injection enhanced oil recovery (EOR) may not be possible without additional external gas supply and gas infrastructure upgrades. Work is being done to determine the Hibernia gas requirements for the gasflood and the EOR project. There are some nearby 3rd party gas sources that could supply gas to Hibernia but the capability for gas import and/or gas commercialization does not currently exist as there is no gas transportation infrastructure in the region. Work with these 3rd parties is planned to determine the available gas volumes, timing, intra-field pipeline options, and commercialization requirements. Additional studies underway are a review of the regional gas supply and demand and Hibernia topsides infrastructure upgrades and flow assurance impacts. EOR using gas injection would be the first step in providing utilization of stranded gas resources.

Path Forward
The current focus is completing the study phase and making progress on the WAG pilot. As study results become available they will be incorporated into the latest simulation models in order to update the performance predictions for the pilot. The pilot engineering studies will be completed allowing for the facilities and well designs to be finalized. Current time lines plan for a startup of the WAG pilot in the second half of 2014.

It is expected that it will take at least two years before sufficient data is gathered from the pilot to determine success or failure. During that time, additional studies will be conducted to evaluate potential alternate sources of gas available to Hibernia and to assess the optimum use of the gas supply within the Hibernia field. In addition, additional fault blocks will be evaluated in simulation to help understand the next phase of WAG if the pilot results are positive.

Ultimately, the study and pilot results will allow for an improved evaluation of the next phase of development for the Hibernia field. The field-wide implementation will optimize the gas utilization for the entire field to achieve maximum benefits for the stakeholders.

Summary
The Gas Utilization Study potentially marks a new era in development of the Hibernia field. The next phase of development is being guided by a disciplined EOR assessment process to ensure technical uncertainties and risks are appropriately identified and managed to support investment decisions. The assessment process is utilizing a full spectrum of technology including specialized laboratory data acquisition and compositional reservoir simulation.

WAG injection in blocks currently undergoing waterflood is currently the primary EOR option being considered for Hibernia. The study described in this paper will lead to:

• Plans for implementation of an EOR pilot scheme to demonstrate the benefits and reduce risk
• Establishment of a field-wide EOR Development Plan.

Integrating all aspects of the study scope has required close coordination between efforts and studies underway at Hibernia Management and Development Company (HMDC), ExxonMobil Upstream Research Company (EMURC), Memorial University of Newfoundland (Memorial), and other contractors.
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References


SI Metric Conversion Factors

\begin{verbatim}

API \quad 141.5/(131.5+\text{oAPI}) \quad = \quad g/cm^3
\text{cal} \quad \times \quad 4.184* E+00 \quad = \quad J
\text{cp} \quad \times \quad 1.0* \quad E-03 \quad = \quad Pa \cdot s
\text{F} \quad \times \quad \left(\text{F-32}/1.8\right) \quad = \quad ^\circ C
\text{psi} \quad \times \quad 6.894 \, 757 \quad E-03 \quad = \quad MPa
\text{scf} \quad \times \quad 2.831 \, 685 \quad E-02 \quad = \quad m^3
\text{STB} \quad \times \quad 1.589 \, 873 \quad E-01 \quad = \quad m^3

\end{verbatim}


Figure 1. Hibernia GBS Development/Location

Figure 2. Hibernia and Ben Nevis-Avalon Reservoirs
Figure 3.
Hibernia Historical and Planned Production

Figure 4.
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Hibernia B16-59 Swelling Test

Figure 7.
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Different initial Oil-Water Steady-State starting states to generate multiple trajectories
Figure 8.
Design of the MMP Coreflooding Apparatus

Figure 9.
Full-Field Model Simulation Gridding Relative to WAG Sector Model Gridding

Hibernia Reservoir Simulation Models

WAG Pilot Sector Simulation Models

100m x 100m Grid
50m x 50m Grid
25m x 25m Grid