EERC
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June 1, 2015

Ms. Karlene Fine
North Dakota Industrial Commission
ATTN: Oil and Gas Research Program
State Capitol – 14th Floor
600 East Boulevard Avenue, Department 405
Bismarck, ND 58505-0840

Dear Ms. Fine:

Subject: EERC Proposal Entitled "Improved Characterization and Modeling of Tight Oil Formations for CO_2 Enhanced Oil Recovery Potential and Storage Capacity Estimation" for a North Dakota Industrial Commission Oil and Gas Research Program Funding Request

The Energy & Environmental Research Center (EERC) is proposing a project to conduct research activities that will generate insight regarding the potential to use CO_2 for enhanced oil recovery and CO_2 storage in the Bakken Formation.

Enclosed please find an original and one copy of the subject proposal along with a check for the $100 application fee.

If you have any questions, please contact me by telephone at (701) 777-5287 or by e-mail at jsorensen@undeerc.org.

Sincerely,

James A. Sorensen
Senior Research Manager

Approved by:

Thomas A. Erickson, Director
Energy & Environmental Research Center

JAS/kal

Enclosures

Oil and Gas Research Program

North Dakota

Industrial Commission

Application

Project Title: Improved Characterization and Modeling of Tight Oil Formations for CO_2 Enhanced Oil Recovery Potential and Storage Capacity Estimation

Applicant: Energy & Environmental Research Center

Principal Investigator: James A. Sorensen

Date of Application: June 1, 2015

Amount of Request: $400,000

Total Amount of Proposed Project: $2,650,000

Duration of Project: 3 Years

Point of Contact (POC): James A. Sorensen

POC Telephone: (701) 777-5287

POC E-Mail Address: jsorensen@undeerc.org

POC Address:

15 North 23rd Street, Stop 9018

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ABSTRACT

Objective: Total oil-in-place estimates for the Bakken Petroleum System range from 300 billion barrels (Bbbl) to over 900 Bbbl. Most estimates for primary recovery range from 3% to 5%. With such low primary recovery factors and such a large resource, small improvements in productivity could increase North Dakota's technically recoverable oil by billions of barrels. Previous Energy & Environmental Research Center (EERC) research indicates that as much as 4 to 7 Bbbl of incremental oil may be produced through the use of carbon dioxide (CO_2). However, pilot-scale CO_2 injection tests in the Bakken have had limited success, and there is no clear, straightforward answer regarding the most effective approach for improving oil productivity in the Bakken. A better understanding of the fundamental mechanisms controlling the interactions between CO_2, oil, and the tight rocks of the Bakken Formation is necessary to develop the knowledge necessary to make informed decisions regarding the development of effective injection and production schemes. The EERC seeks funding for a research project to develop improved tools and techniques to evaluate fluid flow in the tight rocks of the Bakken Formation, including the shales, resulting in an ability to better determine the enhanced oil recovery (EOR) potential of the Bakken. The objective is to generate improved reservoir characterization data and integrate those data with reservoir modeling to develop previously unavailable insight regarding the use of CO_2 for EOR in the Bakken Formation. The proposed project has already received funding from the U.S. Department of Energy (DOE) and the North Dakota Lignite Energy Council (LEC). This project complements the EERC's Phase II Bakken CO_2 Storage and Enhanced Recovery Program, and the results of both efforts will be made available to the North Dakota Industrial Commission (NDIC). Additional detail on this complementary effort can be found in Appendixes A and B to the EERC proposal.

Expected Results: The results of the proposed work will provide insight regarding relationships between Bakken oil, key reservoir attributes (particularly the nature of micro- and nanoscale pore networks), and CO_2 under reservoir conditions toward the efficient use of CO_2 for EOR.

Duration: The duration of the proposed project is 36 months (November 1, 2014, to October 31, 2017).

Total Project Cost: The estimated cost of the project is $2,650,000. The amount requested from the Oil and Gas Research Council is $400,000. Cofunding in the form of cash has been provided as follows: DOE = $2,000,000 and LEC = $250,000. DOE is currently contemplating adding up to $500,000 cash to the project budget, but it is anticipated that DOE's decision regarding the precise amount and timing of add-on funding will not be made until later in 2015. As such, the budget presented in this proposal only includes the DOE funding that has already been awarded to the EERC for this project. Marathon Oil Company has also provided currently unenumerated in-kind cost share in the form of access to core samples from at least three North Dakota wells.

Participants: Participants include the EERC, DOE, LEC, and—to date—Marathon Oil Company.

PROJECT DESCRIPTION

Objectives

Total oil-in-place reserve estimates for the Bakken Formation range from a minimum of 300 billion barrels (Bbbl) to over 900 Bbbl. Most estimates for primary recovery range from approximately 3% to 5% (LeFever and Helms, 2008). With such low primary recovery factors associated with this massive resource, even small improvements in productivity will add billions of barrels to the recoverable resource. The Energy & Environmental Research Center (EERC) intends to use new reservoir characterization and laboratory analytical data and state-of-the-art modeling to determine the viability of using carbon dioxide (CO_2) for enhanced oil recovery (EOR) in the Bakken Formation.

Since 2012, the EERC has been conducting the Bakken CO_2 Storage and Enhanced Recovery Program. Phase I of the program ended in May 2014.The program is in its second phase, which is scheduled to run until March 2016 (see Appendix A, program prospectus). The Bakken CO_2 Storage and Enhanced Recovery Program is currently supported by a combination of cash and in-kind contributions from Marathon Oil Company, Continental Resources Ltd., Kinder Morgan, Hess, XTO, Baker Hughes, Schlumberger, Computer Modelling Group Ltd., and the U.S. Department of Energy (DOE). The objective of the Program is to use new and existing reservoir characterization and laboratory analytical data coupled with state-of-the-art static and dynamic computer modeling to design and implement pilot-scale field injection tests. The goal of those tests is to determine the viability of injecting CO_2 into the Bakken Formation for simultaneous carbon storage and EOR.

Generally speaking, the initial results of the Bakken CO_2 Storage and Enhanced Recovery Program efforts suggest that CO_2 may be effective in enhancing oil production from the Bakken by as much as 4 to 7 Bbbl of incremental oil (Sorensen and others, 2014). However, there is no clear, straightforward answer regarding the most effective approach for using CO_2 to improve productivity. The results generated thus far support a conclusion that an unconventional resource will require unconventional approaches. It is clear that a better understanding of the fundamental mechanisms controlling the interactions between CO_2, oil, and other reservoir fluids in these unique formations is necessary to develop effective approaches to EOR. This same information is critical to determine the size and nature of the CO_2 market that exists in the Bakken for EOR, which in turn is necessary for the oil industry to make informed decisions about the potential deployment of CO_2 EOR projects in the Bakken.

With these needs in mind, DOE has recently awarded funding to the EERC in support of a new, separate project entitled "Improved Characterization and Modeling of Tight Oil Formations for CO_2 Enhanced Oil Recovery and Potential and Storage Capacity Estimation" (hereby referred to as the "Tight Oil CO_2 EOR and Storage Project"). This new project will be complementary to the existing Bakken CO_2 Storage and Enhanced Recovery Program. (See Appendix B, comparison table.) The Tight Oil CO_2 EOR and Storage Project began November 1, 2014, and will run for 36 months, ending October 31, 2017. Total DOE funding for this project is $2 million, which will be split between two 18-month phases, with the North Dakota Lignite Energy Council (LEC) also providing a cash contribution of $250,000. The EERC is requesting that the Oil and Gas Research Program (OGRP) provide a cash contribution of $400,000 to be used as cost share for the Tight Oil CO_2 EOR and Storage Project. Because this new project is complementary to the existing Bakken CO_2 Storage and Enhanced Recovery Program, the OGRP will be provided with access to the results of that Program at the same level and timing as the members of the Bakken CO_2 Storage and Enhanced Recovery Program.

Methodology

While CO_2 injection for EOR has been successfully applied to conventional reservoirs for decades (Jarrell and others, 2002), recent pilot tests in the Bakken have not been commercially successful (Sorensen and others, 2014). This is likely because those pilot tests used conventional approaches that are not applicable to unconventional reservoirs. Before CO_2 injection in the Bakken for EOR and storage can be widely implemented, the characteristics of the rocks and physical–chemical mechanisms affecting CO_2 permeation and oil extraction in tight, organic-rich, oil-wet and mixed-wet systems must be determined. Recent laboratory-based testing of these formations at the EERC (Hawthorne and others, 2013) suggests that permeation of CO_2 into the rock matrix and/or microfracture networks in these tight formations may be much more extensive than previously thought, even within the Bakken shales. However, because of the limitation of using traditional laboratory analyses to identify micro- and nanoscale fracture networks and pore configurations in tight rocks, the degree to which these features affected CO_2 permeation and oil extraction have not been quantitatively evaluated.

To truly understand the CO_2 EOR potential in the Bakken, it is critical to better identify and understand the various physical and chemical factors that affect CO_2 permeation into, and oil extraction out of, the matrix. It is also necessary to better understand CO_2 sweep efficiency, oil mobility, and transport through both the fracture networks and the rock matrix. The EERC proposes to address these needs by using samples collected from the tight, fractured reservoir and oil-wet, organic-rich shales within the Bakken system to:

- Develop methods to better detect and characterize the macro-, micro-, and nanoscale pores and fracture networks within tight, fractured reservoirs and within organic-rich sealing formations.
- Determine if there are significant correlations between fracture network characteristics and the physical, geochemical, and/or geomechanical properties of the rock that can be used to improve well log calibration and interpretation.

- Evaluate the rate of CO_2 transport within, and oil extraction from, Bakken reservoir rocks and shales, and determine how differences in fracture network characteristics affect CO_2 permeation and oil extraction in both types of tight rocks.
- Assess how CO_2 capillary entry pressure at the interface between the Middle Member of the Bakken and the shale members is affected by the wetting fluid of the organic-rich shales.
- Develop improved methods to integrate rock characterization data into geocellular and simulation models to improve their ability to predict the CO_2 EOR potential in the Bakken.

Marathon Oil Company has committed to providing the EERC with the rock samples necessary to conduct this scope of work. Laboratory-based activities will be conducted primarily at EERC facilities, with some special rock analytical work scheduled to be conducted at Ingrain, a Houston-based commercial laboratory that specializes in advanced rock analyses. All modeling efforts will be conducted at the EERC. The EERC will conduct a suite of experimental activities to evaluate the interactions between CO_2 and Bakken rocks, with an emphasis on developing permeation/extraction rate data. References cited in this proposal are presented in Appendix C. The activities will be organized in five tasks.

Task 1.0 – Project Management and Planning. This task will focus on ensuring the overall success of the project by providing experienced management to each task and to the project as a whole. The EERC project manager will ensure that the project is carried out within budget, schedule, and scope.

Task 2.0 – Sample Selection and Detailed Baseline Characterization. This task will entail sample collection and analysis of the geochemical, geomechanical, and petrophysical properties of a suite of samples collected from the Middle Bakken and Bakken shales. These analyses will establish the baseline characteristics for comparison with advanced fracture network characterization, correlation with geophysical well logs, and incorporation into the geologic models. The analyses will improve the accuracy of geologic and simulation models in predicting the interactions between CO_2 and Bakken rocks and will assist in the interpretation of the permeation test results. Petrographic analyses include optical microscopy (OM), x-ray fluorescence (XRF), x-ray diffraction (XRD), and scanning electron microscopy scanning electron microscopy (SEM) coupled with electron dispersive scanning (EDS). The XRF, XRD, and SEM–EDS analytical data will be used to support core-to-log correlation activities and multimineral petrophysical analysis (MMPA) of well logs which, in turn, will be incorporated into the models. Geomechanical studies will focus on mechanical strength testing.

Task 3.0 – Development of Improved Methodologies to Identify Multiscale Fracture Networks and Pore Characteristics. This task will entail the characterization of macro-, micro-, and nanoscale fracture networks and pore spaces within the Bakken samples. Fracture networks will be first identified on the macroscale through visual core descriptions and whole-core computed tomography (CT) scanning. Areas of interest will be further evaluated using micro-CT scanning, ultraviolet fluorescence spectroscopy, OM and SEM–EDS imaging to better characterize macro- and, possibly, microscale features. Finally, field emission–SEM and focused ion beam–SEM imaging techniques will be used to characterize connective fractures down to the smallest apertures that present technology can determine. These data will be used as input into geocellular models.

Task 4.0 – CO_2 Transport, Permeation, and Oil Extraction Testing. This task will entail laboratory-based CO_2 exposure testing to better understand the transport of CO_2 within Bakken shales and Middle lithofacies. These experiments will measure the hydrocarbons that are extracted from the rock samples, thus providing data on the ability of CO_2 under reservoir conditions to mobilize oil from Bakken rocks. The data collected through these tests will be interpreted in conjunction with the data collected through Tasks 2 and 3. Permeation rates will be used to inform the simulation workflow on the sweep efficiency, while those data and oil extraction rates will inform the EOR simulations.

Task 5.0 – MMPA, Modeling, and Simulation. A detailed petrophysical analysis will be performed to correlate geophysical logs with laboratory data. A multimineral probabilistic approach will be followed in order to match mineral volumes with zones with varying degrees of natural fractures. The MMPA uses well log data and core data to provide an estimate of residual and producible hydrocarbons, effective porosity, and lithofacies-based permeabilities. The MMPA is calibrated to core analytical data and well log-based bulk density, matrix density, porosity, and irreducible water saturation data. The use of MMPA yields a detailed, accurate reservoir model that can be used for CO_2 injection and EOR simulations.

The characterization efforts performed in Tasks 2–5 and the results of the MMPA will be utilized to construct at least two geocellular models (a Middle Bakken model and a shale model) as the basis to run numerical simulation for estimating and validating the CO_2 EOR potential and storage capacity of the Bakken. Because the geologic models statistically vary, a high-, mid-, and low-case of each geocellular model will be developed based on the uncertainty analysis. In the Middle Bakken models, numerical simulation will be performed to investigate the quantity of CO_2 permeation into, and oil extraction out of, the matrix portion of the Middle Bakken rocks to determine CO_2 storage capacity and CO_2 EOR potential under a variety of matrix and fracture permeability scenarios. In the shale model, simulations will be run to investigate the effects of a variety of properties on the ability of Bakken shales to store and/or contain injected CO_2, and possibly produce oil as a result of that injection.

Anticipated Results

The results generated by the proposed activities will provide quantitative data regarding natural fracture networks in the Bakken from macro- to nanoscale levels, CO_2 transport and fluid flow in the Bakken, and the effects CO_2 will have on mobilizing oil. Those data will be used to develop improved models, which in turn will support the development of effective injection and production strategies that can be applied to future field tests. If positive results are achieved, then the application of those results can have a significant positive effect on the ultimate recovery of oil from North Dakota’s vast Bakken resources. The technical insight gained by this project will enable operators to make informed decisions regarding the use of CO_2, and possibly other gases, for EOR in the Bakken.

Facilities and Resources

The proposed effort will be conducted at the EERC, a high-tech, nonprofit branch of the University of North Dakota (UND), Grand Forks, North Dakota. The EERC has a diverse, multidisciplinary team of engineers, geologists, and scientists with extensive research and operational experience and cross-training in characterizing, modeling, predictive simulation, monitoring operations, and risk assessment of CO_2 storage and CO_2 EOR projects. The EERC is committed to providing the necessary personnel resources and experience to effectively carry out the activities outlined in this proposal. The EERC laboratories pertinent to this effort include the Environmental Chemistry Laboratory, the Applied Geology Laboratory, and the Natural Materials Analytical Research Laboratory (see Appendix D). In addition to the equipment housed in the EERC's laboratories, this project proposes to utilize an FE (field emission)–SEM located at UND's Petroleum Engineering Department.

Ingrain is a service company that specializes in state-of-the-art core analysis for shale plays and complex carbonates using Digital Rock Physics. Ingrain will be contracted by the EERC to conduct some of the advanced rock characterization activities. More detailed information on Ingrain's capabilities is provided in Appendix E.

Techniques to Be Used, Their Availability and Capability

Core-based lithofacies and fracture studies will be conducted on slabbed core samples that have been provided by Marathon. Selected core-based analytical activities will be conducted at the EERC using currently available geomechanical testing equipment, optical microscopes, relative permeability testing equipment, and XRD and SEM systems (see Appendix D for detailed description of relevant EERC laboratory capabilities). Advanced characterization efforts described in Task 3 will be conducted at Ingrain facilities (see Appendix E for description of relevant Ingrain capabilities). CO_2 permeation and oil extraction experiments will be conducted at the EERC using equipment and techniques described in Hawthorne and others (2013) (see Appendix F). Static and dynamic modeling activities will be conducted using industry standard software on computer hardware currently existing at the EERC.

Environmental and Economic Impacts While Project Is Under Way

No significant environmental or economic impacts are anticipated as a result of these activities.

Ultimate Technological and Economic Impacts

The North Dakota Department of Mineral Resources estimates that original oil in place for the North Dakota-only portion of the Bakken Petroleum System (including the Three Forks) is approximately 170 Bbbl. If the application of CO_2 for EOR could improve the recovery factor by a modest 1.1%, that improvement in recovery would translate to an additional 1.87 Bbbl of oil production from the

Bakken/Three Forks. Assuming an average oil price of $60/bbl, this would equate to approximately $112 billion worth of oil.

Why the Project Is Needed

Maximizing the productivity of the Bakken system and prolonging the productive life of the play are essential to maintaining long-term economic growth of the oil industry in North Dakota. In essence, without a qualified EOR strategy, the bountiful oil resource of the Bakken system will not be fully realized. The tight, unconventional nature of the Bakken system requires innovative approaches to EOR, and the proposed research activities are necessary to expand the critical knowledge base regarding the potential use of CO_2. The results of the project will provide industry and the state of North Dakota with a foundation for developing a pathway to efficiently and economically improve Bakken oil recovery.

STANDARDS OF SUCCESS

Success will be measured according to the timely achievement of project milestones and development of deliverables that meet the goals of the project. The value to North Dakota is improved understanding of the Bakken with respect to future EOR and potentially improved oil production from the Bakken. Results may directly influence industry practices and lead to improved oil recovery, with a potential of over 1 Bbbl of incremental recovery. It has been estimated that a 10-to-20-year life span for the Bakken play in North Dakota will equate to 3000 to 3500 long-term jobs (Helms, 2010). Successful development of EOR technologies for the Bakken play would extend the life span of those jobs for at least another decade. Success of the project will also be based on the development of previously unavailable data sets and production of technical documents for public dissemination. The EERC will produce high-quality publications to be downloadable from the OGRC Web site and technical publications peer-reviewed by organizations such as SPE targeted to the oil and gas audience.

BACKGROUND/QUALIFICATIONS

The multidisciplinary project team will be led by Mr. James Sorensen. Mr. Sorensen has been overseeing and successfully completing large, multitask projects as a Senior Research Manager at the EERC for over 15 years. Mr. Sorensen has been a Plains CO_2 Reduction (PCOR) Partnership task leader for geologic site characterization and storage capacity estimation since the inception of the program. He has also served as the project manager and lead principal investigator (PI) on a joint industry–DOE-sponsored project to evaluate the feasibility of CO_2-based EOR in the Bakken Petroleum System and has been an author or coauthor on several technical papers on that subject. Other EERC team members include Dr. Steven Hawthorne, a Senior Research Manager with expertise in CO_2 extraction and in evaluating the impacts of CO_2 exposure on various geologic materials; Ms. Bethany Kurz, a Senior Research Manager who has been directly involved in projects to characterize and evaluate the suitability of both conventional and unconventional reservoirs for simultaneous CO_2 storage and EOR; and Dr. Lu Jin, a Reservoir Engineer with expertise in modeling and simulation of multiphase flow in porous media, improved oil recovery technologies, and phase behavior in unconventional reservoirs. Mr. John A. Harju, Associate Director for Research, will serve as project advisor. Mr. Harju has expertise in carbon storage, geologic characterization, EOR, geochemistry, technology development, and analytical chemistry, especially as applied to the upstream oil and gas industry chemistry. Resumes are included in Appendix G.

Since 2008, the EERC has conducted a series of multidisciplinary research projects, funded at a level of more than $5 million by industry and government stakeholders, to identify key attributes of successful Bakken wells, examine potential EOR technologies, identify and evaluate a wide variety of environmental and operational challenges facing development of the Bakken, and provide technically based guidance to stakeholders regarding future exploitation efforts. Much of this work has been done under the umbrella of two distinctive EERC research programs, the Bakken Production and Optimization Program (BPOP), and the Bakken CO_2 Storage and Enhanced Recovery Program. Among the many topic areas upon which the EERC efforts have been focused are geology, geochemistry, geomechanics, and engineering. The results of the program have been published in several final reports (Sorensen and others, 2010; Schmidt and others, 2011; Sorensen and others, 2014) and numerous SPE papers (Hawthorne and others, 2013; Kurtoglu and others, 2013; Klenner and others, 2014; Liu and others, 2014).

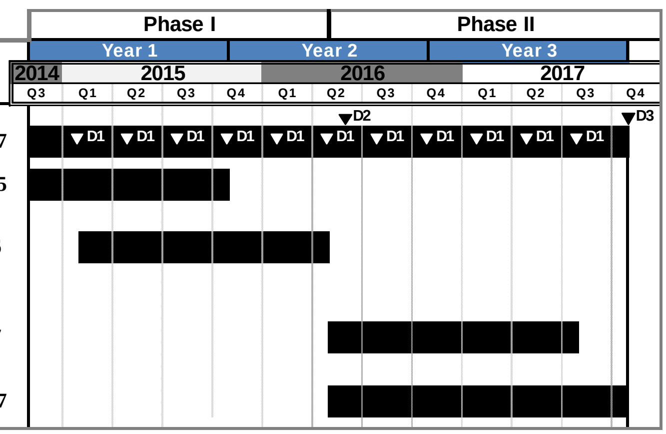
MANAGEMENT

Mr. Sorensen will be responsible for the overall project management and effective communication between all project partners and with EERC project personnel. Periodic meetings with the project team will be conducted to ensure that the project is progressing according to schedule and budget, ensure that project goals are being met, enable rapid resolution of any problems that may arise during the project, and mitigate any potential technical or nontechnical risks. Quarterly progress reports will be used to communicate project budget, schedule, and technical achievement to all sponsors.

TIMETABLE

The duration of the proposed project is 3 years as shown below. Please note that this project started November 1, 2014, upon award from DOE with the stipulation that the EERC would seek cost share from nonfederal sponsors.

	Start Date	End Date
Task 1 – Project Management and Planning	**11/1/14**	**10/31/17**
Task 2 – Sample Selection and Detailed Baseline Characterization	**11/1/14**	**10/31/15**
Task 3 – Development of Improved Methodologies to Identify Multiscale Fracture Networks and Pore Characteristics	**2/1/15**	**4/30/16**
Task 4 – CO_2 Transport, Permeation, and Oil Extraction Testing	**5/1/16**	**7/31/17**
Task 5 – MMPA, Modeling, and Simulation	**5/1/16**	**10/31/17**



Deliverable (D): D1 – Quarterly Progress Report (due 30 days after the end of each calendar quarter); D2 – Interim Report, due May 31, 2016; D3 – Final Report, due October 31, 2017.

The total cost of the project is $2,650,000. The amount requested from OGRC is $400,000. Cofunding in the form of cash has already been provided as follows: DOE = $2,000,000 and LEC = $250,000 (verification of funds received can be found in Appendix H). DOE is currently contemplating adding up to $500,000 cash to the project budget, but it is anticipated that DOE's decision regarding the precise amount and timing of add-on funding will not be made until later in 2015. As such, the budget presented in this proposal only includes DOE funding that has already been awarded for this project.

BUDGET

CATEGORY	NDIC OGRC SHARE	LEC SHARE	DOE SHARE	PROJECT TOTAL
Labor	$ 374,979	$ 141,296	$ 1,279,690	$ 1,795,965
Travel	$ 3,129	$ -	$ 82,567	$ 85,696
Equipment > $5000	$ -	$ -	$ 13,000	$ 13,000
Supplies	$ 903	$ 4,757	$ 11,393	$ 17,053
Software Tools and Licenses	$ 18,060	$ 21,070	$ 114,290	$ 153,420
Other*	$ 513	$ 102	$ 4,533	$ 5,148
Laboratory Fees & Services				
Natural Materials Analytical Research Lab	$ -	$ 82,775	$ 48,607	$ 131,382
GC/MS Lab	$ -	$ -	$ 176,001	$ 176,001
Graphics Service	$ 2,416	$ -	$ 7,111	$ 9,527
Shop & Operations Fee	$ -	$ -	$ 2,442	$ 2,442
Outside Lab	$ -	$ -	$ 258,108	$ 258,108
Freight	$ -	$ -	$ 2,258	$ 2,258
Total Project Costs – U.S. Dollars	$ 400,000	$ 250,000	$ 2,000,000	$ 2,650,000

The labor, analytical, and modeling expenses and expenses associated with overall project management and reporting are based on EERC experiences in conducting similar projects. Further budget justification can be found in Appendix I. If the requested amount of funding is not available, then the proposed objectives will be unattainable because project success is directly tied to the integration of the various technical activities.

CONFIDENTIAL INFORMATION

There is no confidential information.

PATENTS/RIGHTS TO TECHNICAL DATA

Patents or rights do not apply to this proposal.

STATUS OF ONGOING PROJECTS

The EERC has previously been awarded OGRC funding for several different projects. Active projects include the *Plains CO_2 Reduction Partnership*; the *Program to Determine the Uniqueness of the Three Forks Bench Reserves, Determine Optimal Well Density in the Bakken Pool,* and *Optimize Bakken Production* (also known as the *Bakken Production Optimization Program*, or BPOP); the project known as the *Oil Characterization Study*; and the *Produced Fluids Gathering Pipeline Study* (commissioned by the 64th North Dakota Legislative Assembly). The status of those projects is presented in Appendix J.

APPENDIX A

BAKKEN CO_2 STORAGE AND ENHANCED RECOVERY PROGRAM PROSPECTUS

Bakken CO_2 Storage and Enhanced Recovery Program

Program Introduction

The Energy & Environmental Research Center (EERC) recently completed Phase I of the Bakken CO_2 Storage and Enhanced Recovery Program. The results were promising, but it is clear that the knowledge gained from the laboratory- and modeling-based studies needs to be validated in the field. With that in mind, the EERC has initiated Phase II of the program, which encompasses two distinct efforts. Phase IIA focuses on additional laboratory- and modeling-based investigations to support the design of an injection/production scheme, and Phase IIB focuses on providing technical support (additional laboratory work, modeling, and monitoring) to a pilot-scale field demonstration. To attain the ultimate goal of conducting pilot-scale injection tests, the program will focus on answering the following key questions:

- What are the characteristics of a good candidate site for CO_2-based enhanced oil recovery (EOR)?
- Which zone or zones within the Bakken petroleum system should be targeted for injection?
- Which type of injection/production schemes might be the most effective?
- What site-specific data need to be collected prior to, during, and after the injection test?
- What is the expected time frame for CO_2 to affect production?

Costs Shared by a Consortium of Industry and the Federal Government

As a partner in this ongoing research program, the U.S. Department of Energy (DOE) committed $2.6 million in matching funds to support a consortium of industry partners conducting research focused on the potential to use CO_2 for EOR in the Bakken–Three Forks play. The EERC—along with Continental Resources, Inc.; Marathon Oil Company; Kinder Morgan; Baker Hughes, Inc.; Computer Modelling Group Ltd.; DOE; Hess Corporation; XTO Energy; and Schlumberger—is seeking additional organizations interested in participating in the consortium of industry partners. Participation can be achieved by committing cash and/or in-kind cost share to support program activities, thereby leveraging the combined funding and expertise of all consortium members.

Opportunities to Share in Results

This is a partner-driven program with the goal of providing stakeholders with new information and data regarding the ability to realize improvements in oil productivity through CO_2 injection in tight oil-bearing formations. Utilizing a consortium approach minimizes corporate financial and staffing resources and makes results readily available to consortium companies.

Forms of Participation:

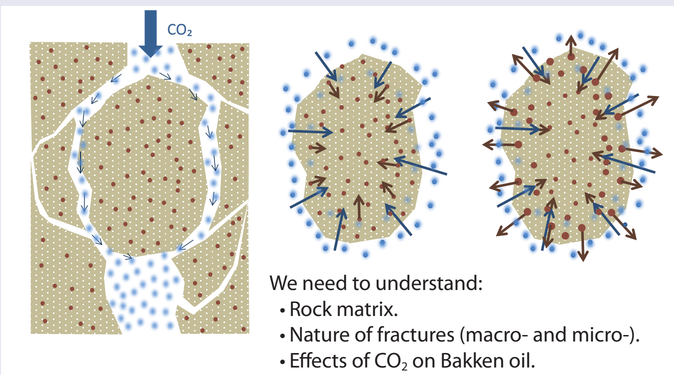
- **Member at Large** – The participant pays a membership fee of US$250,000. Up to US$100,000 of the fee may be in the form of documented in-kind contributions. For this fee, the participant will have full access to quarterly project update materials, all project results, invitations to all project update meetings, and limited analytical services.
- **Site Host for DOE Study** – The participant provides a site for the pilot test, obtains the necessary CO_2 for injection, conducts the injection and production activities, and provides relevant data to the project team. The EERC applies DOE funding to conduct laboratory, modeling, and field-based activities to support the design, implementation, and monitoring of a pilot-scale CO_2 EOR test in the field. There can be up to two hosts for the DOE study.
- **Site Host for Additional Field Tests** – A limited portion of DOE funding can go toward additional field tests. If the participant wants the EERC to characterize, model, or monitor a test at its location, a customized budget and scope of work can be developed for that test, with the participant providing cash contributions to support selected, directed EERC efforts. The specific scope and the cash contribution necessary to accomplish that scope are negotiable.

Program Details

Examinations of Hydrocarbon Extraction from Tight Oil Formations Using CO_2

Experiments to quantify the ability of CO_2 to extract hydrocarbons from rock samples collected from key selected lithofacies within the Bakken–Three Forks play will be conducted:

- "Before and after" analyses of selected rock samples used in the extraction experiments will determine the effects of CO_2 on matrix parameters as well as the depth and rate of CO_2 penetration into the matrix.
- Experiments on rocks using other extraction media (e.g., surfactants, foams, other gases, or combinations of gases) will examine their ability to remove hydrocarbons from tight rocks.

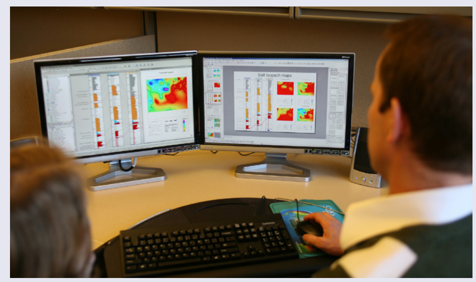


Conceptual mechanisms for CO_2 interactions with rock and oil in the Bakken Formation.

Fracture Characterization and Modeling

Microfractures will be systematically characterized in several core samples of key Bakken and Three Forks lithofacies. Those microfracture data will be integrated into improved static geologic models of a selected reservoir. Activities include:

- Detailed scanning electron microsopy and ultraviolet fluorescence examinations of samples representing key lithofacies.
- Integrating microfracture data into a static geologic model of a select Bakken reservoir.
- Comparing microfracture data to well logs with a goal of correlating microfracture swarms to log responses.



Modeling activities conducted under Phase II will largely be focused on incorporating the results of the Phase I hydrocarbon extraction studies into static and dynamic modeling exercises. Core scale or smaller models will be upscaled into near-wellbore and larger models to help predict CO_2 extraction of hydrocarbons on rock volumes which are too complex to reproduce in the lab environment. Models built in Phase I will be updated with the newly collected data, and dynamic simulations will be performed in order to optimize injection scenarios for a pilot-scale project.

Pilot-Scale Field Test of CO_2 Injection into a Tight Oil Reservoir

The EERC seeks to apply the knowledge gained from the characterization and modeling activities to a pilot-scale field test of CO_2 injection into a Bakken or Three Forks reservoir. The EERC will provide modeling support to the operator partner; conduct minimum miscibility pressure and hydrocarbon extraction studies on site-specific samples of oil and rock; and assist in design, implementation, and monitoring of the test.

To discuss consortium membership, contact:

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Continental Resources · Marathon Oil · Baker Hughes · CMG · Kinder Morgan · Schlumberger · Hess · XTO Energy · NETL

THE UNIVERSITY OF NORTH DAKOTA

APPENDIX B

COMPARISON TABLE OF EERC'S BAKKEN EOR RESEARCH PROJECTS

Comparison of Key Elements of EERC's Past, Present, and Future Bakken Research Projects		
Bakken Phase I		
Partners	**Funding**	**Goals and Key Elements of Work Plan**
U.S. Department of Energy (DOE) North Dakota Industrial Commission Marathon Oil Company Continental Resources TAQA North	\$675,000 cash \$475,000 cash \$50,000 cash, \$163,000 in-kind \$50,000 cash \$75,000 cash	Goal was to generate data and insight regarding the use of CO_2 for Bakken enhanced oil recovery (EOR) and CO_2 storage. A vast majority of the characterization efforts and all of the modeling efforts were focused on the Middle Bakken. The hydrocarbon extraction work was roughly split between Middle Bakken and shales. Minimum miscibility pressure studies were conducted, including support for the development of the new capillary rise method.
Bakken Phase II		
Partners	**Funding**	**Goals and Key Elements of Work Plan**
DOE Computer Modelling Group (CMG) Kinder Morgan Baker Hughes Schlumberger Marathon Oil Company Continental Resources XTO Energy Hess	\$2,623,558 cash \$467,000 in-kind \$250,000 in-kind In-kind to be determined (TBD) In-kind TBD TBD TBD \$150,000 cash, \$100,000 in-kind \$250,000 cash	Goal is to support the deployment of effective CO_2 injection operations for EOR and storage in the Bakken. Conducting a series of laboratory-, modeling-, and field-based activities to quantitatively determine the effects of injecting CO_2 into the Bakken Formation from the perspectives of CO_2 storage and EOR. Emphasis is roughly equally split between work on selected lithofacies of the Middle Bakken and the shales, with one productive bench of the Three Forks also being part of the efforts. Verify and validate the phenomena and mechanisms identified in Phase I with more robust data. Working with CMG and Schlumberger to improve modeling and simulation software for use in tight oil reservoirs. Integrate the lab results in the improved software to more accurately model and simulate the complex processes that occur in these tight, fractured formations. Design and monitor a pilot-scale injection test into one or more Bakken Petroleum System reservoirs.
Tight Oil CO_2 EOR and Storage Project		
Partners	**Funding**	**Goals and Key Elements of Work Plan**
DOE Lignite Energy Council Other	\$2,000,000 cash \$250,000 cash \$400,000 cash	Goal is to build on the knowledge gained from Phases I and II to assess and validate CO_2 transport and fluid flow in fractured tight oil reservoirs of the Bakken. Determine the effects of the wetting fluid on EOR and CO_2 storage. Illuminate the roles that the shale members may play with respect to CO_2 storage, containment, EOR, or possibly even all three. Advanced scanning electron microscopy and carbon tetrachloride scanning techniques will be used to characterize fractures and pore networks at scales ranging from macro- to nano. (Techniques that are not part of the Phase I or II program will be used.) Geomechanical testing will be conducted on rock samples to support development of improved hydraulic fracture models. (Phase I and Phase II efforts do not include any geomechanical testing.) Determine CO_2 permeation and oil extraction rates in tight reservoir rocks and organic-rich shales. Integrate the laboratory-based CO_2 permeation and oil extraction data and the characterization data into geologic models and dynamic simulations to predict CO_2 storage capacity and EOR in the Bakken.

*Elements highlighted in yellow delineate the primary differences between the projects.

APPENDIX C

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APPENDIX D

RELEVANT EERC LABORATORY CAPABILITIES

RELEVANT EERC LABORATORY CAPABILITIES

Applied Geology Laboratory

- Full preparation laboratory, including slab saw, core drills, micronizing mill, and thin-section mill
- Petrographic microscopes utilizing plane- and cross-polarized transmitted light
- Nanovea PS 50 optical profilometer
- Forney 20+-ton universal compression frame
- Trautwein-Geotac flexible wall permeameter
- Hoek-style triaxial and core-flood cells
- Teledyne Isco high-pressure fluid pumps
- Gas porosimeter/pycnometer
- Terraplus RS125 supergamma spectrometer
- Dead weight consolidation frames
- Thermal dilatometer
- Ion chromatograph
- Distillation, saturation, and chemistry equipment

Natural Materials Analytical Research Laboratory

- 4200-square-foot laboratory facility
- JEOL 5800 scanning electron microscope with NORAN instruments energy-dispersive spectrometer (EDS) detector system, GW Electronics enhanced backscatter detector, and NORAN instruments microanalysis system
- JEOL 5800 LV with Princeton Gamma-Tech Spirit Instruments EDS and microanalysis system and a HKL Technology electron backscatter diffraction system.
- QEMSCAN®
- Rigaku ZSK Primus II x-ray fluorescence system
- Bruker AXS D8 advanced x-ray diffraction system

Analytical Research Laboratory

- 4200-square-foot, fully equipped, exceedingly clean laboratory with seven fume hoods
- VG PQ ExCell inductively coupled plasma–mass spectrometer (ICP–MS) with collision cell technology
- PS Analytical Millennium Merlin cold-vapor atomic fluorescence spectrometer
- PS Analytical Millennium Excalibur hydride generation atomic fluorescence spectrometer
- Varian Spectra AA-880Z graphite furnace atomic absorption spectrometer
- Mitsubishi TOX-100 chlorine analyzer with oxidative hydrolysis microcoulometry
- Perkin Elmer Optima 2100 ICP–AES (atomic emission spectroscopy)
- Dionex ISC3000 ion chromatograph (IC) with conductivity detection
- Dionex 2020i IC with UV–Vis (ultraviolet–visible), conductivity, and electrochemical detection
- CEM MDS 2100 microwave with temperature and pressure control
- Pyrohydrolysis/ion-specific electrode for fluorine analysis of fossil fuels

APPENDIX E

INGRAIN DIGITAL ROCK PHYSICS CORE STUDY

INGRAIN

Proposal No. 10092014KM

Digital Rock Physics Core Study

Prepared for:

Energy & Environmental Research Center

Houston, Texas

October 9, 2014

Digital Rock Physics Core Study

Introduction

Ingrain Inc. is pleased to offer the following proposal for shale rock characterization providing the latest technology commercially available in Digital Rock Physics (DRP). This proposal describes a multi-scale workflow that begins with the whole core (CoreHD®) and systematically classifies the rock to ensure our work at each sampling scale is representative of the prior volume as we progress through our analysis – from the meter to the centimeter to the nanometer scale and back. These analyses, along with Ingrain's proprietary fluid flow algorithms, allow us to compute shale reservoir properties and provide clear 3D renderings of the pore structure that controls reservoir properties.

Ingrain brings several advantages to the process of shale reservoir characterization:

- New methodologies to identify and select zones of interest
- Rich understanding of tight rock properties
- Better insights from high-resolution pore-scale analysis
- Extensive experience in complex reservoir types (unconventionals, carbonates)
- Ability to work in wells not cored (sidewall cores, cuttings)
- Significantly shorter turnaround time – days not months

Objectives

The principle objectives of this project are to:

- Understand customers´ objectives and match technical analysis with tailored deliverables
- Provide sensitivity analysis for more effective completions and recovery

Scope of Work

The Ingrain workflow consists of three major stages, followed by report preparation and delivery. A depiction of the integrated workflow is shown in Figure 1.

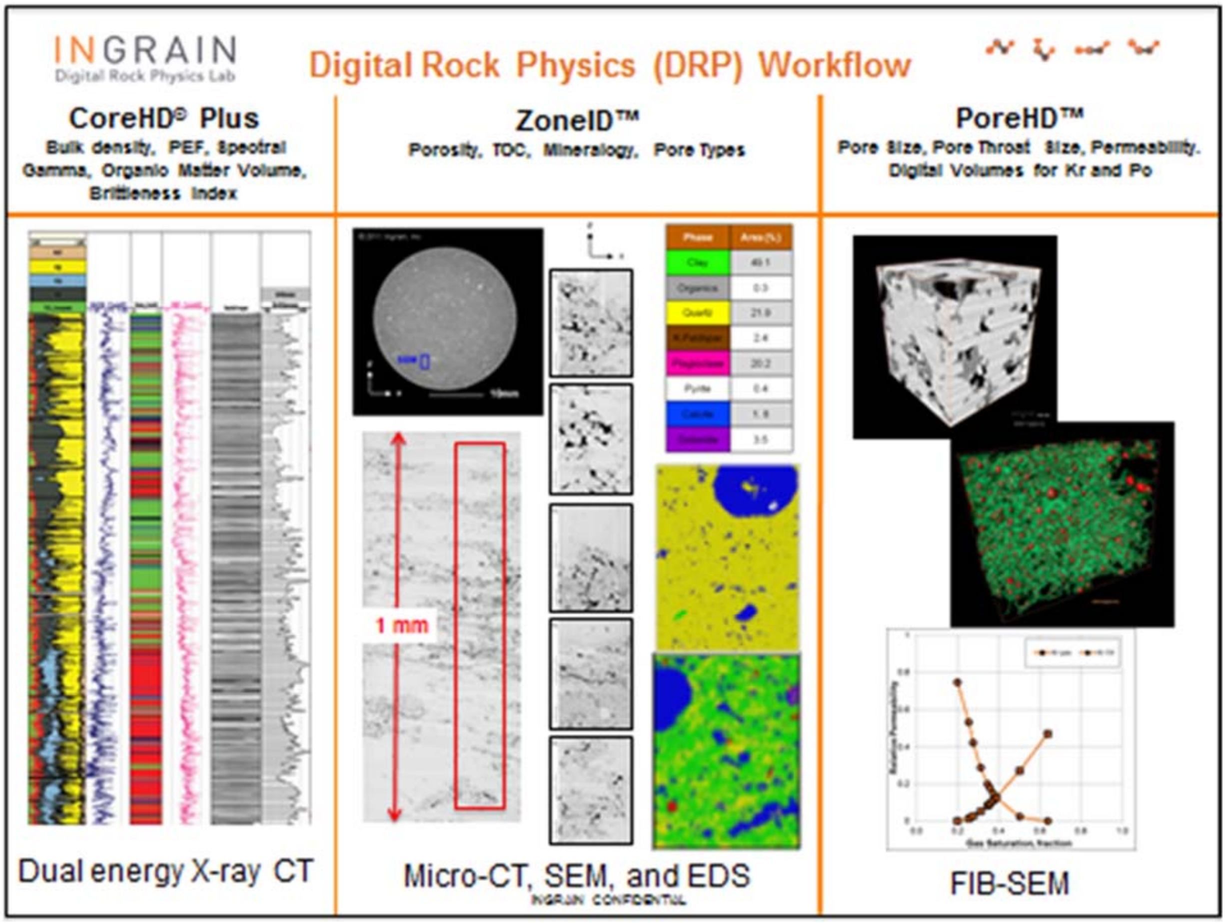


Figure 1: Schematic illustration of Ingrain's multi-stage shale reservoir characterization workflow using Digital Rock Physics. Key element is multi-scale analysis to get representative rock for 3D SCAL analysis (connected porosity, directional perm.).

CoreHD®: Whole core, continuous CT scanning for characterizing rock type, heterogeneity, and sampling locations

Ingrain's CoreHD® Suite provides early visibility into the critical properties of whole core through continuous, high-resolution rock property logs in relevant timeframes. The CoreHD® service consists of high-resolution (about 500 CT slices per linear foot of whole core) X-ray CT imaging of whole or slabbed core, followed by computation of separate logs for bulk density (RhoB) and photoelectric index (PEF). The bulk density and PEF logs are exclusive to Ingrain and provide quantitative measures to help discriminate lithology, porosity, rock facies, and depositional sequences. Figure 2 shows how the RhoB and PEF data can be cross-plotted to separate the well into multiple facies, and to determine which facies are most likely to be high quality reservoir. In this formation, the lowest density and lowest effective atomic number quadrant of data (Green Facies) likely represents higher porosity and/or higher organic matter content zones. The results and deliverables from this stage include;

- CoreHD® High Definition Whole Core CT Scanning
- Continuous Core Viewer Movie
- Bulk Density Log
- PEF Log
- Data Cross-plots
- Facies Interpretation
- 3D High
- Identification of plug sample locations

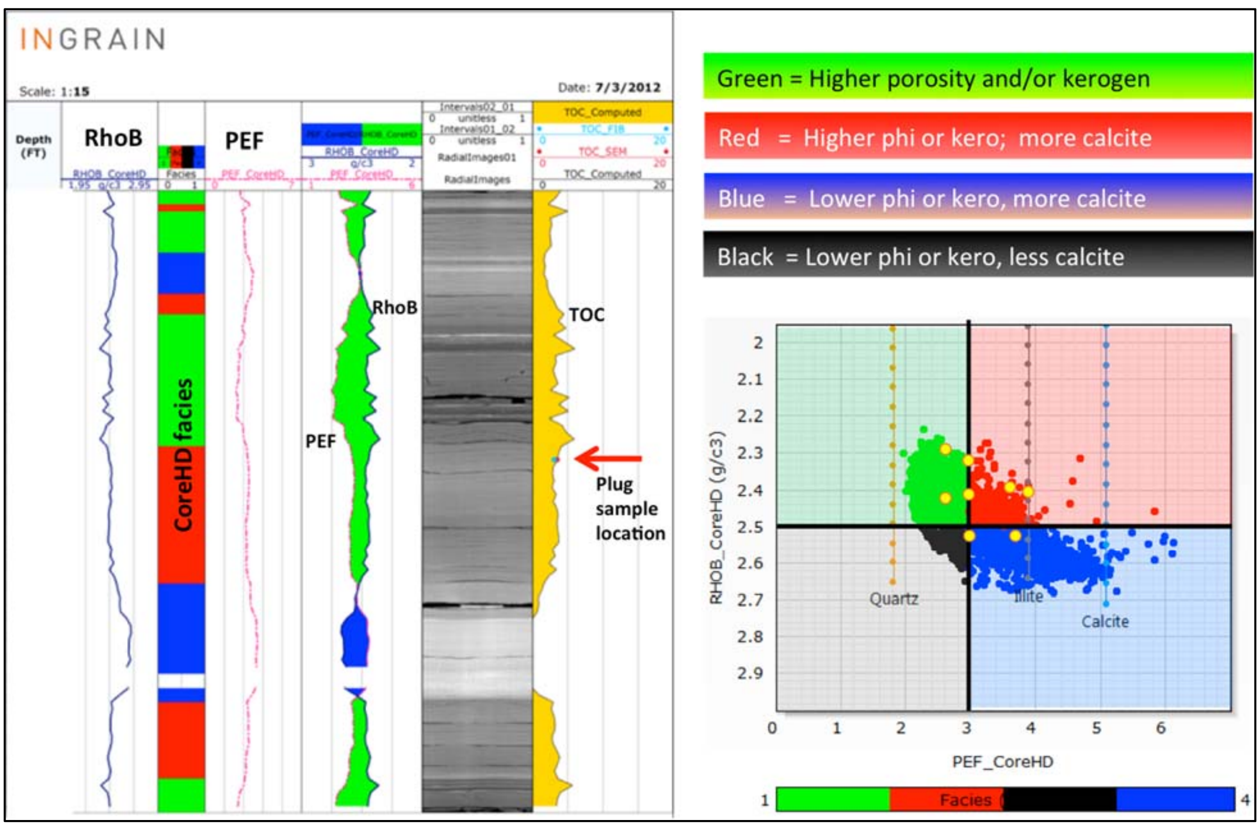


Figure 2: CoreHD® data is used for lithology and facies discrimination, and to aid in upscaling.

CoreHD® Plus: Achieve greater impact from whole core data with additional petrophysical curves.

CoreHD® Plus begins with spectral gamma logging and XRF (X-ray fluorescence) measurements on the whole core. This data, combined with RhoB and PEF, is used to compute the additional curves. Ingrain uses deterministic and empirical relationships based on established petrophysical principles and guided by access to Ingrain's proprietary worldwide database of organic mudstone and shale formations. CoreHD® Plus deliverables include (in standard log display format combined with CoreHD® deliverables:

- Spectral Core Gamma Log
- Lithology Log
- Organic Matter (v/v)
- Brittleness Log

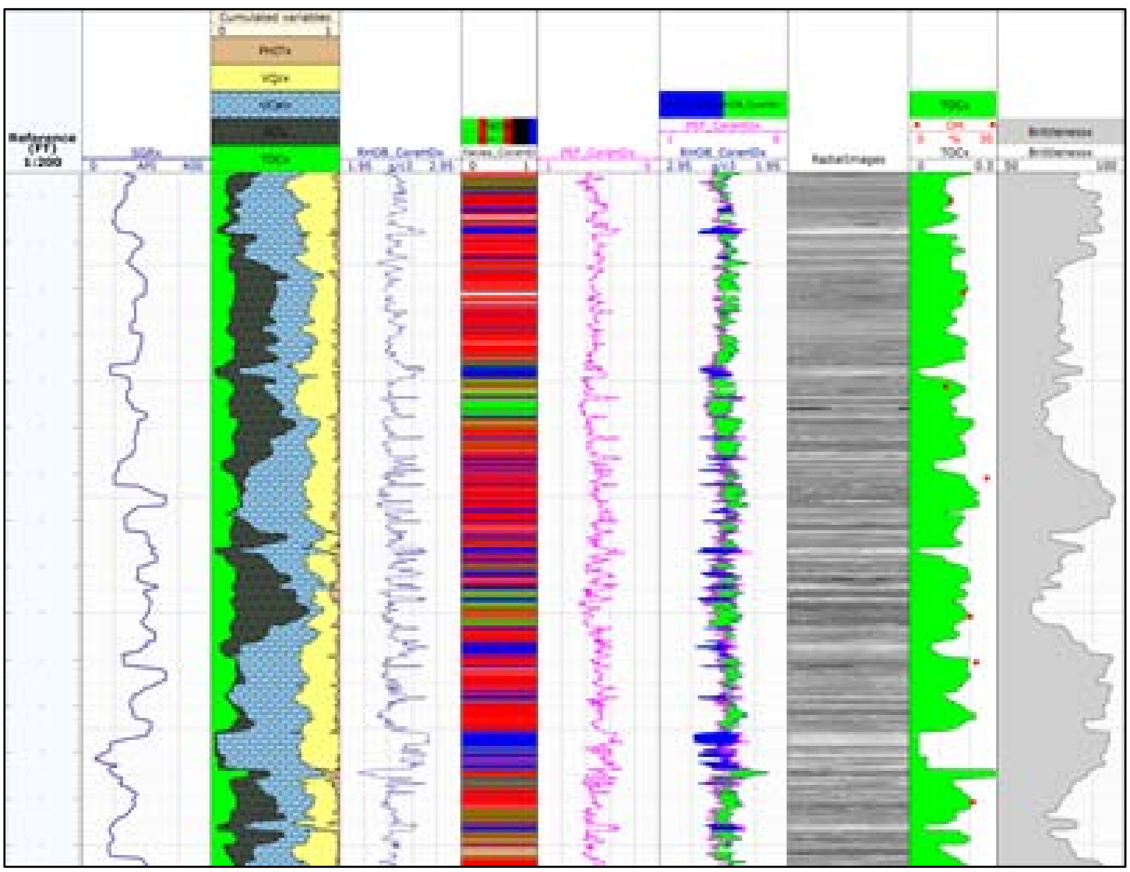


Figure 3: CoreHD® Plus

ZoneID™: Identify target zones with plug to pore scale evaluation targeted to quickly identify shale rock characteristics from micro-CT, SEM, and mineralogical analysis.

Our ZoneID™ service (Figure 4) utilizes both CT and quantitative SEM technologies. This unique offering provides values of porosity and organic matter volume fraction and is also used as a screening tool to ensure selection of representative samples for the subsequent PoreHD™ FIB-SEM analysis. Multiple 2D SEM images are used to obtain porosity and organic matter volume fraction for each ion-milled sample. Both secondary electron (SE) and energy-selective backscatter (ESB) images will be provided for each sample. SE Images give maximum resolution of the porosity and ESB images help discriminate between different solid components (minerals and organic matter). Deliverables for ZoneID™ include:

- MicroCT Projection Images
- Secondary Electron Images
- Backscatter Electron Images
- Pore Volume Fraction
- Organic Matter Volume Fraction
- High Density Volume Fraction
- Pore Volume Fraction Associated with Organic Matter
- Data Plots
- Bulk Density
- Volume Fractions of Selected Elements

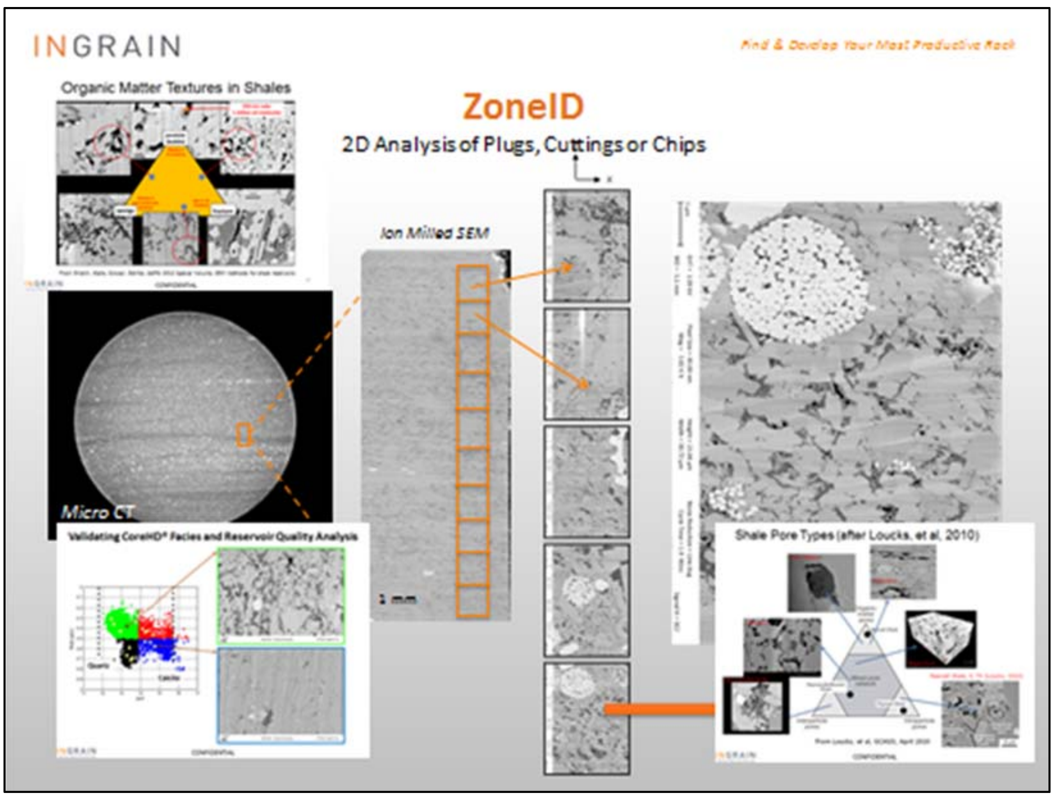
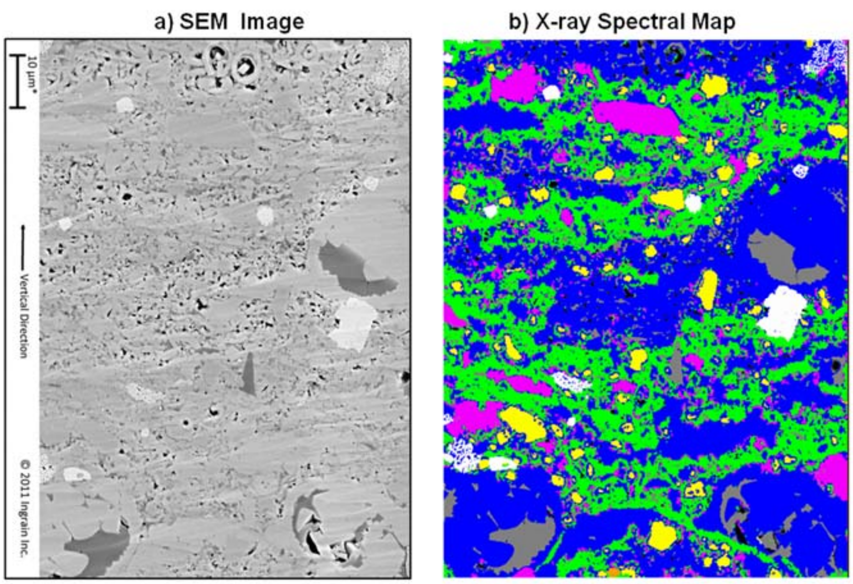


Figure 4: ZoneID™ schematic

Energy-dispersive X-ray Spectroscopy (EDS)

Using SEM acquisition technology, Ingrain's X-ray spectral map display offers a visual mineral distribution with different colors which corresponds to minerals present in the rock. This analysis will provide volume fractions of various minerals in the rock (Figure 5). Deliverables include:

- Mineralogy distribution map
- Mineralogy volume fraction table



c) Mineral Distribution (% by vol)

clay	27.7
pore	1.7
organic	7.2
calcite	48.7
qtz	4.3
plagioclase	8.1
pyrite	2.2
TiO2	0.1
Total	**100**

Figure 5:

a) SEM image of the sample

b) X-ray spectral map showing different colors that correspond to minerals present in the rocks. Notice how the green color (clay) highlights the horizontal distribution of clay minerals between the framework calcite grains.

c) Mineral volume fractions in sample

PoreHD™: Three-dimensional computation of permeability, porosity, and organic material from computations on FIB-SEM rock volume

PoreHD™ analysis begins with nanometer-scale FIB-SEM pore and matrix imaging in 3D. This is followed by segmentation, image processing, and creation of digital rock volume. All deliverable rock properties are derived from analysis and calculations are based on the same digital rock volume, ensuring internal consistency of delivered data. PoreHD™ deliverables include:

- 3D Movies of Digital Rock Volumes
- Absolute Permeability – Horizontal and Vertical
- Porosity – Total, Connected and Isolated
- Porosity Associated with Organic Matter

A major objective of the process is to understand the relationships between porosity and permeability for each of the primary producing facies. This information (as illustrated in Figure 6) is an important component in shale reservoir characterization. Digital Rock Physics will also reveal details of the shale pore types and which ones are prevalent in the key producing facies (Figure 7). Porosity associated with organic matter is especially critical to good reservoir quality. The number of samples in each facies required to establish these trends depends on the vertical variability of the target formation(s) and the client's acreage position within the play. PoreHD™ volumes can also be used for further advanced rock properties computations, such as two-phase relative permeability, capillary pressure, and other special core analyses.

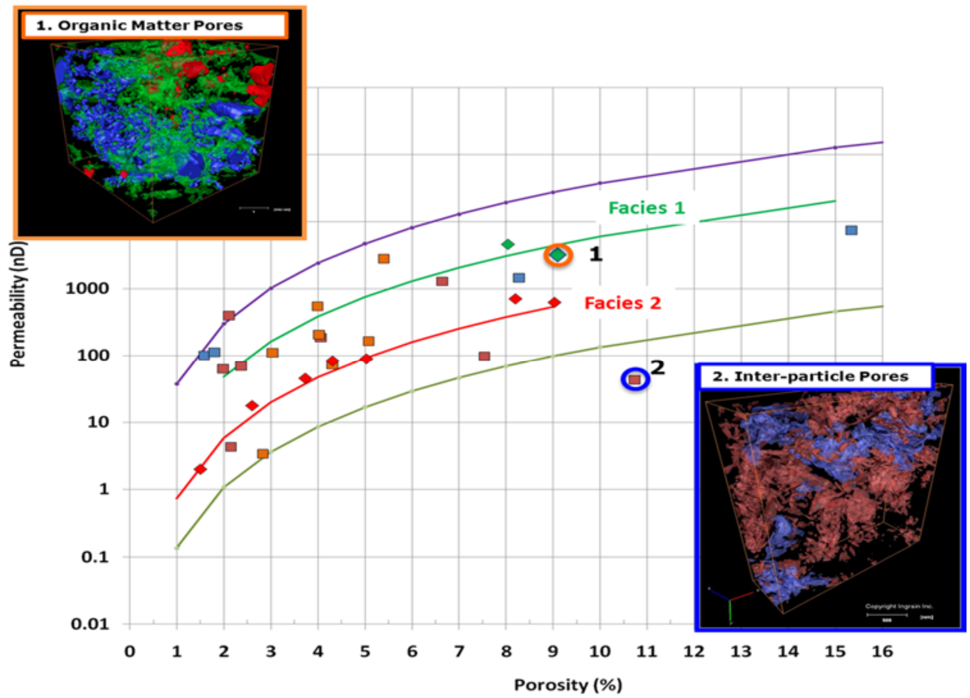


Figure 6: 3D FIB-SEM analysis from Ingrain can help relate facies and shale pore types to porosity-permeability trends. These trends can then be integrated with facies logs from CoreHD® to improve net/gross, reserves, and producibility estimates.

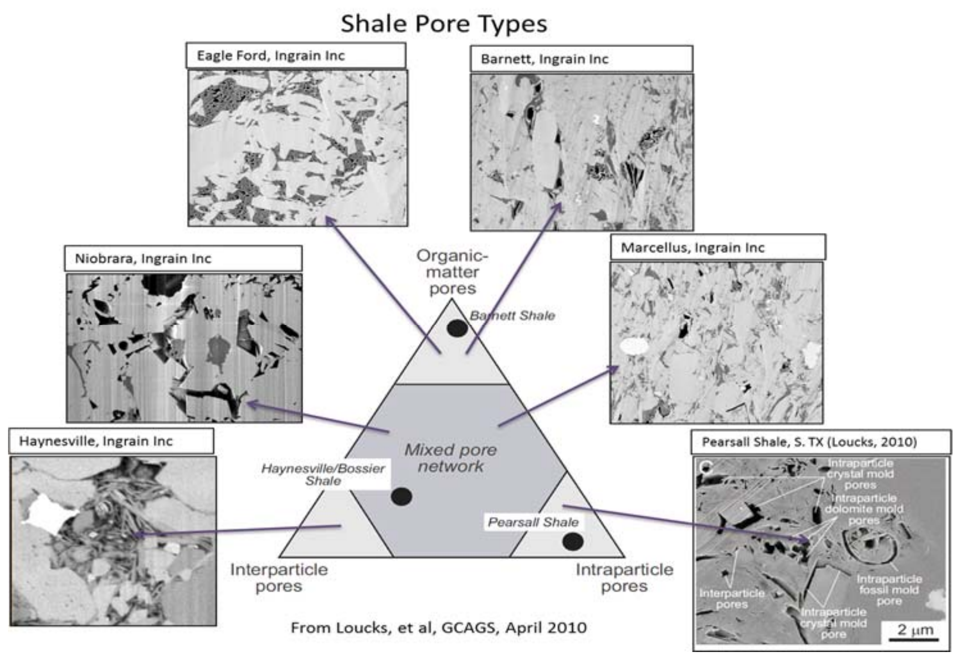


Figure 7: Shales pore types vary among different formations, but also within individual formations. Generally organic matter porosity is a key component to good reservoir quality.

Shalepay™ Upscaled Logs

Upscale ZoneID™ and PoreHD™ data to calibrate CoreHD® Plus Logs and integrate for additional porosity and permeability curves (Figure 8). Shalepay™ Upscaled Logs include:

- CoreHD® and CoreHD® Plus Logs Calibrated with Advanced Workflow Data
- Porosity Log
- Permeability Log

**These logs may not be available for some formations*

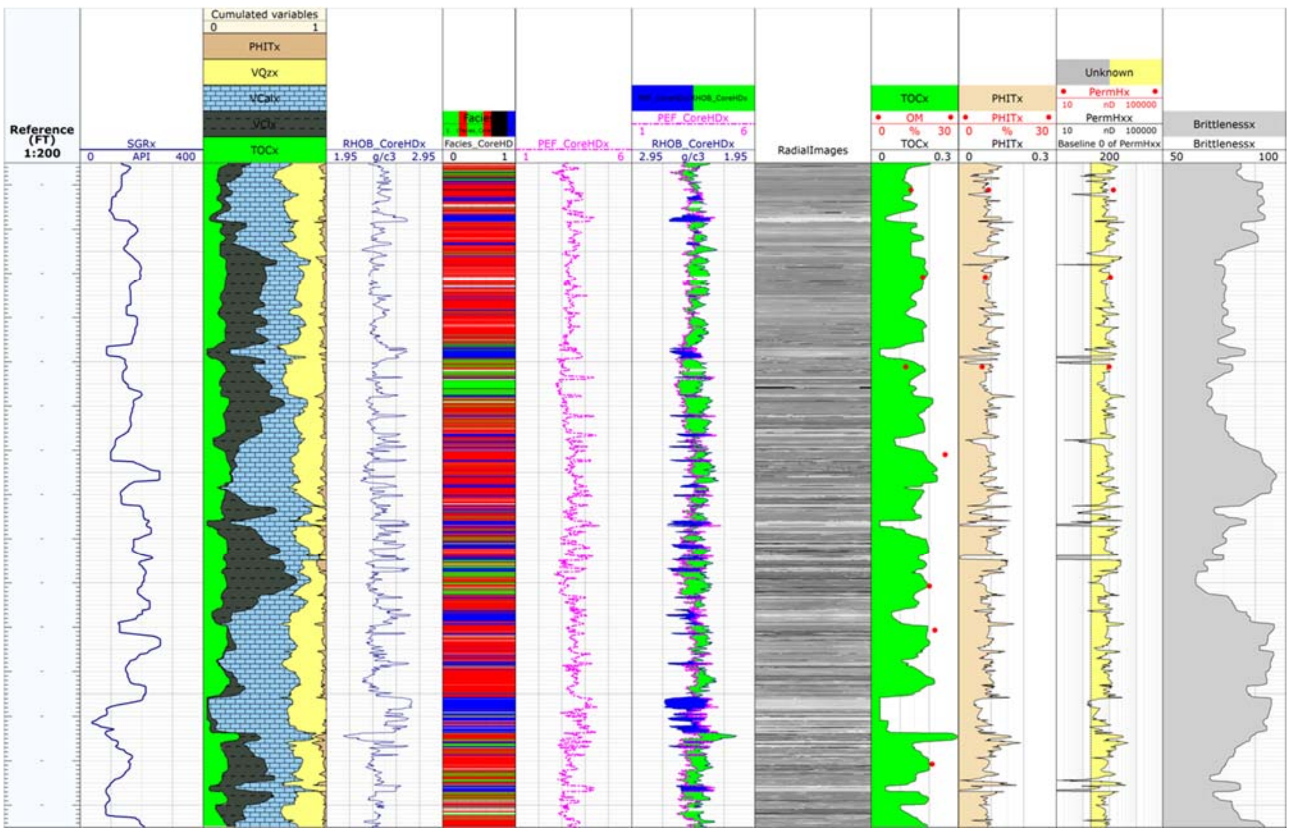


Figure 8: ZoneID™ and PoreHD™ are combined with CoreHD®Plus data to create upscaled logs of porosity, and permeability.

Data Usage

The data may be compiled into Ingrain's Digital Core Library to be used in basin data packages, Ingrain's multi-client studies, and/or as a subscription service. Ingrain will have the right to use the data for publications, presentation, technical papers and marketing purposes. Ingrain will also have the right to sell or license to third parties the Ingrain data, images, movies and interpretive products that result from this project.

Final Report

Upon completion of each individual job, Ingrain will deliver a report in PDF format containing rock properties data and selected images from the rock samples illustrating the findings of each analysis. Other digital data such as image files, movie files and tabular density and photoelectric factor values will also be provided. Results and reports will be made available for download using a secure FTP site.

APPENDIX F

METHODS FOR CO_2 PERMEATION AND OIL EXTRACTION TESTING

SPE SPE-167200-MS

Hydrocarbon Mobilization Mechanisms from Upper, Middle, and Lower Bakken Reservoir Rocks Exposed to CO_2

Steven B. Hawthorne, Charles D. Gorecki, SPE, James A. Sorensen, SPE, Edward N. Steadman, John A. Harju, Energy & Environmental Research Center; Steven Melzer, Melzer Consulting

This paper was prepared for presentation at the SPE Unconventional Resources Conference-Canada held in Calgary, Alberta, Canada, 5–7 November 2013.

Abstract

Efforts to increase Bakken oil recovery factors above a few percent could include carbon dioxide (CO_2) enhanced oil recovery (EOR). CO_2 EOR processes are expected to be very different in tight reservoirs compared to conventional reservoirs. During CO_2 EOR in conventional reservoirs, CO_2 flows through the permeable rock matrix, and oil is mobilized by a combination of oil swelling, reduced viscosity, hydrocarbon stripping, and CO_2 displacement especially when above the minimum miscibility pressure. In the Bakken, CO_2 flow will be dominated by fracture flow, and not significantly through the rock matrix. Fracture-dominated CO_2 flow could essentially eliminate the displacement mechanisms responsible for increased recovery in conventional reservoirs. As such, other mechanisms must be optimized in tight reservoirs such as the Bakken.

Conceptual steps for the Bakken include: (1) CO_2 flows into and through the fractures, (2) unfractured rock matrix is exposed to CO_2 at fracture surfaces, (3) CO_2 permeates the rock driven by pressure, carrying some hydrocarbon inward; however, the oil is also swelling and extruding some oil out of the pores, (4) oil migrates to the bulk CO_2 in the fractures via swelling and reduced viscosity, and (5) as the CO_2 pressure gradient gets smaller, oil production is slowly driven by concentration gradient diffusion from pores into the bulk CO_2 in the fractures.

To investigate these concepts, rock samples from the Middle Bakken (low permeability), Upper and Lower Bakken (very low permeability), and a conventional reservoir (high permeability) were exposed to CO_2 at Bakken conditions of 110°C and 5000 psi (230°F, 34.5 MPa) to determine the effects of CO_2 exposure time on hydrocarbon production. Varying geometries of each rock ranging from small (mm) "chips" to 1 cm-diameter rods were exposed for up to 96 hours, and mobilized hydrocarbons were collected for analysis. Nearly complete (>95%) hydrocarbon recovery occurs in hours from the middle Bakken reservoir rock, and even faster with the more permeable conventional matrices. Unexpectedly, nearly complete recovery of hydrocarbons can even be achieved from the very tight source shales from the Lower and Upper Bakken, but requires longer exposure times and smaller rock sample sizes (i.e., high surface area to volume ratio). These results demonstrate that CO_2 is capable of recovering hydrocarbons from Bakken source and reservoir rock (i.e., the thermodynamics of CO_2 oil recovery are favorable), but that long periods of exposure combined with high rock surface areas are required (i.e., the kinetics of the recovery process are slow). The present study reports experimental methods and the resultant data to investigate the proposed mechanisms that will control CO_2 EOR in tight formations. Implications for CO_2 EOR processes in unconventional reservoirs are discussed.

Introduction

The development of the Bakken and Three Forks Formations in North Dakota, Montana, and Saskatchewan is unprecedented with respect to the fast-pace of drilling, completion, and production. Technologies used to drill and complete wells in this low permeability, low porosity play have advanced very rapidly in an attempt to maximize the extraction of recoverable portions of the estimated 160 to 900 billion barrels of oil in place (Nordeng and Helms, 2010; Continental Resources, 2013). Unfortunately, even with the application of advanced technologies, oil recoveries are typically only about 3-6 % of the oil in place (Bohrer et al. 2008, Nordeng and Helms, 2010.) These low recovery factors are largely because there remain large gaps in knowledge of the physical and geochemical properties of the Bakken and Three Forks reservoirs, the combination of factors that affect production, and the potential for enhanced oil recovery (EOR) techniques, such as CO_2-based EOR. In addition, both the Upper and Lower Bakken shales contain substantial oil that are not currently considered to be amenable to production. An increased understanding of these factors that leads to even a 1% increase in recovery of oil from the Bakken could produce an additional 1.6 to 9 billion barrels of recovered oil based on the current range of resource estimates.

We propose that CO_2-based EOR mechanistic processes will be very different for these tight formations from those that control CO_2 recovery of oil from conventional reservoirs. CO_2-induced processes that are important to EOR in conventional (i.e., permeable) formations, including oil swelling, lowered oil viscosity, and the formation of multiple contact "miscible" mixed CO_2/oil phases are likely to also enhance oil recovery from tight formations (Jarrel et al. 2002). However, we propose that the displacement mechanism of oil production caused by the action of CO_2 flowing ***through*** conventional reservoir rock matrix will not apply to tight formations. In tight formations, the bulk CO_2 is expected to flow through natural and produced fractures, but not significantly through the non-fractured rock matrix. Thus, oil remaining in the unfractured rock will not experience significant sweeping (displacement) flow of CO_2 from injection to production areas, but will only see CO_2 that permeates into the rock after the CO_2 first fills the fracture spaces.

The present study reports the results of initial CO_2-exposure experiments designed to mimic the proposed mechanisms in an effort to better understand and, hopefully, to better exploit these processes to enhance EOR in the Bakken play. It is important to note that these investigations focus solely on processes that control the transport of oil from the rock matrix into the CO_2-filled fractures, but do not address subsequent engineering, completion, and production steps needed to move the hydrocarbons to the production well.

Mechanistic Considerations

As noted above, we propose that the different flow patterns of CO_2 (and other EOR fluids) will be substantially different in conventional reservoirs (where CO_2 flows through the rock matrix and sweeps the oil out in a manner mimicked by the sand-packed and oil-saturated slim tube), and unconventional tight hydraulically fractured reservoirs where we expect that CO_2 will flow most rapidly through the major and minor fractures, but not significantly ***through*** the unfractured rock matrix.

The conceptual mechanisms we propose for CO_2 EOR in tight hydraulically fractured systems are shown in Figure 1. During the initial phases of CO_2 injection (Step 1), the CO_2 flows rapidly through fractures, but not through the rock matrix itself. The CO_2 then begins to permeate the rock matrix driven by the pressure gradient caused by CO_2 injection (Step 2). The initial permeation of CO_2 into the rock matrix could potentially reduce oil production by carrying oil near the surface deeper into the rock matrix. Conversely, the oil swelling caused by the CO_2 could yield increases of oil during the pressurization process. As CO_2 continues to permeate the rock, the oil will increasingly migrate to the rock surface (and into the fractures) based on swelling and lowered viscosity caused by the CO_2 (Step 3). The CO_2 pressure then begins to equalize throughout the rock matrix (Step 4). At this point, oil swelling and lowered viscosity, and the possible formation of a CO_2/oil miscible phase continue to enhance oil mobilization. Finally, as pressure equilibrium is approached, concentration driven diffusion of hydrocarbons in CO_2 from the rock interior to the bulk CO_2 in the fractures may become the dominating process.

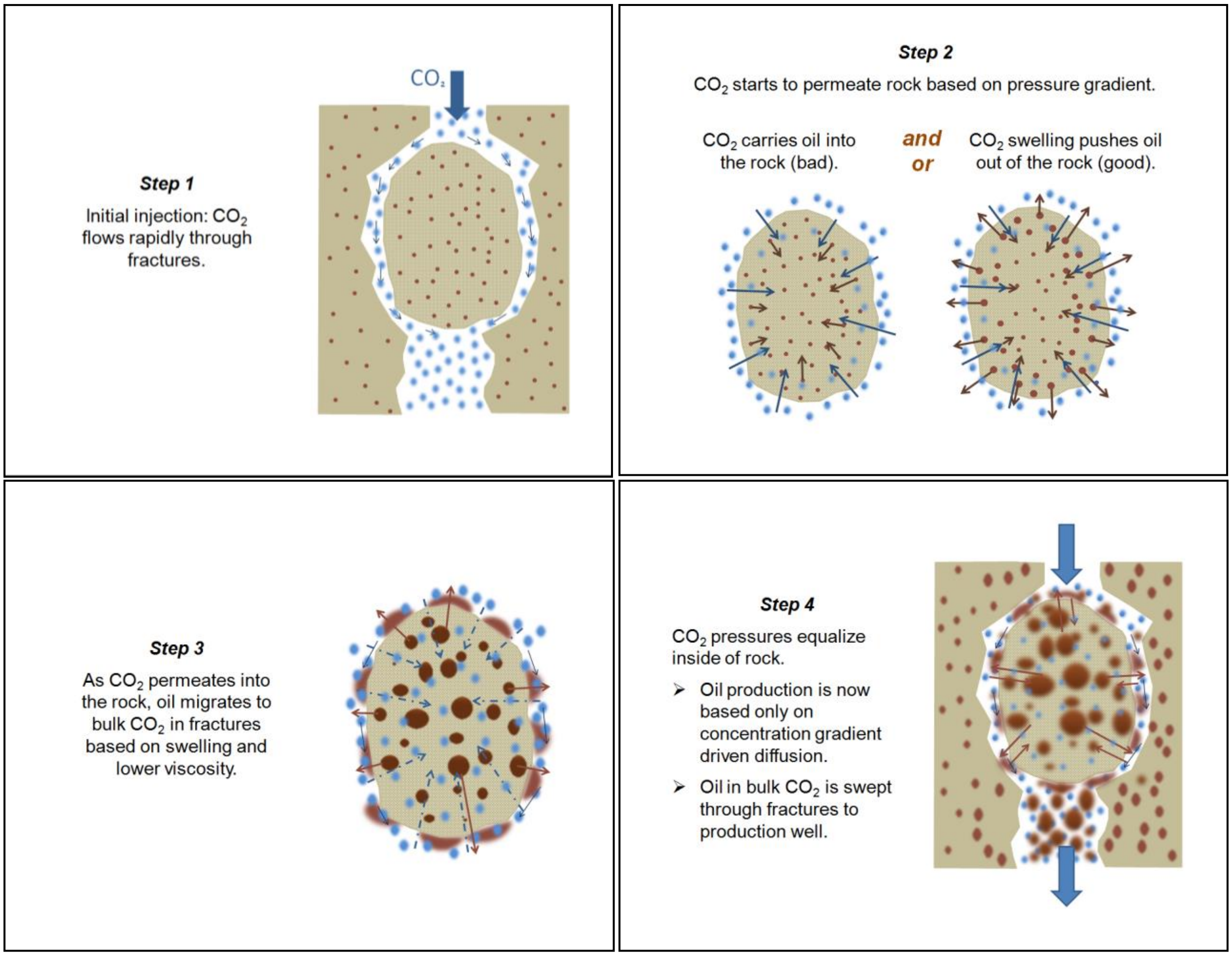


Figure 1. Conceptual steps for CO_2 EOR in fractured tight reservoirs. The individual steps are described in the text.

As in any chemical/physical process, there are two overall controlling factors that must be satisfied, i.e., the thermodynamics of the process (i.e., is CO_2 capable of mobilizing oil in tight formations under the temperature/pressure conditions of that reservoir?) and the kinetics of that process (i.e., does the mobilization of the oil occur rapidly enough to be useful?). The experiments we report here are an attempt to answer those two fundamental questions.

Test Samples

Samples were obtained from two locations in the Bakken Formation. Samples of Middle Bakken reservoir rock and both Upper and Lower source shales from the same bore hole in a thermally-mature area of the formation in North Dakota were provided by an operator. Middle and Lower Bakken samples from another well were also obtained from the North Dakota Geological Survey core library, and also represented a thermally-mature region. In the regions sampled, Middle Bakken porosities range from 4.5 to 8.1%, and permeabilities from 0.002 to 0.04 millidarcies (Kurtoglu et al. 2013). Values for the porosity and permeability of Lower and Upper shales are not available, but permeability is expected to be orders of magnitude lower compared to Middle Bakken reservoir rock. A sample from a conventional sandstone reservoir was also obtained to act as a reference sample that would display the "fastest" CO_2-enhanced scenario under the experimental conditions used. Typical values in that region of the conventional reservoir are ca. 25% porosity and ca. 800 to 1100 millidarcies permeability.

Different geometries (Figure 2) were prepared from the bulk samples including 3-4 cm long round rods made with a ca. 1-cm coring bit, 3-4 cm long X ca. 9 X 9 mm square rods cut with a high-pressure water jet, 2-3 mm thick X ca. 9 X 9 mm squares ("chicklets") by flaking of the square rods along natural fracture planes, and smaller particles prepared by crushing the samples to pass a 3.5 mm sieve. Crude oil samples were also obtained from similar locations to estimate MMP, and for use as calibration standards. MMP values for the three crude oil samples determined by capillary rise vanishing interfacial tension (Ayira and Rao, 2011) ranged from ca. 2800 to 3000 psi.

Figure 2. Typical reservoir and source rock samples prepared for CO_2 exposure. Samples are placed in the 10 mL extraction vessel (15 mm i.d. X 57 mm long, lower right), and exposed to CO_2 as described in the text.

Experimental Methods

All CO_2 exposures were performed at reservoir conditions of 5000 psi and 110 ^{o}C. Exposures were performed using an ISCO model 210 SFX extractor with the high-pressure CO_2 supplied by an ISCO model 260D syringe pump (ISCO-Teledyne, Lincoln, Nebraska, USA) set to deliver a constant 5000 psi delivery of CO_2 to the extraction unit. Rock samples were placed into the 10-mL sample cell shown in Figure 2. Note that the 5- to 8-gram samples were not sealed to the cell wall in any way (in contrast to what would be done, for example, for a high-pressure permeation test), so that the CO_2 was free to flow ***around*** the pieces of rock samples rather than being forced ***through*** the rock matrix, in order to mimic the fracture flow dominance we anticipate in tight hydraulically fractured systems. CO_2 entered the cell through the top of the cell, and exited through the bottom of the cell to pass through a heated flow restrictor that controlled the CO_2 flow (measured as liquid CO_2 at the pump) at 1.5 mL/minute. The heated outlet of the restrictor was placed in a vial containing 15 mL of methylene chloride to collect the produced hydrocarbons. CO_2 outlet flow could be continuous (dynamic mode) or stopped (static mode) as controlled by a shut-off valve located between the extraction cell outlet and the outlet restrictor. More detailed descriptions of the CO_2 exposure instrumentation and operation is given in (Hawthorne, 1990).

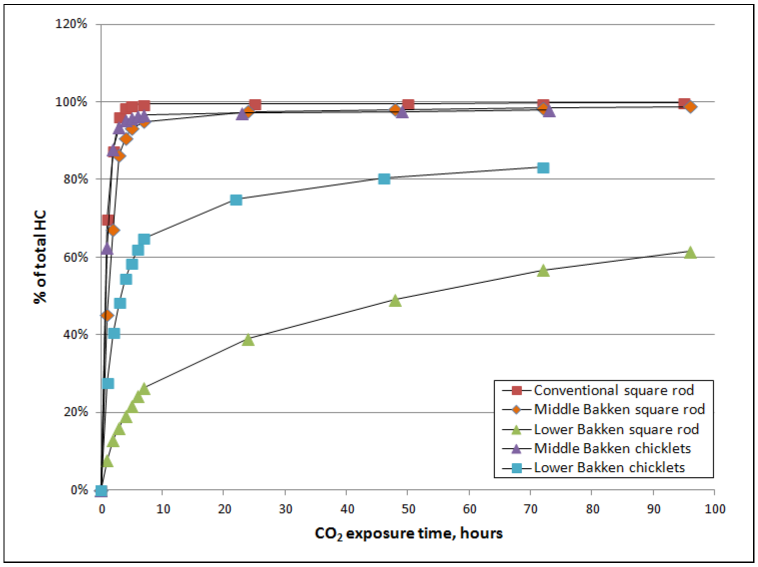
Produced hydrocarbons (C7+) collected at the restrictor outlet were analyzed using capillary gas chromatography coupled with a flame ionization detector (GC/FID) using tetradecylbenzene as a quantitative internal standard, and the Bakken crude oils as calibration standards. After the CO_2 exposures were completed, the residual rock samples were crushed to a powder, and extracted with a 1:2 acetone/methylene chloride solvent with the aid of sonication for several hours. Replicate extractions were performed until no more significant hydrocarbon could be extracted. The sum of all the collected CO_2 extracts and the rock residue solvent extracts was considered to be 100% of the hydrocarbon in the rock matrix.

Experimental Results

1. *Initial 96 hour exposures with static (non-flowing) CO_2:*

Because of the low permeability of the Bakken reservoir and source rocks, it was expected that hydrocarbon recovery using CO_2 would be very slow, even with the small rock samples being exposed. Therefore, the initial hydrocarbon mobilization experiments were conducted for 96 hours. For the first day, the sample was pressurized to 5000 psi (110 ^{o}C) under static (non-flowing) conditions for 50 minutes, followed by a 10-minute dynamic sweep with CO_2 to collect the mobilized hydrocarbons as described above. Approximately 15 mL of dense CO_2 (ca. 2 cell void volumes) swept the cell during the 10-minute dynamic collection step. (Note that the instrumentation automatically maintained the CO_2 pressure and temperature at 5000 psi and 110 ^{o}C, regardless of whether the CO_2 flow was static or dynamic.) This one-hour sequence was repeated for 7 hours, then followed by longer static exposures with 10-minute collections of the mobilized hydrocarbons at 24, 48, 72, and 96 hours. The remaining rock residue was then solvent extracted to determine residual hydrocarbons as described above.

Results of the 96 hour exposures are shown in Figure 3. As might be expected based on its high permeability, hydrocarbons were rapidly recovered to nearly 100% from the conventional reservoir rock square rod sample. These results clearly demonstrated that, even though the CO_2 is not flushing through the reservoir rock, but is only surrounding it (followed by the recovery mechanisms discussed above); the hydrocarbon recovery is not only rapid, but highly efficient. Surprisingly, the recoveries from the Middle Bakken were also high and quite rapid from the square rod. While it took only ca. 2 hours to recover 90% from the conventional reservoir square rod, 90% recovery was achieved by ca. 4 hours from the Middle Bakken square rod. Also, recovery rates from the smaller Middle Bakken "chicklets" were essentially the same as from the conventional square rod sample.



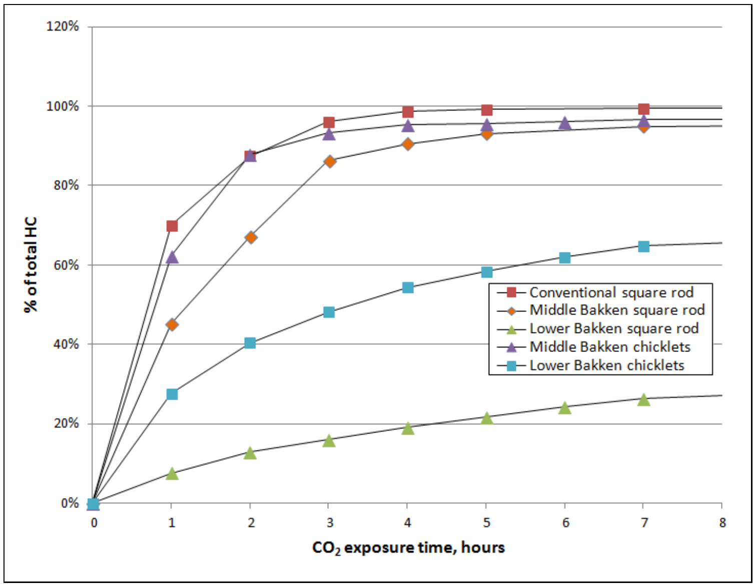


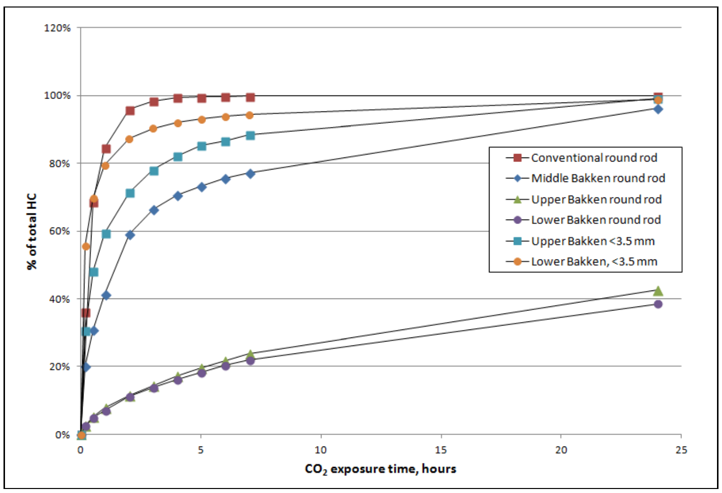
Figure 3: CO_2 mobilization of hydrocarbons from Middle Bakken, Lower Bakken, and a conventional reservoir rock with 96 hours of exposure at 5000 psi and 110 ^{o}C. The lower plot has the time scale expanded to show hydrocarbon recovery during the first 8 hours of exposure. "Square rod" indicates a ca. 9X9X40 mm rectangular rod and "chicklets" indicates ca. 3X9X9 mm flat squares.

As would be expected, recovery from the even tighter Lower Bakken sample was much slower from the square rods and only ca. 60% of the hydrocarbon was recovered in 96 hours, but still surprisingly high considering the very low permeability of this source shale. In addition, hydrocarbon recovery in 96 hours from the Lower Bakken shale increased to >80% as the thinner "chicklets" were exposed to the CO_2, as would be expected since smaller particles require less time for CO_2 mobilization of interior hydrocarbons as proposed in Figure 1 and the related mechanistic discussion.

2. Hydrocarbon recovery under dynamic (flowing) CO_2 conditions:

Since the times involved to achieve such high recoveries in a reservoir are likely to be much too long to be practical, and since even very small (e.g., 1%) increases in oil recovery represent a tremendous amount of additional oil produced, additional shorter exposures were performed under dynamic (flowing CO_2) conditions using the operator-provided Lower, Middle, and Upper Bakken samples obtained from a single bore hole. CO_2 flow was continuous during the first 7 hours of extraction, then static from 7-24 hours, followed by a one hour dynamic collection of the produced hydrocarbons. In order to obtain data to investigate the very early exposure steps outlined in Figure 1, samples were collected from 0-10, 10-30, and 30-60 minutes followed by hour-long collection periods.

As shown in Figure 4, recovery from the Upper and Lower Bakken round rods is very slow, and only achieves ca. 40% after 24 hours of CO_2 exposure. As noted for the other Middle Bakken sample in Figure 3, recovery from the Middle Bakken round rod is nearly as fast as that from the permeable conventional reservoir round rod, demonstrating that on the cm scale CO_2 is fairly efficient at recovering hydrocarbons from the rock interior. As expected based on mass transfer consideration in the very low permeability Upper and Lower Bakken shales, increasing the surface area by grinding to < 3.5 mm dramatically raises the recovery rates, with nearly complete hydrocarbon recovery achieved after 24 hours of CO_2 exposure (Figure 4).



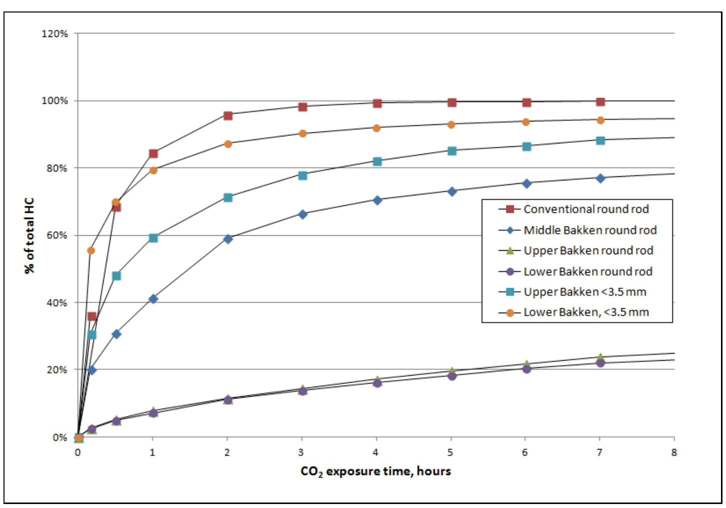


Figure 4. CO_2 mobilization of hydrocarbons from Upper Bakken, Middle Bakken, Lower Bakken (all from the same bore hole), and a conventional reservoir rock with 24 hours of CO_2 exposure at 5000 psi and 110 ^oC. The lower plot has the time scale expanded to show hydrocarbon recovery during the first 8 hours of exposure. "Round rods" refer to cylinders with a diameter of ca. 10 mm X ca. 40 mm long. "<3.5 mm" indicates rock crushed to pass a 3.5 mm screen.

3. Effect of hydrocarbon molecular weight on recovery rates with CO_2.

Bulk effects of CO_2 dissolving into the oil in the rock matrix (i.e., swelling and lowered viscosity) would be expected to show little molecular weight preference in the recovered hydrocarbons. In contrast, recovery processes that involve mobilizing hydrocarbons into the CO_2 would favor lighter hydrocarbons, both because they have higher solubility than higher molecular weight hydrocarbons, and because formation of a new "miscible" phase of mixed CO_2/hydrocarbons favors lower over higher molecular weight hydrocarbons. Therefore, it is useful to observe the molecular weight distribution in the hydrocarbons recovered during the CO_2 exposures. As shown in Figure 5 for the round rod samples, there is a great degree of preference for CO_2 recovery of lighter versus the heavier hydrocarbons, as is especially evident from the tighter Upper and Lower Bakken shales. For example, the C7 hydrocarbons are recovered ca. 10-fold faster than the C20 hydrocarbons from the Upper and Lower Bakken shales. Although the same range of hydrocarbons could not be observed from the Middle Bakken sample (because of their loss during transport and storage of the core sample), some preference for lighter hydrocarbons is also observed for the Middle Bakken sample. The implications of these results are discussed below.

Implications of the Experimental Results

The experimental results discussed above support the overall mechanism proposed in Figure 1 for hydrocarbon recovery from tight formations. Some interpretations of these results in reference to the steps described in Figure 1 are:

Step 1: Since the rock samples are not sealed in the extraction vessel, the step of flowing the CO_2 around the sample rather than through the rock matrix should be valid to represent fractured tight systems such as the Bakken.

Step 2: Since there is no apparent lag in oil recovery, even when samples are collected during the first 10 minutes of exposure, the concern that the initial pressurization could reduce hydrocarbon production by carrying hydrocarbons into the rock matrix does not seem to be significant. Similarly, the absence of an especially fast recovery in the first few minutes indicates that the initial oil swelling is not a significant recovery mechanism. (Although it should be noted that these observations on small samples may not be relevant in the actual reservoir conditions.)

Step 3: While both oil swelling and lowered oil viscosity caused by CO_2 dissolving into the oil are likely to enhance recovery, the high degree of preference to produce lower molecular weight hydrocarbons shown in Figure 5 shows that mobilization of hydrocarbons into the CO_2 (rather than dissolution of CO_2 into the bulk oil) is a dominant recovery process. This could be from solvation of the oil hydrocarbons into the bulk CO_2 phase, and/or generation of a new "miscible" mixed CO_2/hydrocarbon phase, since both of these processes select for lighter hydrocarbons. (Note that that the 5000 psi exposures are substantially above the MMP for Bakken oils of ca. 2800 psi.)

Step 4: The exponential decrease in recovery rates with time, and the large effect on sample particle size both support a mass transfer limited transport of hydrocarbons from the interior of the rock to the bulk CO_2 at the surface, but speculation on the exact mechanism is difficult based on the available experimental results. However, the overall lesson is that the more surface area per mass of rock that can be accessed by CO_2, the faster hydrocarbons will be recovered.

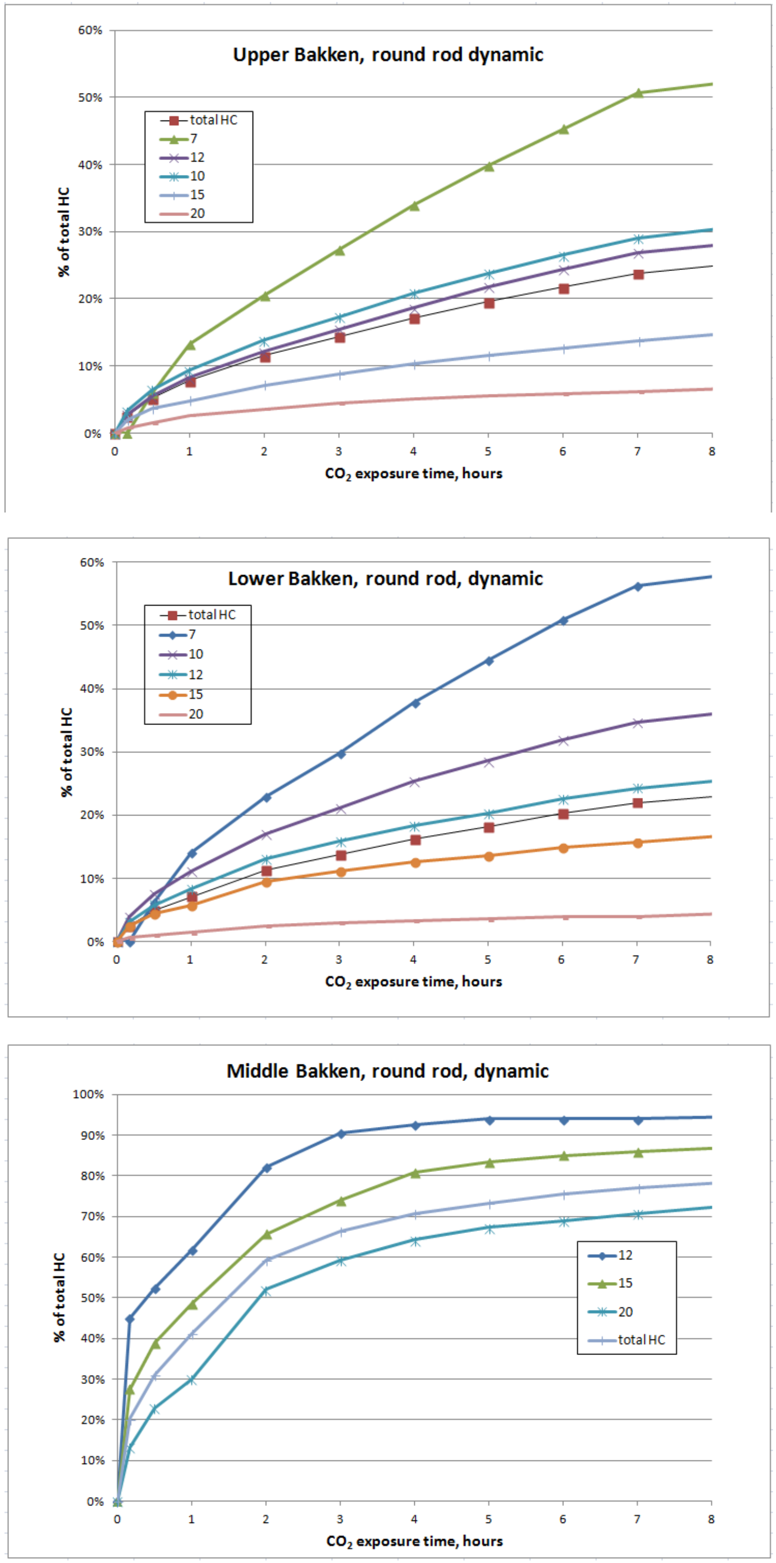


Figure 5: Recovery rates of different molecular weight alkanes under dynamic CO_2 exposures (5000 psi, 110 ^oC) from ca. 10 mm diameter X 40 mm long round rods of Upper, Middle, and Lower Bakken source and reservoir rocks from a single bore hole. "7" indicates the total C7 alkanes as defined by chromatographic retention times. The same definition applies to the other carbon numbers shown. "total HC" indicates the total hydrocarbon mass recovered regardless of molecular weight.

Summary of Observations and Conclusions

The results of these initial experiments clearly support important observations regarding hydrocarbon recovery from the Bakken formation:

1. Hydrocarbons can be recovered at high efficiencies from low permeability reservoirs using CO_2, even from very tight source rock shales, but it may take a very long time.

2. Since nearly complete recovery of oil from 10 mm diameter rods can be achieved with longer exposures, even from the very tight Lower and Upper Bakken shales, the pores in the source shales must have sufficient connectivity to be accessed by CO_2, even if very slowly.

3. The ability of CO_2 to mobilize Bakken hydrocarbons is sufficient (i.e., the thermodynamic requirements are met), but the rates of the recovery may not be sufficiently rapid (the kinetics of the process may be too slow).

4. Higher surface areas (smaller rock particles) greatly enhance the rate of hydrocarbon recovery.

5. It is unlikely that traditional approaches to CO_2 EOR in conventional reservoirs will be efficient in tight formations.

6. Understanding these mechanisms may help to design realistic processes for CO_2 EOR in the Bakken system. Achieving even the seemingly modest goal of obtaining an additional 1% oil recovery represents an enormous amount of recovered oil.

The results of these initial experiments demonstrate that oil can be recovered from tight formations such as the Bakken using CO_2, and support the proposed differences in CO_2 EOR processes in conventional and tight fractured reservoirs. However, these initial studies must be substantially expanded to better understand the factors that control oil recovery. Future studies including (but not limited to) the effects of different CO_2 injection scenarios, different reservoir temperature and pressure conditions, different source and reservoir rock formations, and different sample geometries are needed to better understand, model, and exploit CO_2 EOR in tight fractured formations.

Acknowledgments

The authors thank Basak Kurtoglu (Marathon Oil) and the North Dakota Geological Survey for providing the samples used in these investigations. Financial support from the U.S. Department of Energy, National Energy Technology Laboratories (NETL) and the North Dakota Oil and Gas Research Council, and laboratory work by David Miller and Carol Grabanski (Energy and Environmental Research Center) are also gratefully acknowledged.

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APPENDIX G

RESUMES OF KEY PERSONNEL

JAMES A. SORENSEN
Senior Research Manager
Energy & Environmental Research Center (EERC), University of North Dakota (UND)
15 North 23rd Street, Stop 9018, Grand Forks, North Dakota 58202-9018 USA
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Principal Areas of Expertise
Mr. Sorensen's principal areas of interest and expertise include tight oil resource assessment and development, carbon dioxide utilization and storage in geologic formations, and environmental issues associated with the oil and gas industry.

Education
B.S., Geology, University of North Dakota, 1991.
Postgraduate course work in Geology and Hydrogeology, 1993–1995.

Professional Experience
1999–Present: Senior Research Manager, EERC, UND. Mr. Sorensen currently serves as manager and co-principal investigator for several research programs, including the Plains CO_2 Reduction (PCOR) Partnership, a multiyear program focused on developing strategies for reducing carbon dioxide emissions in nine states and four Canadian provinces. He has also conducted projects to develop an improved understanding of the Bakken petroleum system, including efforts to examine the potential to use carbon dioxide for enhanced oil recovery in the Bakken. Responsibilities include supervision of research personnel, preparing and executing work plans, budget preparation and management, writing technical reports and papers, presentation of work plans and results at conferences and client meetings, and proposal writing and presentation.

1997–1999: Program Manager, EERC, UND. Mr. Sorensen managed projects on topics that included produced water management, environmental fate of natural gas-processing chemicals, coalbed methane, and gas methane hydrates.

1993–1997: Geologist, EERC, UND. Mr. Sorensen conducted a variety of field-based hydrogeologic investigations throughout the United States and Canada. Activities were primarily focused on the subsurface mobility of constituents associated with natural gas production sites.

1991–1993: Research Specialist, EERC, UND. Mr. Sorensen assembled and maintained comprehensive databases related to oil and gas drilling, production, and waste management.

Professional Memberships
Society of Petroleum Engineers

Publications and Presentations
Has coauthored nearly 200 publications.

DR. STEVEN B. HAWTHORNE
Senior Research Manager
Energy & Environmental Research Center (EERC), University of North Dakota (UND)
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Principal Areas of Expertise

Dr. Hawthorne's principal areas of interest and expertise include environmental chemistry and analysis and supercritical and subcritical (superheated) fluid extraction and reactions. Recent projects focus on investigating the processes controlling CO_2 storage and enhanced oil recovery in unconventional reservoirs, the development of analytical chemical methods to determine the bioavailability and fate of environmentally aged pollutants, and the study of the chemical behavior and practical uses of supercritical and superheated fluids including carbon dioxide, hydrogen sulfide, and water.

Education

Ph.D., Analytical Environmental Chemistry, University of Colorado (Boulder), 1984.
    Dissertation: "The Emission of Organic Compounds from Shale Oil Wastewaters."
M.S., Analytical Chemistry, South Dakota State University, 1978.
B.S., Chemistry, South Dakota State University, 1976.

Experience

1984–Present	Senior Research Manager, Environmental Chemistry, EERC, UND.
1992	Adjunct Professor, Departments of Chemistry, University of Waterloo, Ontario, and UND.
1992	Visiting Researcher, University of Helsinki, Finland (with Professor Marja-Liisa Riekkola).
1990	Visiting Researcher, Department of Chemistry, University of Leeds, England (with Professors Keith Bartle and Anthony Clifford).

Professional Service and Honors

- The Keene P. Dimick Award for Outstanding Accomplishments in Chromatography presented at The Pittsburgh Conference (1995)
- 5th International Symposium on Supercritical Fluid Chromatography and Extraction *Award of Excellence* for "Pioneering achievements in the development of analytical supercritical fluid technology" (1994)
- ISCO Award for Significant Contributions to Instrumentation for Separations (1993)
- U.S. Department of Energy Distinguished Lecturer (1991)
- Technical Reviewer for National Research Council
- Technical Reviewer for several government and private funding agencies and professional journals

Invited Lectures

- Over 250 invited lectures since 1990 in the United States, Canada, Europe, Australia, New Zealand, and the Far East.

Publications

- Over 200 peer-reviewed publications, primarily in the areas of environmental chemistry and supercritical CO_2, enhanced oil recovery (EOR) in unconventional reservoirs including fundamental and applied studies.

DR. LU JIN
Research Engineer
Energy & Environmental Research Center (EERC), University of North Dakota (UND)
15 North 23rd Street, Stop 9018, Grand Forks, North Dakota 58202-9018 USA
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Principal Areas of Expertise
Dr. Jin's principal areas of interest and expertise include modeling and simulation of multiphase flow in porous media, improved oil recovery technologies, and old oilfield redevelopment and phase behavior in unconventional reservoirs. He is particularly interested in subsurface oil–water interactions, transition-zone development, and residual oil distribution identification.

Qualifications
Ph.D., Petroleum Engineering, Louisiana State University, 2013.
M.S., Petroleum Engineering, Louisiana State University, 2009.
B.S., Petroleum Engineering, Northeast Petroleum University, 2005.

Professional Experience
2015–Present: Research Engineer, Reservoir Engineering, EERC, UND. Dr. Jin's responsibilities include developing geophysical models of the subsurface and running dynamic simulations to determine the long-term fate of produced/injected fluids, including hydrocarbons, CO_2 storage, and brine, using oil and gas industry simulation software.

2014–2015: Reservoir Engineer, InPetro Technologies, Inc., Houston, Texas. Dr. Jin's responsibilities included developing simulation and analytical models for unconventional reservoir development, especially for shale oil reservoirs; analyzing fluid PVT (pressure, volume, temperature) change during depletion and considering pore-size distribution (PSD) in simulations. Application of a new model in the Eagle Ford and Bakken Formations shows that oil reserves could be improved as much as 30% by integrating PVT and PSD effects.

2013–2014: Reservoir Consultant, Joint Industrial Program (JIP), Louisiana State University, and Pluspetrol, Baton Rouge, Louisiana. Dr. Jin's responsibilities included simulating cold production of heavy oil in Massambala Field, Angola, identifying the mechanisms of high water cut in current wells, optimizing the perforation length for conventional wells, and proposing two well systems which could improve cumulative oil up to 80% or reduce produced water 75%, respectively.

2011–2013: Senior Teaching Assistant, Drilling Fluids Laboratory, Louisiana State University, Baton Rouge, Louisiana. Served as lecturer and oversaw four teaching assistants and 80–100 students each year as well as supervised three senior students completing their senior design projects.

2007–2013: Research Assistant, Department of Petroleum Engineering, Louisiana State University, Baton Rouge, Louisiana. Dr. Jin's responsibilities included modeling and evaluating the performance of Downhole Water Loop (DWL) well system in different oil fields, developing economical models for evaluation of the DWL system in various reservoir and market conditions, and identifying best reservoir candidates for the system; oil production rate could be improved as much as 200%. Constructed software (toolbox) using ECLIPSE and VBA for complex well system simulation, applied batch processing technology in simulation, achieved automatic task queuing, and reduced simulation time 67%.

Summer 2012: Internship, High Plains Operating Company, LLC (HPOC), San Francisco, California. Dr. Jin's responsibilities included simulating and analyzing the extra water production problems in the Ojo Encino Field, New Mexico, designing a DWS well system to produce oil from the thick transition zone, which could improve oil production rate by up to 20%.

Summer 2011: Internship, JIP, Louisiana State University, and HPOC, Baton Rouge, Louisiana. Dr. Jin's responsibilities included simulating performance of vertical and horizontal wells in the Ojo Encino Field, New Mexico, diagnosing water coning/cresting problems in the thick transition zone, determining the best location for water injection to minimize pressure interference, and suggesting well type to develop the field, which saved costs up to 30%.

2005–2007: Production Consultant, JIP, China University of Petroleum, and CNPC. Dr. Jin's responsibilities included optimizing a large gas pipeline network in China, proposing new optimization algorithm and programming a software package for best operation in different conditions, reducing operational cost up to 23% (more than $20,000/day).

Publications and Presentations
Has authored or coauthored numerous publications.

BETHANY A. KURZ
Senior Research Manager
Energy & Environmental Research Center (EERC), University of North Dakota (UND)
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Principal Areas of Expertise

Ms. Kurz's principal areas of interest and expertise include the evaluation of water supply sources for the oil and gas industry, produced water and drilling waste management, and characterization of geologic media for carbon storage and/or CO_2-based enhanced oil recovery.

Qualifications

M.S. (Summa Cum Laude), Hydrogeology, University of North Dakota, Grand Forks, ND, 1998.
B.S. (Summa Cum Laude), Geochemistry, Bridgewater State University, Bridgewater, MA, 1995.
Computer: ArcGIS, SWAT, ERMapper, ERDAS Imagine, MS Word, Excel, Access, Project Manager, Power Point, Corel Draw, Surfer, MODFLOW, WATSUTRA, Aquifer Test.
Analytical: Ion chromatograph, total organic carbon analyzer, inductively coupled plasma emission spectrometer, gas chromatograph, ion-selective electrodes, laser-induced breakdown spectroscopy (LIBS).
Fieldwork: Monitoring well and in situ microcosm (ISM) installation; soil vapor extraction system (SVE) design, installation, and optimization; groundwater sampling, analysis, and monitoring; wind-monitoring system installation; and wind data collection and analysis.

Professional Experience

2011–Present: Senior Research Manager, Oil and Gas Research Program, EERC, UND. Ms. Kurz oversees several of the EERC's analytical research laboratories that focus on classical and advanced wet-chemistry analyses; petrochemical and geomechanical evaluation of rocks and soils; and mineralogical assessment of natural materials using optical microscopy, x-ray fluorescence, x-ray diffraction, and scanning electron microscopy. Additional activities include the development and testing of proppants for use in hydraulic fracturing, evaluation of water supply sources for the oil and gas industry, produced water management, and characterization of geologic media for carbon storage.

2002–2011: Senior Research Manager, Water Management and Flood Mitigation Strategies, EERC, UND. Ms. Kurz's responsibilities included project management, technical report and proposal writing, public outreach, and the development of new research focus areas. Research activities included the evaluation of nontraditional water supply sources, development of strategies to address future water shortages, flood and drought mitigation, watershed-scale water quality assessments using hydrologic models, and public education and outreach on various water and energy issues.

1998–2002: Research Scientist, Subsurface Remediation Research and Wind Energy Research, EERC, UND. Ms. Kurz's responsibilities included managing and conducting research involving remediation technologies for contaminated groundwater and soils, groundwater sampling and analysis, technical report writing, and proposal research and preparation. She also assisted in research related to wind energy development in the region, with an emphasis on wind resource assessment, education and outreach, database development, and windsmith training curriculum development.

1997–1998: Research Assistant, Water Quality Laboratory, Department of Geology and Geological Engineering, UND. Ms. Kurz's duties included the operation and maintenance of a water quality laboratory containing several analytical instruments, including an ion chromatograph, inductively coupled plasma emission spectrometer, total organic carbon analyzer, and several ion selective electrodes.

Publications and Presentations
Has coauthored more than 60 professional publications and presentations

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Principal Areas of Expertise
Mr. Harju's principal areas of interest and expertise include carbon sequestration, enhanced oil recovery, waste management, geochemistry, technology development, hydrology, and analytical chemistry, especially as applied to the upstream oil and gas industry.

Qualifications
B.S., Geology, University of North Dakota, 1986.
Postgraduate course work in Management, Economics, Marketing, Education, Climatology, Weathering and Soils, Geochemistry, Geochemical Modeling, Hydrogeochemistry, Hydrogeology, Contaminant Hydrogeology, Advanced Physical Hydrogeology, and Geostatistics.

Professional Experience
2002–Present: EERC, UND, Grand Forks, North Dakota.
2011–Present: Associate Director for Research. Mr. Harju oversees the activities of a team of scientists and engineers focused on research, development, demonstration, and commercialization of energy and environmental technologies. Strategic energy and environmental issues include zero-emission coal utilization; CO_2 capture and sequestration; energy and water sustainability; hydrogen and fuel cells; advanced air emission control technologies, emphasizing SO_x, NO_x, air toxics, fine particulate, and mercury control; renewable energy; wind energy; water management; flood prevention; global climate change; waste utilization; energy efficiency; and contaminant cleanup.

2003–2011: Associate Director for Research. Mr. Harju's responsibilities included developing and administering programs involving petroleum technology, natural resource evaluations, water management and contamination cleanup and building industry–government–academic teams to carry out research, development, demonstration, and commercialization of energy and environmental products and technologies.

2002–2003: Senior Research Advisor. Mr. Harju's responsibilities included development, marketing, management, and dissemination of market-oriented research; development of programs focused on the environmental and health effects of power and natural resource production, contaminant cleanup, water management, and analytical techniques; publication and presentation of results; client interactions; and advisor to internal staff.

1999–2002: Vice President, Crystal Solutions, LLC, Laramie, Wyoming. Mr. Harju's firm was involved in commercial E&P produced water management, regulatory permitting and compliance, and environmental impact monitoring and analysis.

1997–2002: Gas Research Institute (GRI) (now Gas Technology Institute [GTI]), Chicago, Illinois.
2000–2002: Principal Scientist, Produced Water Management. Mr. Harju's responsibilities included development and deployment of produced water management technologies and methodologies for cost-effective and environmentally responsible management of oil and gas produced water.
1998–2000: Program Team Leader, Soil, Water, and Waste. Mr. Harju's responsibilities included project and program management related to the development of environmental technologies and informational products related to the North American oil and gas industry; formulation of RFPs, proposal review, and contract formulation; technology transfer activities; and staff and contractor supervision. Mr. Harju served as Manager of the Environmentally Acceptable Endpoints project, a multiyear, $8MM effort focused on a rigorous determination of appropriate cleanup levels for hydrocarbons and other energy-derived contaminants in soils. He also led GRI/GTI involvement with numerous industry environmental consortia and organizations, including PERF, SPE, AGA, IPEC, and API.

1997–1998: Principal Technology Manager, Soil and Water Quality.
1997: Associate Technology Manager, Soil and Water Quality.

1988–1996: EERC, UND, Grand Forks, North Dakota.
1994–1996: Senior Research Manager, Oil and Gas Group. Mr. Harju's responsibilities included the following:
- Program Manager for program to assess the environmental transport and fate of oil- and gas-derived contaminants, focused on mercury and sweetening and dehydration processes.
- Project Manager for field demonstration of innovative produced water treatment technology using freeze crystallization and evaporation at oil and gas industry site.
- Program Manager for environmental transport and fate assessment of MEA and its degradation compounds at Canadian sour gas-processing site.
- Program Manager for demonstration of unique design for oil and gas surface impoundments.
- Director, National Mine Land Reclamation Center for Western Region.
- Co-Principal Investigator on project exploring feasibility of underground coal gasification in southern Thailand.
- Consultant to International Atomic Energy Agency for program entitled "Solid Wastes and Disposal Methods Associated with Electricity Generation Fuel Chains."

1994: Research Manager.
1990–1994: Hydrogeologist.
1989–1990: Research Specialist.
1988–1989: Laboratory Technician.

Synergistic Activities

Member, National Petroleum Council

Outgoing Chairman, Interstate Oil & Gas Compact Commission, Chairman, Energy Resources, Research and Technology Committee

Member, U.S. Department of Energy Unconventional Resources Technology Advisory Committee

Member, Rocky Mountain Association of Geologists

Publications and Presentations

Has authored and coauthored numerous publications.

APPENDIX H

VERIFICATION OF MATCHING FUNDS

ASSISTANCE AGREEMENT

1. Award No.	2. Modification No.	3. Effective Date	4. CFDA No.
DE-FE0024454		11/01/2014	81.089

5. Awarded To	6. Sponsoring Office	7. Period of Performance
University Of North Dakota Attn: DAVID SCHMIDT PO BOX 7134 GRAND FORKS ND 582027134	Office of Fossil Energy	11/01/2014 through 04/30/2016

8. Type of Agreement	9. Authority	10. Purchase Request or Funding Document No.
☐ Grant ☒ Cooperative Agreement ☐ Other	PL95-91DOE Organization Act, as amended by PL 109-58 Energy Policy Act 2005	15FE000268

11. Remittance Address	12. Total Amount	13. Funds Obligated
University Of North Dakota Attn: DAVID SCHMIDT PO BOX 7134 GRAND FORKS ND 582027134	Govt. Share: $2,000,000.00 Cost Share : $500,000.00 Total : $2,500,000.00	This action: $2,000,000.00 Total : $2,000,000.00

14. Principal Investigator	15. Program Manager	16. Administrator
James A. Sorensen (701) 777-5287	Erik J. Albenze Phone: 412-386-4528	DEPT OF ENERGY NATIONAL ENERGY TECH LAB 626 Cochrans Mill Road PO Box 10940 Pittsburgh PA 15236-0940

17. Submit Payment Requests To	18. Paying Office	19. Submit Reports To
Payment - Direct Payment from U.S. Dept of Treasury	Payment - Direct Payment from U.S. Dept of Treasury	See Reporting Requirement Checklist

20. Accounting and Appropriation Data

CO2 ROZ FOA

21. Research Title and/or Description of Project

IMPROVED CHARACTERIZATION AND MODELING OF TIGHT OIL FORMATIONS FOR CO2 ENHANCED OIL RECOVERY POTENTIAL AND STORAGE CAPACITY ESTIMATION

For the Recipient		For the United States of America	
22. Signature of Person Authorized to Sign		25. Signature of Grants/Agreements Officer Signature on File	
23. Name and Title	24. Date Signed	26. Name of Officer Angela M. Harshman	27. Date Signed 10/31/2014

CONTINUATION SHEET	REFERENCE NO. OF DOCUMENT BEING CONTINUED DE-FE0024454	PAGE 2 OF 13

NAME OF OFFEROR OR CONTRACTOR
University Of North Dakota

ITEM NO. (A)	SUPPLIES/SERVICES (B)	QUANTITY (C)	UNIT (D)	UNIT PRICE (E)	AMOUNT (F)
	DUNS Number: 102280781 NEW AWARD DE-FE0024454 TITLED: "Improved Characterization and Modeling of Tight Oil Formations for CO2 Enhanced Oil Recovery Potential and Storage Capacity Estimation". Period of Performance: 11/01/2014 - 10/31/2017 Budget Periods: Budget Period 1 11/01/2014-04/30/2016 Budget Period 2 05/01/2016-10/31/2017 This Cooperative Agreement consist of the following: Special Terms and Conditions Attachment 1 Intellectual Property Provisions Attachment 2 Statement of Project Objectives Attachment 3 Reporting Requirement Checklist Attachment 4 Budget Pages ------------------------------ NETL Award Adminstrator: Harolynne Blackwell 412-386-4829 Harolynne.Blackwell@netl.doe.gov Recipient Business Point of Contact: Sheryl Landis 701-777-5124 slandis@undeerc.org ASAP: YES Extent Competed: COMPETED Davis-Bacon Act: NO PI: James A. Sorensen Fund: 00150 Appr Year: 2014 Allottee: 31 Report Entity: 220316 Object Class: 25500 Program: 1611060 Project: 0000000 WFO: 0000000 Local Use: 0000000				

EERC
Energy & Environmental Research Center
UNIVERSITY OF NORTH DAKOTA
15 North 23rd Street — Stop 9018 / Grand Forks, ND 58202-9018 / Phone: (701) 777-5000 Fax: 777-5181
Web Site: www.undeerc.org

INVOICE

Lignite Energy Council
1016 Owens Avenue, Suite 200
PO Box 2277
Bismarck, ND 58502-2277

Attn: Dr. Michael Jones
Vice President of Research & Development

INVOICE DATE: December 9, 2014

AMOUNT DUE: US$250,000

Make check payable to:
University of North Dakota EERC

EXPLANATION OF CHARGES:
Improved Characterization and Modeling of Tight Oil Formations for CO_2 Enhanced Oil Recovery Potential and Storage Capacity Estimation

REMIT TO:
ENERGY & ENVIRONMENTAL RESEARCH CENTER
UNIVERSITY OF NORTH DAKOTA
ACCOUNTING OFFICE
ATTN: DIANE SKEAN
15 NORTH 23RD STREET, STOP 9018
GRAND FORKS, ND 58202-9018

DIRECT QUESTIONS TO:
Paul Arnason
Contracts Officer
Phone: (701) 777-5036
parnason@undeerc.org

Payment of this invoice constitutes financial support of the University of North Dakota Energy & Environmental Research Center's (EERC) Improved Characterization and Modeling of Tight Oil Formations for CO_2 Enhanced Oil Recovery Potential and Storage Capacity Estimation Program (the Project) as described in EERC Proposal No. 2015-0065, during the planned Project period from November 1, 2014, through October 31, 2017. Lignite Energy Council (Sponsor) understands these nonfederal funds will be utilized as cost share to the EERC's Cooperative Agreement with the U.S. Department of Energy, Agreement DE-FC0024454. Sponsor will benefit from the Project's deliverables as detailed in EERC Proposal No. 2015-0065. The EERC will exercise its best judgment in conducting this research project; any material changes, technical or financial, will be discussed and a mutually acceptable path forward will be followed once written confirmation is received from the Sponsor.

THANK YOU FOR YOUR SUPPORT

c: Jim Sorensen
Paul Arnason
EERC Accounting

S:\PAA\DOE Tight Oil (DE-FE0024454)\LEC Invoice Agreement.doc

APPENDIX I

BUDGET JUSTIFICATION

BUDGET JUSTIFICATION

ENERGY & ENVIRONMENTAL RESEARCH CENTER (EERC)

BACKGROUND

The EERC is an independently organized multidisciplinary research center within the University of North Dakota (UND). The EERC is funded through federal and nonfederal grants, contracts, and other agreements. Although the EERC is not affiliated with any one academic department, university faculty may participate in a project, depending on the scope of work and expertise required to perform the project.

INTELLECTUAL PROPERTY

The applicable federal intellectual property (IP) regulations will govern any resulting research agreement(s). In the event that IP with the potential to generate revenue to which the EERC is entitled is developed under this project, such IP, including rights, title, interest, and obligations, may be transferred to the EERC Foundation, a separate legal entity.

BUDGET INFORMATION

The proposed work will be done on a cost-reimbursable basis. The distribution of costs between budget categories (labor, travel, supplies, equipment, etc.) and among funding sources of the same scope of work is for planning purposes only. The project manager may incur and allocate allowable project costs among the funding sources for this scope of work in accordance with Office of Management and Budget (OMB) Circular A-21.

Escalation of labor and EERC recharge center rates is incorporated into the budget when a project's duration extends beyond the university's current fiscal year (July 1 – June 30). Escalation is calculated by prorating an average annual increase over the anticipated life of the project.

The cost of this project is based on a specific start date indicated at the top of the EERC budget. Any delay in the start of this project may result in a budget increase. Budget category descriptions presented below are for informational purposes; some categories may not appear in the budget.

Labor: Estimated labor includes direct salaries and fringe benefits. Salary estimates are based on the scope of work and prior experience on projects of similar scope. Salary costs incurred are based on direct hourly effort on the project. Fringe benefits consist of two components which are budgeted as 66% of direct labor. The first component is a fixed percentage approved annually by the UND cognizant audit agency, the Department of Health and Human Services. This portion of the rate covers vacation, holiday, and sick leave (VSL) and is applied to direct labor for permanent staff eligible for VSL benefits. Only the actual approved rate will be charged to the project. The second component is estimated on the basis of historical data and is charged as actual expenses for items such as health, life, and unemployment insurance; social security; worker's compensation; and UND retirement contributions. The following table represents a breakdown by labor category and hours for technical staff for the proposed effort.

Labor Categories	Labor Hrs
Research Scientists/Engineers	11,894
Research Technicians	895
Senior Management	448
Technical Support Services	959
	14,196

Travel: Travel may include site visits, fieldwork, meetings, and conferences. Travel costs are estimated and paid in accordance with OMB Circular A-21, Section 53, and UND travel policies, which can be found at http://und.edu/finance-operations (Policies & Procedures, A–Z Policy Index, Travel). Daily meal rates are based on U.S. General Services Administration (GSA) rates unless further limited by UND travel policies; other estimates such as airfare, lodging, etc., are based on historical costs. Miscellaneous travel costs may include taxis, parking fees, Internet charges, long-distance phone, copies, faxes, shipping, and postage.

Equipment: A Nikon X-Y motorized stage and accessories along with the associated software will be purchased to enhance our existing Nikon OM to allow for automated, whole thin-section-scanning capabilities using both transmitted light and UVF. It will provide for more accurate and more efficient identification of fracture networks on an entire thin section through visual analysis and image analysis. The images created by this capability will greatly enable the fractal analysis methods at the thin-section scale. In addition, this will also provide us with the new capability of being able to assign a coordinate system to thin sections that will allow for cross-referencing using SEM. Thus, specific fractures identified using OM can then be easily referenced and examined using SEM.

Supplies: Supplies include items and materials that are necessary for the research project and can be directly identified to the project. Supply and material estimates are based on prior experience with similar projects. Examples of supply items are chemicals, gases, glassware, nuts, bolts, piping, data storage, paper, memory, software, toner cartridges, maps, sample containers, minor equipment (value less than $5000), signage, safety items, subscriptions, books, and reference materials. General purpose office supplies (pencils, pens, paper clips, staples, Post-it notes, etc.) are included in the F&A cost.

Software Tools and License: The COMSOL software is needed to perform modeling at the pore-scale, which will then be interpreted and up-scaled to the larger CMG platform geo-models to be used throughout the project.

Subcontracts: N/A

Professional Fees: Not applicable.

Communications: Telephone, cell phone, and fax line charges are included in the F&A cost; however, direct project costs may include line charges at remote locations, long-distance telephone charges, postage, and other data or document transportation costs that can be directly identified to a project. Estimated costs are based on prior experience with similar projects.

Printing and Duplicating: Page rates are established annually by the university's duplicating center. Printing and duplicating costs are allocated to the appropriate funding source. Estimated costs are based on prior experience with similar projects.

Food: Expenditures for project partner meetings where the primary purpose is dissemination of technical information may include the cost of food. The project will not be charged for any costs exceeding the applicable GSA meal rate. EERC employees in attendance will not receive per diem reimbursement for meals that are paid by project funds. The estimated cost is based on the number and location of project partner meetings.

Professional Development: Fees are for memberships in technical areas directly related to work on this project. Technical journals and newsletters received as a result of a membership are used throughout the development and execution of the project by the research team.

Operating Fees: Operating fees generally include EERC recharge centers, outside laboratories, and freight.

EERC recharge center rates are established annually.

Laboratory and analytical recharge fees are charged on a per-sample, hourly, or daily rate. Additionally, laboratory analyses may be performed outside the university when necessary. The estimated cost is based on the test protocol required for the scope of work.

Graphics recharge fees are based on an hourly rate for production of such items as report figures, posters, and/or images for presentations, maps, schematics, Web site design, brochures, and photographs. The estimated cost is based on prior experience with similar projects.

Shop and operation recharge fees are for expenses directly associated with the operation of the pilot plant, including safety training, personal safety items (protective eyeglasses, boots, gloves), and annual physicals for pilot plant personnel. The estimated cost is based on the estimated hours for pilot plant personnel.

Outside Labs will be utilized to perform a suite of geochemical, geomechanical, and petrophysical analyses on rock samples to aid in calibration and correlation with well logs and to improve the accuracy of geologic and simulation models in predicting the interactions between CO_2 and tight, fractured reservoirs.

Freight expenditures generally occur for outgoing items and field sample shipments.

Facilities and Administrative Cost: The facilities and administrative rate of 50.5% (indirect cost rate) included in this proposal is approved by the Department of Health and Human Services. Facilities and administrative cost is calculated on modified total direct costs (MTDC). MTDC is defined as total direct costs less individual capital expenditures, such as equipment or software costing $5000 or more with a useful life of greater than 1 year, as well as subawards in excess of the first $25,000 for each award. The facilities and administrative rate has been applied to each line item presented in the budget table.

APPENDIX J

STATUS OF ON-GOING PROJECTS

STATUS OF ONGOING PROJECTS

1. **G-015-030 "Plains CO_2 Reduction Partnership Program (PCOR) – Phase III"**
   - Oil and Gas Research Council (OGRC) funding $500,000; total project cost $116,760,635.
   - Period of Performance: October 1, 2007 – September 30, 2017.
   - The PCOR Partnership is one of seven regional partnerships awarded in 2003 by the U.S. Department of Energy's National Energy Technology Laboratory to determine the best approaches for the geologic storage of CO_2, as well as safely and permanently demonstrate this technique. Currently in its eighth year of the demonstration phase, the Plains CO_2 Reduction (PCOR) Partnership is testing the validity of different characterization, modeling and simulation, risk assessment, and monitoring techniques and technologies at its Bell Creek and Aquistore demonstration projects.
2. **G-030-060 "Program to Determine the Uniqueness of Three Forks Bench Reserves, Determine Optimal Well Density in the Bakken Pool, and Optimize Bakken Production"** (also known as the Bakken Production Optimization Program, or BPOP)
   - OGRC funding $8,554,500 (includes $6.26M subcontract to Continental Resources); total project cost $116,030,000 (includes $106M in-kind from Continental Resources).
   - Period of Performance: June 1, 2013 – June 30, 2016.
   - This is a 3-year program led by the Energy & Environmental Research Center (EERC), in close coordination with Continental Resources, Inc., and several of the Williston Basin's premier operating companies. The goal of this program is to simultaneously improve Bakken system oil recovery while reducing its environmental footprint. This program is investigating new technologies and approaches to simultaneously increase understanding of potential petroleum reserves in the Bakken/Three Forks system and decrease recovery costs in an environmentally sound manner. Now 2 years into the program, the EERC has been heavily involved in headline topics of flaring reduction, TENORM (technologically enhanced naturally occurring radioactive material) disposal, saline and hydrocarbon spills remediation, and crude oil characterization as it applies to transport-by-rail.
3. **G-Sandia 01 "Oil Characterization Study"**
   - OGRC funding $150,000. This study is complementary to funding of $119,957 provided to the EERC by Sandia National Laboratories.
   - Period of Performance: February 1, 2015 – June 30, 2016.
   - This project is intended to assess oil properties relative to its safe storage and transport. The EERC, in collaboration with Sandia National Laboratories, has completed a literature review of

available data on crude oil properties and prepared a draft sampling, analysis, and experimental plan that forms the basis for subsequent Phase II crude oil characterization activities.

4. **Contract number to be determined "Produced Fluids Gathering Pipeline Study,"** commissioned by the 64th North Dakota Legislative Assembly
   - OGRC funding: $1,500,000.
   - Period of Performance: April 20, 2015 – June 30, 2017.
   - This project focuses on conducting an analysis of crude oil and produced water pipelines including construction standards, depths, pressures, monitoring systems, maintenance, types of materials used in the pipeline backfill, and analysis of the ratio of spills and leaks occurring in this state in comparison to other large oil and gas-producing states with substantial volumes of produced water. The EERC will analyze the existing regulations on construction and monitoring of crude oil and produced water pipelines, determine the feasibility and cost-effectiveness of requiring leak detection and monitoring technology on new and existing pipeline systems, and provide a report with recommendations to the North Dakota Industrial Commission and the Energy Development and Transmission Committee by December 1. Work on this project has just begun. Data-gathering efforts will conclude by the end of June, leading into technoeconomic assessments of monitoring approaches and final reporting in September.