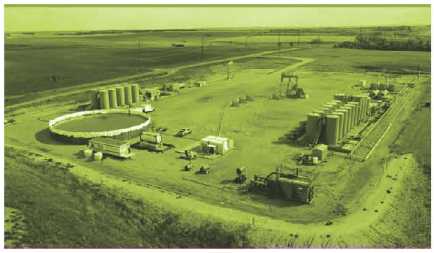
Bakken Production Optimization Program

FINAL REPORT

May 2020 – August 2023



EERC

UND UNIVERSITY OF NORTH DAKOTA

Contract No. G-051-98

August 2023

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ACKNOWLEDGMENTS

The EERC would like to thank all state and industry program partners for their active participation in this program. Without active engagement from all partners, this program would not have been able to accomplish the numerous tangible, high-impact results described in this final report. Although the EERC led this effort, it could not have achieved this success alone. The successes of this program were made possible only by enthusiastic participation of partner companies and state agencies.

The EERC would specifically like to thank the following companies and North Dakota State agencies:

- ConocoPhillips
- Devon Energy
- Liberty Resources LLC
- Marathon Oil
- North Dakota Industrial Commission
- Chord Energy (formerly known as Oasis)
- Oil and Gas Research Council
- Petro-Hunt LLC
- Hess Corporation
- Computer Modelling Group
- Rock Flow Dynamics
- XTO Energy (a subsidiary of ExxonMobil)

Additionally, the program received extensive support, collaboration, and cooperation from the U.S. Department of Energy, the North Dakota Petroleum Council, the North Dakota Geological Survey, the North Dakota Oil & Gas Division, and the North Dakota Pipeline Authority.

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EXECUTIVE SUMMARY BPOP 3.0

The Bakken Production Optimization Program (BPOP) was established in June 2013 to facilitate Bakken petroleum system (BPS) oil recovery while simultaneously reducing the environmental footprint of oil and gas development. From May 1, 2020, to August 31, 2023, activities were conducted under BPOP 3.0. The BPOP 3.0 activities were administered by the Energy & Environmental Research Center (EERC), with funding from the North Dakota Industrial Commission (NDIC) Oil and Gas Research Program (OGRP), the U.S. Department of Energy (DOE), several Bakken operating companies, and a reservoir simulation software company. Two operating companies and two technical service providers also provided in-kind cost share. The total value of BPOP 3.0 was over $12,700,000, with $6,000,000 provided by NDIC OGRP. The overall purpose of the program is to address emerging opportunities and challenges related to Bakken development. The knowledge derived from BPOP can assist industry and the state of North Dakota during times like this. The goals of BPOP are to:

- Develop knowledge that will enhance overall Bakken production efficiency, recognizing that improved coordination among various design factors (reservoir management, well design, surface processing, waste management) can significantly improve resource recovery efficiency while reducing potential health, safety, and environmental impacts.

- Conduct applied research in topic areas that positively impact the efficiency of production and reduce the environmental footprint, including the carbon intensity, of Bakken operations.

Significant achievements directly attributable to this program have made measurable, positive impacts to how the business of oil and gas exploration and production is accomplished in North Dakota. Specific achievements between June 2020 and August 2023 include but are not limited to:

- From the fall of 2021 to spring of 2022, Liberty Resources (Liberty,) in partnership with the EERC and EOR ETC, conducted an enhanced oil recovery (EOR) pilot test in a single well in the East Nesson field using produced gas injection with rapid pulses of water. The pilot also used fresh water mixed with surfactant. The data generated by the pilot indicated that the injection cycle resulted in the production of substantial amounts of incremental oil. Decline curve analysis indicates that approximately 8400 barrels (bbl) of incremental oil will be produced from two wells in the drill spacing unit (the injector and an offset well) over the course of 5 years.

- Lessons learned from the East Nesson pilot suggested that it may be possible to achieve similar results using produced water rather than fresh water, applying a more traditional water-alternating-gas (WAG) injection approach rather than the rapid water pulse approach.

- Flare reduction technology, Polar Bear^{SM}, was developed with Steffes Corporation and has been issued four patents. Field testing was initiated and is planned to continue as part of BPOP 4.0.

- A study of 341 refractured wells showed that refracs generally improved the production performance of a well; however, refracs conducted on wells that were originally completed as openhole completions outperformed those performed on cased-hole wells.

- A carbon intensity analytical tool that provides information related to gas flaring, lease gas combustion, and tank vapors for selected wells (as selected by the tool user) was developed.

- An interactive Bakken geological cluster analysis tool was developed. The tool allows users to divide the BPS into subareas (clusters) based on geologic and fluids properties data and analyze a variety of drilling, completion, and production parameters using three different clustering algorithms.

- The results of a study of 275 3-mile lateral wells support the continued development of the longer laterals that benefit operators through reduced costs and lower environmental impact.

- Oil fingerprinting methods were further improved to better understand drainage mechanisms and crude oil volumes in the different lithofacies of the BPS.

- The BPOP Analytics Well Completion & Production Dashboard was developed to illustrate a real-time tool for analyzing production and completion data and calculating optimal completion parameters using machine learning.

- The EERC research team identified several potential mechanisms of souring in the Bakken including thermochemical sulfur reduction (TSR).

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INTRODUCTION

The Bakken Production Optimization Program (BPOP) was established in June 2013 to facilitate Bakken petroleum system (BPS) oil recovery while simultaneously reducing the environmental footprint of oil and gas development. Building upon the results of the previous 6 years of work, from May 1, 2020, to August 31, 2023, a wide variety of activities were conducted under BPOP 3.0. The BPOP 3.0 activities were designed and executed by the Energy & Environmental Research Center (EERC), with funding from the North Dakota Industrial Commission (NDIC) Oil and Gas Research Program (OGRP), the U.S. Department of Energy (DOE), and the North Dakota petroleum industry. Additional in-kind cost share was provided by Liberty Resources through its East Nesson enhanced oil recovery (EOR) pilot and from Oasis Petroleum in the form of unique data sets, including special core and fluid analysis data. In-kind cost share and cash funding were also provided by three technical service providers. The total value of BPOP 3.0 was over $12,700,000, with $6,000,000 provided by NDIC OGRP. The overall purpose of the program is to address emerging opportunities and challenges related to Bakken development. The knowledge derived from BPOP can assist industry and the state of North Dakota during times like this. The goals of BPOP are to:

- Develop knowledge that will enhance overall Bakken production efficiency, recognizing that improved coordination among various design factors (reservoir management, well design, surface processing, waste management) can lead to significant improvements in resource recovery efficiency while reducing potential health, safety, and environment impacts.

- Conduct applied research in topic areas that positively impact production efficiency and reduce operations' environmental footprint, including a reduction in carbon intensity.

As a premier partnership program, BPOP has been cited as an exemplary model by others nationwide. BPOP is a public–private partnership harnessing North Dakota research scientists and industry to maximize the Bakken oil play's productivity while reducing its environmental footprint. This program has demonstrated that state lawmakers, state regulators, and industry can work together for positive results for taxpayers and shareholders alike.

Significant achievements directly attributable to this program have made measurable, positive impacts to how the business of oil and gas exploration and production is accomplished in North Dakota. The following is a small sampling of concrete examples of these impacts:

- From the fall of 2021 to spring of 2022, Liberty Resources (Liberty), in partnership with EERC and EOR ETC, conducted an EOR pilot test in a single well in the East Nesson field using produced gas injection with rapid pulses of water. The pilot also used fresh water mixed with surfactant.
  - Injectivity was readily achieved and was not a constraint on operations.
  - The assessment of the data generated by the pilot indicated that the injection cycle resulted in the production of substantial amounts of incremental oil and was considered to have very positive results. Decline curve analysis indicates that approximately 8400 barrels (bbl) of incremental oil will be produced from two wells in the drill spacing unit (DSU) (the injector and an offset well) over the course of 5 years.
  - The EOR ETC technology allowed for rapid pulsing of water and rich gas, lowered injection pressure, and enabled utilization of common gas lift compression, lowering cost and simplifying supply options. The EOR ETC technology also showed an ability to manage conformance of the injected fluids within the intended reservoir.
  - Lessons learned from the East Nesson pilot suggested that it may be possible to achieve similar results using produced water rather than fresh water, applying a more traditional water-alternating-gas (WAG) injection approach rather than the rapid water pulse approach.
  - Laboratory evaluations and dynamic reservoir modeling made valuable contributions to the pilot design and operation.

- The EERC and Liberty worked on developing a scheme for a second cycle to be conducted under BPOP 4.0 of injection using produced water and rich gas, applying a more traditional WAG approach.

- Flare reduction technology, Polar Bear^{SM}, was developed with Steffes Corporation and has been issued four patents. Field testing was initiated and is planned to continue as part of BPOP 4.0.

- A total of 69 additional refractured wells were identified and added to the EERC database. The updated database includes 341 refractured wells from the North Dakota portion of the Bakken that were refractured as of October 2021. The results showed that refracs generally improved the production performance of the refractured well; however, refracs conducted on wells that were originally completed as openhole completions outperformed those performed on cased-hole wells.

- A carbon intensity analytical tool was developed. The analytical tool accesses a production database and allows the user to conduct investigations with user-friendly options including GIS (geographic information system) map-based selection analytics. The carbon intensity tool provides information related to gas flaring, lease gas combustion, and tank vapors for selected wells (as selected by the tool user).

- An interactive Bakken geological cluster analysis tool was developed. The tool allows users to divide the BPS into subareas (clusters) based on geologic and fluids properties data and analyze a variety of drilling, completion, and production parameters using three different clustering algorithms.

- A study of 3-mile lateral wells was conducted that supports the continued development of the longer laterals that benefit from reduced costs and lower environmental impact. The study included 275 wells within the basin and specifically investigated 2-mile offset wells with similar production potential. The majority of cases (70%) are realizing the anticipated added production. Compared to early 3-mile lateral development, which was driven by geographic constraints, operators are now developing the longer wells in both core and noncore areas.

- Oil fingerprinting methods were further improved to better understand drainage mechanisms and crude oil volumes in the different lithofacies of the BPS.

- The BPOP Analytics Well Completion & Production Dashboard was developed to illustrate a real-time tool for analyzing production and completion data and calculating optimal completion parameters using machine learning.

- The EERC research team identified several potential mechanisms of souring in the Bakken, including thermochemical sulfur reduction (TSR).

The program was initiated in June 2013 with the first phase of BPOP extending through December 2016. The program continued as BPOP 2.0 from November 2016 to May 2020, and again as BPOP 3.0 from May 2020 to August 2023. The achievements of BPOP 3.0 are summarized in this report. Many of the efforts begun under BPOP 3.0 will continue into BPOP 4.0, which was approved for funding by NDIC in July 2023 and will officially start on September 1, 2023. This report is intended for public distribution and is intended to highlight the important work of this public–private partnership in advancing North Dakota's economic and environmental interests directly related to the exploration and production of oil from the Bakken and Three Forks Formations.

A comprehensive list of BPOP 3.0 products is presented in Appendix A.

RESULTS AND DISCUSSION OF BPOP 3.0

Program Management

Partnership

NDIC committed $6.0 million in matching funds over 3+ years to expand the scope and continue support of the highly successful BPOP Program that optimizes petroleum production from the Bakken and Three Forks Formations in North Dakota. The program is a continuation of the collaborative effort between the State of North Dakota through NDIC, North Dakota's petroleum industry, and DOE to develop solutions to challenges in the Bakken. The BPOP 3.0 Program cultivated and maintained the support of eight of the top oil-producing companies in North Dakota, including Chord Energy, ConocoPhillips, Devon Energy, XTO Energy (a subsidiary of ExxonMobil), Hess Corporation, Liberty Resources L.L.C, Marathon Oil Company, and Petro-Hunt, L.L.C.

This was a partner-driven program with the goal of conducting research focused on solutions to optimize petroleum production and reduce the environmental impacts of the development of Bakken resources in North Dakota. Employing a consortium approach for these issues minimized corporate financial and staffing input, made solutions available to consortium companies without dedicating staff resources, and ensured transparency and continued cooperative efforts with the state of North Dakota to assist producers in getting the most out of wellsite economics while reducing the carbon intensity of the Bakken play.

Partnership participation was solicited in the following categories:

- $100,000 a year for large producers with 150 wells or more
- $50,000 a year for small producers with fewer than 150 wells
- $25,000 a year for service companies and nonproducers

Program partner benefits included:

- Ability to guide research efforts to issues highest on individual company priority lists.
- Expedient information sharing among consortium partners.
- Engagement with professional researchers focused on high-priority wellsite productivity and environmental issues.
- Exclusive access for a period of time to all program products via the partners-only BPOP web page.

Partnership in this consortium-facilitated program during the third phase of BPOP is shown in Figure 1.

Outreach and the Bakken Production Optimization Program Website

The BPOP website has been maintained and updated to provide information about the program to the partners and the public. Brief information on BPOP, areas of interest, and current activities are provided on the site. Links to additional Bakken resources are available on the home page.

Figure 1. BPOP 3.0 partners.

A key feature of the site is access to all free BPOP products to the public, and premium BPOP products to members, through the searchable product directory. The product directory includes products created through all years of BPOP as well as products from other EERC Bakken projects. All products are accompanied by a public abstract for a preview of the content. Access to each product is shown by a tag of free or premium, described as:

- Free (public) products are available for download by all.

- Premium (partners-only) products are available exclusively to partners on the website for up to 15 months following an internal and partner-driven external review process prior to release to the public. Selected products, such as fact sheets or reports on high-profile environmental issues, may be released to the public earlier if early release is approved by the membership.

Individual logins are provided to interested people within partner companies. This login provides individuals access to view/download premium products.

Presentation of BPOP Activities

EERC staff attended, participated in, and/or presented results of BPOP activities at over 60 conferences, meetings, workshops, and forums in the United States and Canada, highlighting the technology transfer value of this unique state–industry consortium. The presentations also demonstrated North Dakota's leadership in developing unconventional shale resources and reducing the environmental impact of oil and gas production, particularly with respect to carbon intensity.

Included in this technology transfer were regularly scheduled briefings to state and federal government agencies on program results. The federal briefings demonstrated North Dakota government's leadership in shale development practices and policies to such agencies such as DOE. During this phase of the program, BPOP briefings were given to such state institutions such as NDIC, the OGRP, the Department of Mineral Resources (DMR), the Legislative Management Energy Development and Transmission Committee, the EmPower Commission, the Water Topics Overview Committee, the North Dakota Department of Health (NDDH), and others.

Enhanced Oil Recovery

Total original oil in place (OOIP) for the BPS (which includes the Bakken and Three Forks Formations) has been estimated to be 600 billion barrels (bbl) (Nordeng and Helms, 2010). However, BPS wells have decline rates as high as 85% over the first three years of their lives, and primary recovery factors typically range from 3% to 15% of OOIP. Given the low initial recovery rates and enormous OOIP, even small incremental productivity improvements could dramatically increase technically recoverable oil in the BPS. One potential solution is EOR using rich gas and water injection.

Field-based EOR research within BPOP began in partnership with Liberty Resource during BPOP 2.0 at Liberty's Stomping Horse location (specifically the Leon-Gohrick DSU within the

McGregor field) north of Tioga, North Dakota. The Stomping Horse EOR pilot test used cyclic injection of rich gas (a mixture of methane, ethane, and propane) at multiple wells in the Leon-Gohrick DSU from the summer of 2018 to spring of 2019. Lessons learned from this endeavor were applied to BPOP 3.0., leading to a single-well EOR pilot test conducted once again by Liberty Resources, with support from the EERC, at Liberty's East Nesson field in Mountrail County.

The injection cycle at East Nesson included the application of a gas–water coinjection technology using fresh water developed by EOR ETC, LLC (EOR ETC). The goals of the injection cycle at the East Nesson pilot location were to demonstrate 1) the economic viability of EOR from the BPS by using produced-rich gas in combination with water and surfactants and 2) that the coinjection process can lower the pressure and cost for utilizing produced gas and surfactants to mobilize oil in the reservoirs. The pilot test was designed, permitted, and conducted by Liberty, in partnership with the EERC through BPOP, and EOR ETC. Simulation modeling was led and conducted by the EERC with support from Computer Modelling Group Ltd (CMG). The pilot was commissioned with the start of coinjection of produced gas and water with surfactant on September 9, 2021.

The first injection cycle of the pilot test was concluded on October 11, 2021, after a month of injection into the Haley 10-MBH well at the East Nesson site. The production cycle began on October 12, 2021, without any soaking period. Continuous and periodic data were collected from multiple wells in the DSU as part of the reservoir surveillance program. These data were collected, processed, and analyzed to evaluate the performance of the ongoing pilot test at the site. The pilot production data were integrated into the existing simulation model to improve model accuracy and further model calibration.

The assessment of the East Nesson EOR pilot test indicated that the injection cycle resulted in the production of substantial amounts of incremental oil and was considered to have very positive results. Decline curve analyses conducted by the EERC and Liberty Resources indicate that approximately 8400 bbl of incremental oil will be produced as a result of the EOR test from two wells on the DSU, the Haley 10-MBH well and an offset well. Analysis and interpretation of the data from the first cycle, and subsequent dynamic simulations of different injection and production schemes, suggested that it may be possible to achieve similar results using an approach that applies a more traditional WAG scheme that is able to use rich gas injection alternating with produced water rather than fresh water. If successful, this approach could significantly reduce the cost of the injection.

BPOP 3.0 included a simulation analysis of WAG injection scenarios conducted by the EERC to help Liberty Resources design the second injection cycle at the East Nesson site. Planning included considering the operational constraints (i.e., the produced rich gas availability), gas compression capacity, and production facility capacity. The produced water from the area was considered for possible WAG injection, and the effect of its salinity on the performance of surfactant that could be coinjected with water was also investigated in the simulation work conducted. Efforts to support and evaluate the performance of the planned second injection cycle at the site will continue in the next phase in BPOP 4.0.

As more knowledge is gained about how to optimize injection and production operations, as well as how best to understand and exploit the nature and distribution of fracture networks in the Bakken, the industry will be better positioned to predict and ultimately influence fluid mobility. This will ultimately lead to practical, economically viable approaches to EOR in the Bakken, unlocking billions of barrels of otherwise stranded oil. New field tests are necessary to develop a more complete understanding of those conditions. Thoughtful and creatively engineered field tests within a well-characterized geologic setting will yield the fundamental knowledge needed to take Bakken oil production to the next level.

Optimization

The EERC conducted a variety of activities to address the general challenges facing BPOP operators. The challenges most commonly brought forward by BPOP stakeholders include maintaining a high level of production with minimal environmental impact and competing for investment. Activities that achieve this goal grow Tier 1 and Tier 2 acreage, change the economics for Tier 3, and produce a cleaner barrel of oil. Under BPOP 3.0, the EERC systematically analyzed trends; worked with BPOP operators; and defined approaches to improve process efficiency, identified technologies to reduce flaring and carbon intensity, and provided operational solutions through process modeling and system design.

Working with BPOP partners, the EERC developed a wellsite model to assess tank vapor-phase behavior. Using Aspen HYSYS software, the EERC developed a typical wellsite process and, using a representative treater oil composition, estimated the composition of gas and oil streams present when pressurized oil exits the treater and enters an atmospheric pressure tank. The simulated tank vapor composition was then used to assess natural gas liquid (NGL) recovery potential over a range of pressures. This analysis was then conducted with varying levels of dilution with air to assess the impact of oxygen and nitrogen on the phase behavior of tank vapor NGLs.

Additionally, well economics were investigated using lease operating expense (LOE) data. The inputs used for the economic analysis include LOEs for maintenance, electricity, saltwater disposal (SWD), maintenance water, and chemicals. The analysis considered adjustments to fresh water used for maintenance and anticipated changes to oil and produced water volumes. The findings indicate that existing wells could benefit by reducing costs in the following two areas: 1) costs associated with disposal of produced water and 2) costs associated with reducing maintenance water, which increases oil revenue. Additionally, a 20% reduction in drilling and well costs was examined, considering new wells developed in noncore acreage and assuming the expected reservoir potential remains unchanged. The potential impact to well economics was examined if all three strategies are executed. While the assumption is that production performance may be constrained, economic well performance can be improved by reducing development costs, improving efficiency of maintenance water, and decreasing SWD costs.

The EERC also investigated the application of flared gas injection in production wells, and a model injection of produced gas into oil-producing wells was completed. Routine flaring occurs because of pipeline constraints or production of low-pressure gas that is unable to overcome pipeline pressure. The concept was applied to a multiwell pad and includes rotating injection of

gas in one of the producing wells while producing from the others. The results are encouraging and identify positive economics relative to gas volumes and incremental recovery of oil.

The EERC completed an investigation of irregular flow in horizontal wells. The terms heel and toe are typically used to refer to ends of a horizontal well. The heel being the transition from vertical to horizontal, and the toe referring to where the horizontal section terminates. Geologic markers, either well logs or cuttings, are used as a guide to steer the horizontal trajectory. The subsurface stratigraphy will determine if a well is drilled toe down or toe up following a target (i.e., a gamma signature in the middle Bakken). It is common for a horizontal well to be steered up and down during drilling, resulting in trajectory undulation. These undulations in the horizontal well's trajectory cause hydraulic phenomena for multiphase fluids, creating unsteady production at the surface. A multiphase transient flow model was used to study this behavior and provide insights that may lead to improvements in production efficiency.

A carbon intensity analytical tool was developed. The analytical tool accesses a production database and allows the user to conduct investigations with user-friendly options including GIS (geographic information system) map-based selection analytics. The carbon intensity tool provides information related to gas flaring, lease gas combustion, and tank vapors for selected wells (as selected by the tool user).

Flare Reduction Through Polar Bear^{SM}

After the significant oil price crash in 2020 and the adoption of environmental social governance (ESG) standards, the oil and gas industry has made significant strides and reduced flaring to approximately 5%. Flaring is the number one contributor to carbon intensity in North Dakota's upstream oil and gas business; achieving zero flaring is essential to producing the cleanest barrel of oil in the nation. The EERC's response to flare reduction is Polar Bear. Polar Bear technology is an innovative low-cost compression can be useful for gas capture at locations where capture is otherwise not technically or economically viable. Polar Bear was initially acquired through a license agreement with Equinor, a major energy company headquartered in Norway that was a member of BPOP when it had assets in the Bakken play. The EERC and BPOP partnerships have advanced the Polar Bear technology, resulting in new intellectual property and steps toward commercialization.

Currently, EERC is under a joint development agreement with Steffes Corporation, a leading oilfield facility manufacturer in North Dakota. Steffes aided in prototype design and testing. A laboratory has been developed at the EERC to test compressors. Multiple nondisclosure agreements have been signed with BPOP partners to test prototypes in the field. Equation-of-state (EOS) modeling has been completed for the process. Four patents have been issued by the U.S. Patent and Trade Office. Field testing is expected in BPOP 4.0.

Produced Fluid Characterization

The optimization of crude oil production in North Dakota requires an accurate understanding of the fluids being produced. Crude oil, associated gas, and produced water are complex mixtures, and their chemical and physical properties can vary geographically over the life of a well. Over

the first 6 years of BPOP, a large amount of fluids data was acquired, and a database of fluids information was created. The EERC continued to maintain and expand this valuable database and coordinate data analysis activities throughout BPOP 3.0.

To better understand drainage mechanisms and the contribution of crude oil volumes from the different lithofacies of the BPS, oil fingerprinting methods were improved. Several sample preparation methods were adapted in the laboratory, including extraction of 1) oil/bitumen from rock using sonication and Soxhlet extractors and 2) fractional separation using an open column to improve the results of gas chromatography–mass spectrometry (GC–MS) analysis. Aromatic and saturate fractions were analyzed separately, and relative abundances of various groups of compounds were evaluated. This knowledge was used to select the most informative hydrocarbon indicators for the oil fingerprinting purpose.

Optimization of the hydrocarbon extraction method from core (source rocks, reservoir) using a sonication technique was a focus during this BPOP iteration. Access to a BPS well for the purpose of temporal fluid collection and analysis was provided by a BPOP partner. Temporal fluid sample collection activities for a newly producing well and its associated parent well on the same location, in the southeast portion of the Bakken, were initiated in mid-September 2021 and are ongoing. Samples of core from the newly producing well were subjected to processes for extracting in situ fluids from the pore space. The process involved extracting small amounts of the existing oil for GC analysis and extracting salts that are reconstituted with water and analyzing to determine a compositional profile of the in situ formation water.

H_2S Study

The objective of the H_2S study is to understand H_2S generation mechanisms in Bakken wells, which might reduce the risk of souring and help operators to develop mitigation strategies for H_2S. The EERC identified several potential mechanisms of souring in the Bakken including TSR, bacterial sulfur reduction (BSR), generation of H_2S by the source rock, and a process involving fracking fluids. The team coordinated trips for H_2S sampling to about 40 wells with BPOP partners.

H_2S samples for the isotope analysis were collected. Oil, water, and anhydrite samples were collected for elemental analysis and S isotope measurements. Successful laboratory experiments were conducted to simulate H_2S generation by the source rocks. The preliminary results of the H_2S study were presented at the June 2023 Unconventional Resources Technology Conference (URTeC) in Denver, Colorado, and the June 2023 Rocky Mountain Section–American Association of Petroleum Geologists (RMS–AAPG) annual meeting in Bismarck, North Dakota.

The first iterations of experiments simulating TSR involving oil, brine, and anhydrites only detected traces of H_2S. Additional work must be done to simulate the souring process in a lab environment. However, the research team acquired new experience and knowledge of experimental settings, required materials, procedures, and learned lessons from the challenging high-temperature/pressure tests.

Completion and Production Data Analytics

In response to feedback from BPOP partners and the North Dakota OGRP, the EERC data analytics team investigated multiple topics during BPOP 3.0. Specific activities included Bakken Well Refracturing efforts, Well Completion Optimization, as well as the development of the Bakken Geological Cluster Analysis Tool, and the BPOP Analytics Well Completion & Production Dashboard. The EERC team also applied advanced statistical analytical techniques to other key topical areas, including Bakken Core Area Expansion, Parent–Child Well Interactions, Data Extraction from the NDIC Oil and Gas Database, and DSU Completion Optimization Calculations.

Bakken Well Refracturing

The main objectives of the Bakken well refracturing study were to 1) update the master database at the EERC of wells that have been refractured in the North Dakota portion of the BPS by identifying newly refractured wells since the previous study by Dalkhaa and others (2020); 2) revise the evaluation of production performance of the refractured wells that were previously identified, and conduct an evaluation of the production performance of the newly refractured wells identified in this update; 3) update the analysis of the impact of frac hits from refracturing; and 4) update the assessment of refracture economics using a decision-tree modeling approach.

Sixty-nine additional refractured wells were identified and added to the database. The updated database includes 341 refractured wells from the North Dakota portion of the Bakken as of October 2021, constituting the data set used in the present study. A production performance analysis of the refractured wells was completed, which included changes in daily oil production rates, peak oil production rates, gas-oil ratio (GOR), and estimated ultimate oil recovery (EUR). EUR was obtained through decline curve analysis (DCA). DCA results provided the inputs to the economic analyses. Economic modeling was completed using stochastic modeling for uncertain oil prices, refrac costs, and operational expenses (OPEX) combined with decision tree analysis. The report, "Refracturing in the Bakken—An Updated Analysis of Data from 341 Wells Across North Dakota," was completed and uploaded to the BPOP members' website (Zhao and others, 2023). The results showed that refracs generally improved the production performance of the refractured well; however, refracs conducted on wells that were originally completed as openhole completions outperformed those performed on cased-hole wells. For example, the median incremental EURs for the openhole and cased-hole wells under the baseline scenario were 609 and 411 thousand stock tank barrels (Mstb), respectively. Refracs conducted on openhole wells also had greater uplift, higher oil rates, and lower postrefrac GORs than refracs conducted on cased-hole wells, all of which provides supporting evidence that well refracs conducted on openhole wells accessed previously undrained portions of the reservoir.

Bakken Geological Cluster Analysis Tool

An interactive Bakken geological cluster analysis tool was developed using a web-based tool. The tool allows users to divide the BPS into subareas (clusters) using three different clustering algorithms and publicly available geological, geochemical, oil and gas properties, and water chemistry data. The tool uses a GIS-based interface to select wells and includes descriptive

statistics and graphical results of the clustering algorithms to summarize the results. Users can explore different numbers of clusters and observe the feature importance and descriptive statistics for each cluster. The Bakken Geological Cluster Analysis Tool is available to BPOP members through the website under Product Type/Interactive Tools.

Well Completion Optimization

The well completion optimization analysis focused on four subareas (clusters) of the BPS previously identified by the geologic cluster analysis tool, which subdivided the BPS wells into groups using measurements of geological and geochemical variables, oil and gas properties, and water chemistry. Distinctive geological characteristics characterized the four clusters. For each cluster, a machine learning predictive model was built using the names of fields, operators, and service companies and the values of different completion parameters to predict 6-month cumulative oil production. The goal of running the completion optimization calculations for each cluster (i.e., four separate predictive models) was to minimize variations attributable to geologic heterogeneity, strengthen the predictive models, and overcome some of the overfitting challenges encountered in previous efforts. The calculations suggested that well completion parameters can be optimized within each cluster and that targeted production performance can be achieved using optimized completion practices. The predictive modeling calculated four different completion strategies in each cluster.

BPOP Analytics Well Completion & Production Dashboard

The BPOP Analytics Well Completion & Production Dashboard was developed to illustrate a real-time tool for analyzing production and completion data and calculating optimal completion parameters using machine learning. The tool uses a GIS interface to select wells and run various statistics and analyses for the selected wells, including scatter plots of well performance versus well completion parameters, bubble and heat maps to visualize well performance, a tool to calculate optimal completion design parameters using a gradient-boosting algorithm, and a well/information search utility. The BPOP Analytics Well Completion & Production Dashboard is available to BPOP members through the website under Product Type/Interactive Tools.

Bakken Core Area Expansion

A report, "A Data-Driven Analysis of Bakken Core Area Expansion and Implications for Future Development Potential," was developed. The work classified wells by their productivity, used the classifications to delineate the core area in the Bakken, and investigated recent core area development. In addition, the work identified key drivers for the recent Bakken core expansion and analyzed potential remaining development opportunities in the Bakken.

Parent–Child Well Interactions

A report entitled "Data-Driven Analysis of Parent–Child Interactions in the Bakken" was completed and is available on the BPOP members' website (Min and others, 2023). This study focused on the impact of parent–child well interactions on production in the Bakken. The primary goal of the study was to utilize machine learning-based approaches to characterize the causes of

production impacts from parent–child well interactions and evaluate combinations of well spacing and completion designs to maximize parent–child well production and minimize the risk of frac-hits. The study also investigated the impact of refracturing of the parent well on parent–child well interactions and strategies to reduce frac-hits and promote uniform fracture growth while stimulating child wells. To characterize the causes of production impacts from parent–child well interactions, five well design parameters were examined: 1) well spacing, 2) injected proppant in the child well, 3) injected proppant in the parent well, 4) time difference between parent and child well completions, and 5) cumulative oil production of the parent well.

3-Mile Lateral Study

Operators submitted plans to DMR for 3-mile lateral well development beginning in 2020–2021. The forecast for a 3-mile spacing unit versus a 2-mile spacing unit anticipates a 50% increase in production, for a 25% increase in capital investment. The benefits of which are less surface impact and a reduction in facilities for the same acreage potential. BPOP kicked off a study to understand the history of extended laterals and anticipate the impact to future Bakken development. The study described collective development plans, identified existing extended lateral completions, characterized the development history, analyzed well data, and provided case studies comparing 2-mile and 3-mile laterals. The study included 235 wells that could be identified as 3-mile laterals and was followed by an update in 2022 at the BPOP annual meeting to include a total of 275 wells. The earliest 3-mile lateral well was completed in 2009, with a larger number of wells completed between 2018–2019. Where past 3-mile development is primarily driven by geographic constraints, the new proposed developments include noncore areas and are driven by economic factors. Although the data set appeared significant, the study was complicated by differences in completion methods that do not allow a fair comparison of 2-mile to 3-mile lateral wells. Overcoming this challenge, eight case study areas were identified in which wells of similar completion methods could be compared. Detailed review and machine learning was utilized to analyze and determine results. The study reinforces that 50% uplift for 3-mile laterals compared to 2-mile laterals is achievable and supports the continued development for long-reach lateral wells in the Bakken.

Data Extraction from the NDIC Oil and Gas Database

A semiautomated method was developed for data extraction from the NDIC oil and gas database. Completion information for the wells stimulated in 2019–2022 was obtained from Form 6 (PDF files) using the Microsoft Azure application. The developed data extraction method can be used in various applications, including extraction of reservoir property information, chemistry of produced water, and other oil and gas data stored in forms. The 2019–2022 well completion information extracted from the Form 6 files will be used to update the underlying database for the BPOP Analytics Well Completion & Production Dashboard.

DSU Completion Optimization Calculations

The first goal of this effort was to improve the quality of the available data using an expanded and updated database of over 14,000 wells, encompassing a broader extent of the BPS. Secondly, well completion optimization evaluations on a DSU level were completed in five subareas of the

BPS that were defined in a previous EERC study to minimize variations attributable to geologic heterogeneity, thereby strengthening the predictive models. A report entitled "Data Quality Improvement and DSU Completion Optimization Calculations – Studies of Well Completion Optimization and Best Operational Practices of the Bakken Petroleum System" was completed and uploaded to the BPOP members' website (Chakhmakhchev and others, 2022).

Partnership and Financial Information

The NDIC Oil and Gas Research Council, a consortium of Bakken producers and service companies, and DOE sponsored BPOP 3.0. As presented in Table 1, the initially proposed budget for this program was $12,000,000, with NDIC providing 50% cost share.

As the program progressed, the EERC retained some existing and gained additional industry partners and secured an additional $718,016 of industry cost share to match BPOP 3.0. At the culmination of BPOP 3.0, the NDIC cost share was 47% and other participants equaled 53%.

The EERC would specifically like to thank the following companies and North Dakota state agencies for their partnership in BPOP 3.0.

- ConocoPhillips
- Devon Energy
- Liberty Resources LLC
- Marathon Oil
- North Dakota Industrial Commission
- Chord Energy (formerly known as Oasis)
- Oil and Gas Research Council
- Petro-Hunt LLC
- Hess Corporation
- Computer Modelling Group
- Rock Flow Dynamics
- XTO Energy (a subsidiary of ExxonMobil)

Please note that in addition to the funds presented below, the EERC received $200,000 more from industry; however, that $200,000 will be carried over to match specifically for the Liberty second injection cycle in BPOP 4.0, which could not be accomplished during BPOP 3.0.

Table 1 enumerates the evolution of the budget over the course of the program.

Table 1. BPOP – Budget Evolution

Sponsors	Original Budget*	Final Budget
NDIC Share – Cash	$6,000,000	$6,000,000
Industry Share – Cash**	$500,000	$1,620,000
Liberty – In-Kind	$4,000,000	$1,440,471
DOE – Cash	$1,500,000	$1,499,501
Oasis – In-Kind		$2,109,144
EOR ETC – In-kind		$20,400
CMG – In-kind		$28,500
Total	**$12,000,000**	**$12,718,016**
% NDIC Share	**50%**	**47%**
% Other Cost Share	**50%**	**53%**

* EERC Proposal 2016-0105.

** Total cash contributions from industry totaled $1,820,000; however, approximately $200,000 will be carried over to match BPOP 4.0.

Expenses to date by funding source are listed in Table 2.

Table 2. BPOP – Expenses to Date

Sponsors	Final Budget	Actual Expenses as of 8/15/2023*
NDIC Share – Cash	$6,000,000	$5,919,192
Industry Share – Cash	$1,620,000	$1,584,370
Liberty Resources – In-Kind	$1,440,471	$1,440,471
DOE – Cash	$1,499,501	$1,499,501
Chord Energy (Oasis) – In-Kind	$2,109,144	$2,109,144
EOR ETC – In-kind	$20,400	$20,400
CMG – In-kind	$28,500	$28,500
Total	**$12,718,016**	**$12,601,578**

* As of the date of this report, not all expenses have been posted. It is expected that all remaining funds will be spent by 8/31/2023.

CONCLUSION

BPOP represents a highly successful, award-winning collaboration between the state of North Dakota and the petroleum industry. The work performed within BPOP has achieved the stated goal of continuing to address emerging threats and issues to petroleum production in North Dakota. This premier partnership program has been cited as an exemplary model by others nationwide. It has demonstrated that state lawmakers, state regulators, and industry can work together for positive results for shareholders and taxpayers alike.

Industry and state stakeholders have expressed a desire to maximize productivity of wells and DSUs, increase the ultimate recovery of oil, and reduce the carbon intensity of Bakken

operations. Stakeholders are interested in optimizing primary production throughout the Bakken play, including Tier 2 and 3 acreages, determining how to best implement commercial-scale EOR using rich gas and/or CO_2, reducing flaring and fugitive methane emissions, mitigating well souring, and improving operational efficiencies. Technical advances that result from the proposed activities will not only serve to support the long-term productivity and economic vitality of Bakken assets but will also demonstrably reduce the carbon intensity of Bakken oil, thereby enhancing the ESG standing of operators.

At the time of this report, the state of North Dakota has opted to extend this successful program for an additional 2 years under the banner of BPOP 4.0. Devon Energy has provided a letter of support and intention to provide significant in-kind cost share focused on evaluating the potential for EOR in the Bakken using CO_2 captured from anthropogenic sources in the region, to support a goal of ultimately conducting a pilot EOR test using CO_2. Liberty Resources has committed significant in-kind cost share to conduct a second injection cycle as part of its EOR pilot at the East Nesson location. DOE has signed on as an anchoring partner, specifically providing funding to support the development and field testing of the Polar Bear technology. The EERC also anticipates ongoing support from current industry partners and continues to solicit additional, substantial partners interested in leveraging their corporate research power with this collaborative state–industry framework.

The goals of the next phase of BPOP are to provide that industry, and its state and federal partners, with science-based insight to improve Bakken efficiencies and maintain the long-term economic and environmental sustainability of the Bakken play in North Dakota. Through BPOP, the EERC will strive to provide stakeholders with the knowledge needed to plan and implement innovative development strategies to lead the Bakken, and North Dakota, into the next decade of economic growth.

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Bakken Production Optimization Program

EERC UNIVERSITY OF NORTH DAKOTA

APPENDIX A

LIST OF BAKKEN PRODUCTION OPTIMIZATION PROGRAM (BPOP) 3.0 PRODUCTS

LIST OF BAKKEN PRODUCTION OPTIMIZATION PROGRAM (BPOP) PRODUCTS

Product Type	Product	Date
Tool	BPOP Website	Ongoing
	Bakken Geological Cluster Analysis Tool	10/01/21
	BPOP Analytics Well Completion & Production Dashboard	9/21/22
	Carbon Intensity Tool	9/26/22
Reports	Quarterly Progress Reports	Many
	Bakken Production Optimization Program – 3.0 Final Report	8/31/23
Meetings	BPOP Annual Meeting	9/27/22
	BPOP Annual Meeting	September 27–28, 2022
Presentations to Oil & Gas Research Program (OGRP)	BPOP 2.0 Final Presentation	8/4/20
	The Annual BPOP Presentation	2/23/22
Manuscript	Report on the First Rich Gas EOR Cyclic Multiwell Huff N Puff Pilot in the Bakken Tight Oil Play	10/19/20
	Optimizing conformance control for gas injection EOR in unconventional reservoirs	5/11/22
	Data-Driven Analysis for Causality of Parent–Child Interactions in the Bakken	June 2023
Journal Articles	Comparison of CO_2 and Produced Gas Hydrocarbons to Dissolve and Mobilize Bakken Crude Oil at 10.3, 20.7, and 34.5 MPa and 110°C *Energy & Fuels*	8/25/20
	Turtles and Snakes: Evidence for Molecular Shape-Selective Migration of Crude Oil Hydrocarbons in the Bakken Petroleum System	6/21/21
	Optimization of operational strategies for rich gas enhanced oil recovery based on a pilot test in the Bakken tight oil reservoir	4/19/23
	Investigation of Souring Mechanisms in Williston Basin Bakken Production: Did the Source Rocks of the Bakken and Madison Formations Generate H_2S?	6/23/23
	Laboratory Simulations of H_2S Generation in the Bakken Petroleum System	6/13/23
Reports	A slide deck entitled “Tank Vapor Management”	4/30/21
	Using Cluster Analysis to Enhance Completion Optimization Studies of the Bakken Petroleum System	4/30/21
	2021 Bakken EOR Topical Report – Findings and Conclusions Derived from Several Bakken Enhanced Oil Recovery Studies	4/30/21
	Studies of Well Completion Optimization and Best Operational Practices of the Bakken Petroleum System	10/26/21

Continued . . .

Product Type	Product	Date
Reports	Efforts to Apply Machine Learning and Big Data Analytics Toward Enhanced Oil Recovery in the Bakken	1/31/22
	Data Quality Improvement and DSU Completion Optimization Calculations – Studies of Well Completion Optimization and Best Operational Practices of the Bakken Petroleum System	May 2022
	Fluid Fingerprinting in Reservoirs and Source Rocks Collected at the Study Well, Williston Basin, North Dakota	6/9/23
	Fluid Fingerprinting in Reservoirs and Source Rocks Collected at the Study Well, Williston Basin, North Dakota	2023
	Refracturing in the Bakken—An Updated Analysis of Data from 341 Wells Across North Dakota	6/9/23
	A Data-Driven, Machine Learning Analysis of Parent–Child Well Interactions in the Bakken	5/16/23
Presentations	Exploration of a Novel Avenue Toward Wellsite Gas Capture – Power Generation for Mobile Data Centers	7/7/2020
	Analysis of Central Production Facilities	7/23/2020
	3-mile Laterals	9/28/22
	New Bakken Data Analytics Interactive Tool	9/27/22
	Core Area Expansion and Potential Development Opportunity in the Bakken	9/27/22
	Data-Driven Analysis of Parent–Child Interactions in the Bakken	9/27/22
	EERC Bakken Research – Where We've Come from and Where We're Going	9/27/22
	Evaluation of H_2S Generation in Bakken Wells: Goals, Approaches, and Anticipated Results	9/28/22
	Refracturing in the Bakken – An Updated Analysis of Data from 303 Wells Across North Dakota	9/27/22
	The Future of BPOP	9/27/22
	Investigation of H_2S Presence in the Bakken Production	2022
Webinar Presentations	**Product**	**Date**
	Analysis of Central Production Facilities	7/23/20
	Exploration of a Novel Avenue Toward Wellsite Gas Capture – Power Generation for Mobile Data Centers	7/7/20
	Quantifying the Effect of Completion Parameters on Well and DSU [drill spacing unit] Production Using Multilevel Regression	8/27/20
	Predicting Oil Production Using Machine Learning	9/30/20
	Completion Design Optimization in Three Subareas of the Bakken Using Gradient Boosting	10/22/20
	Historical Production and Completion Trends	11/19/20
	Assigning Wells to Drill Spacing Units for Bakken Production Analysis	12/2/20
	Historical Production and Completion Trends	11/19/20

Continued . . .

Product Type	Product	Date
Webinar Presentations	Assigning Wells to Drill Spacing Units for Bakken Production Analysis	12/2/20
	Overview of Current Data Analytics Research Efforts and Discussion	12/17/20
	Exploration of a Novel Avenue Toward Wellsite Gas Capture – Power Generation for Mobile Data Centers	5/4/20
	Analysis of Central Production Facilities	7/23/20
	Overview of Bakken Production Analysis Activities	8/27/20
	Quantifying the Effect of Completion Parameters on Well and DSU Production Using Multilevel Regression	8/27/20
	Predicting Oil Production Using Machine Learning	9/30/20
	Completion Design Optimization in Three Subareas of the Bakken Petroleum System Using Gradient Boosting	10/22/20
	Bakken Historical Production and Completion Trends	11/19/20
	Overview for Assigning Bakken Wellbores to Drill Spacing Units	12/02/20
	Cyclic CO_2 Enhanced Oil Recovery in the Bakken Production System – Opportunities, Potential, and Challenges	8/31/21
	Investigation of Bakken 3-mile Laterals	11/16/21
	Liberty Resources East Nesson Pilot EOR Project Update	11/23/21
	Completion Design Evolution for Saltwater Disposal Injection Wells in the Bakken Play	12/14/21
	Well Completion Optimization	1/26/22
	Winning Operational Strategies of Bakken Operators	2/22/22
	Injection of Gas into Producing Wells to Reduce Flaring	6/15/22
	Prediction of Injection Flow Distribution Using Transient Multiphase Flow Simulation (Liberty EOR Project)	6/02/22
	Geochemical Evaluation of H_2S Generation in the BPS – the Results of the "Sulfur Speciation" Study Completed under the SERC Initiative	5/3/22
	Kickoff for H_2S Study	6/30/22
	Refracturing in the Bakken – An Updated Analysis of Data from 303 Wells Across North Dakota	7/19/22
	Refracturing in the Bakken – An Analysis of Data from Across North Dakota	6/20/22
	The Great COVID-Inspired Price Crash and Subsequent Production Shut-In: Impact on Bakken Oil Recovery	4/19/22
	Completion Optimization in the Bakken Petroleum System Using Data Mining	6/20/22
	Liberty Resources East Nesson Enhanced Oil Recovery Pilot Production Cycle	5/18/22
	East Nesson Bakken Enhanced Oil Recovery Pilot: Coinjection of Produced Gas and a Water/Surfactant Mixture	6/22/22

Continued . . .

Product Type	Product	Date
Webinar Presentations	An Analysis of Bakken Core Area Expansion and Implications for Future Development Potential	6/8/23
	DSU Completion Optimization in Five Areas of the BPS	6/28/23
	Bakken H_2S Study Update: Laboratory Simulations and Field Data	8/23/23
	Water and Oil Fingerprinting to Understand Bakken/Three Forks Communication in a Study Well	7/18/23
	Bakken H_2S Study Update: Laboratory Simulations and Field Data	8/24/23