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Estimating CO_2-EOR Potential and Co-sequestration Capacity in Ohio's Depleted Oil Fields

Srikanta Mishra*, Jared Hawkins, Taylor Hall Barclay and Meghan Harley

Battelle Memorial Institute, Columbus, Ohio, USA

Abstract

The goal of this project is to develop process understanding and evaluate technical and economic feasibility of CO_2 utilization and storage in Ohio. Our focus will be on depleted oil fields in the Clinton sandstone in eastern Ohio at depths ranging from 3400 to 5000 ft and the Knox dolomite in North-Central Ohio at depths ranging from 3000 to 8000 ft. These fields appear to be promising candidates for CO_2-assisted EOR because of poor primary recovery efficiency that leaves behind ~80-90% original oil in place. However, a systematic assessment of enhanced recovery and co-sequestration potential in these under-pressured low-permeability depleted oil fields does not appear to have been undertaken – which is the focus of this research project. This paper describes ongoing activities in the areas of source-sink matching, production history assessment, reservoir characterization and fluid property characterization, as well as plans for reservoir simulation.

Peer-review under responsibility of the Organizing Committee of GHGT-12

Keywords: CO2 utilization; CO2 geologic storage; depleted oil fields; Ohio; Appalachian basin; Clinton sandstone; Knox dolomite

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1. Introduction

Approximately 100 million metric tons of CO_2 are emitted annually by coal-fired power plants in Ohio [1]. Although considerable geologic storage potential has been identified for the sequestration of captured CO_2 emissions in deep saline formations, attention has recently shifted to the possibility of utilizing this CO_2 for

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* Corresponding author. Tel.:+1-614-424-5712.
E-mail address: mishras@battelle.org

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enhanced oil recovery (EOR) in depleted oil fields. This focus on the "utilization" part of carbon capture, utilization and storage (CCUS) is motivated by the value-added proposition of recovering incremental oil while co-sequestering significant amounts of CO_2 in the pore space voided during primary production operations. To that end, the objective of this project funded by the State of Ohio is to develop process understanding and evaluate technical and economic feasibility of CO_2 utilization and storage in Ohio.

This study builds upon preliminary assessments carried out by the Midwest Regional Carbon Sequestration Partnership (MRCSP) for CO_2 storage in depleted oil and gas fields deeper than 2500 feet, where the pressure is sufficiently high to keep CO_2 in a supercritical state [2]. The MRCSP estimates that such depleted oil and gas fields in Ohio have the theoretical potential to store approximately 3.4 billion metric tons of CO_2. These assessments of CO_2 sequestration potential have been undertaken using primarily a simple volumetrics-based screening type analysis that does not consider the full-scale displacement dynamics in an oil-CO_2-brine system.

The two main reservoirs that are potential targets for CO_2 utilization and storage in Ohio are the Clinton sandstone in eastern Ohio at depths ranging from 3400 to 5000 ft. and the Knox dolomite in North-Central Ohio at depths ranging from 2500 to 4500 ft. [3]. Approximately 400 million barrels of oil have been produced from those fields thus far on primary production. It is estimated that EOR can produce roughly an equivalent amount of additional oil via miscible CO_2 injection [4]. However, these assessments of CO_2 EOR potential have utilized either rule-of-thumb estimates, or simple screening type models without a detailed consideration of site-specific conditions.

This study seeks to develop a rigorous framework, thus far lacking, for fully evaluating the potential for CO_2-assisted EOR and geologic storage in Ohio's depleted oil fields. Our approach combines the CO_2 EOR assessment workflow from oil and gas industry with the CO_2 geologic sequestration assessment workflow from MRCSP and related projects to accomplish the study objectives. One outcome of this study will be the development of characterization and modeling protocols suitable for under-pressured and low-permeability reservoirs, as is the case with these depleted oil fields in Ohio, while ensuring that the best information available for the Clinton and the Knox reservoirs are incorporated into geologic characterization, reservoir modeling, and economic studies.

In the section presented below, we first describe the workflow that is being used in this study, followed by preliminary results in a variety of topical areas.

2. Assessment Workflow

The workflow for assessment of CO_2 EOR and co-sequestration potential includes the following elements:

- ***Source-sink matching:*** Characterizing potential stationary sources of CO_2 with respect to their location and size, and comparing that to the distribution of depleted oil fields and their theoretical storage potential.
- ***Production history assessment***: Selection of candidate fields for further study based on production history assessment to estimate: (a) CO_2 sequestration potential based on material balance linked voidage replacement calculations, and (b) CO_2-EOR potential based on screening model calculations using modified Claridge correlations [5].
- ***Reservoir characterization***: Development of geologic framework models for "reference" reservoirs in the Clinton and Knox formations – via integration of well-log, core analysis, seismic and fracture mapping data to create maps of formation thickness, porosity, permeability, connate water saturation and fracture patterns.
- ***Fluid property characterization***: Evaluation of empirical correlations for predicting oil, gas, water, and CO_2 properties characterizing the pressure-volume-temperature (PVT) relationships, e.g., formation volume factor, viscosity, compressibility, solubility, and CO_2-oil minimum miscibility pressure for crude oils representative of Ohio reservoirs.
- ***Reservoir simulation***: Reservoir simulation studies based on the geologic framework models to better understand field-scale areal and vertical sweep efficiencies for both continuous and water-alternating-gas CO_2-EOR processes. Key geologic/engineering factors considered include: reservoir rock and fluid characteristics, permeability heterogeneity, fracture intensity and connectivity, injection pressure conditions, well orientation, and pattern geometries.

- ***Economic analyses***: Assessment of CCUS related infrastructure needs for the oil fields of interest; compilation of information on capital and operating expenses representative of field conditions for CO_2-EOR projects in Ohio; and cost-benefit analysis for CCUS operations.

Preliminary results from the project by topical area are presented below.

3. CO_2 Emissions in Ohio

The lack of a local source of large quantities of pure CO_2 hampers its use for EOR in Ohio; but if CO_2 is captured in the future, then hypothetically this CO_2 could be transported to oil fields for EOR and co-sequestration. The United States Environmental Protection Agency Greenhouse Gas Reporting Program (GHGRP) collected greenhouse gas (GHG) data from large emitting facilities, suppliers of fossil fuels and industrial gases that result in GHG emissions when used, and facilities that inject carbon dioxide underground. The latest version of this database, as compiled in 2012, includes 7049 facilities across the USA [1]. The Ohio data were separated out from the national database for this task, resulting in 260 reporting facilities across the state. The GHGRP program collects more data than can be visually displayed and understood. In order to best evaluate the data, it was re-categorized and simplified. The 54 industry types were shortened to six overarching categories, while the quantity of CO_2 emissions was classified using the same numerical ranges as the NETL national study [6].

After simplifying the CO_2 emissions data for evaluation, the data set was mapped using ESRI's ArcGIS® software. The emitting facilities were color coded based on their industry classification, and the circle used to depict each facility is sized based on the categorized quantity of emissions. **Figure 1** shows pie charts that displays how each of the six re-categorized industry types contributes to the overall emissions in terms of number of facilities (left panel) and quantity of emissions (right panel). The dominant contributor is electricity generation, with 79% of the facilities and 55% of the total emissions. For 2012, Ohio's total CO_2 emissions from 260 stationary sources amounted to 126 million metric tons (MMT), of which the fossil fuel powered electric plants contribute 93 MMT, with coal fired power plants accounting for 83 MMT of this amount [1].

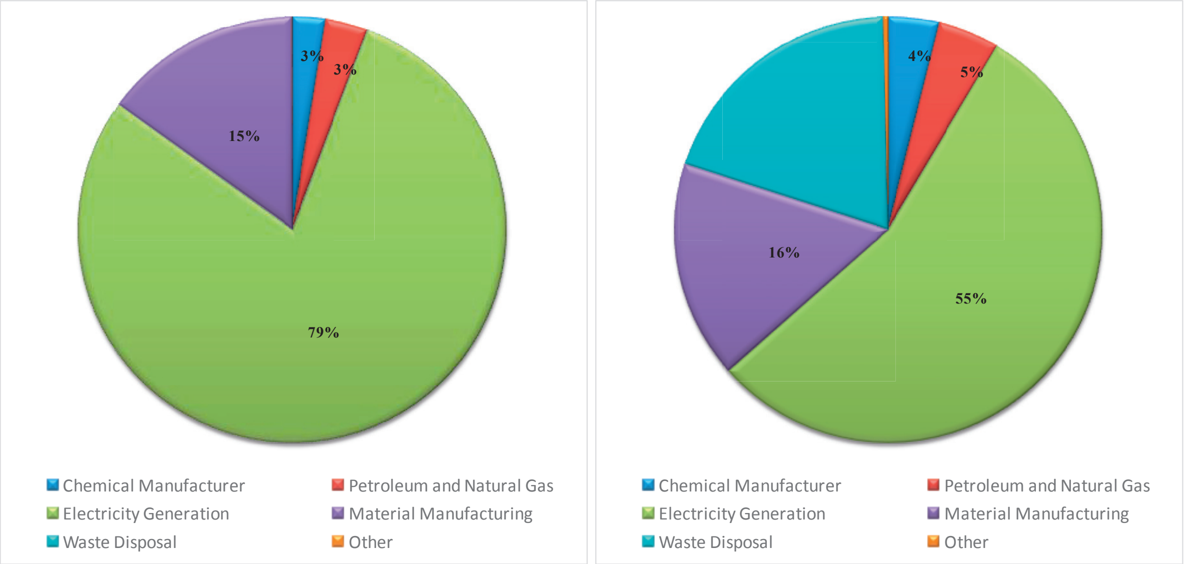

Figure 1. Contribution of different industry groups to Ohio's CO_2 emissions by number of facilities (left panel) and quantity of emissions (right panel).

Figure 2 maps the location of the 50 largest emitters (sources) juxtaposed with the location of the major depleted oil field in Ohio (sinks), as will be discussed in the next section. The colors identify the industry type, while the bubbles are sized according to the quantity emitted. This provides basic information as to geographic location of possible sinks as well as geographic location and size of possible sources. The next steps in data evaluation are to assess the likelihood of these emitters to exist in the future and evaluate the quality of the emissions for capture. For source-sink matching we will review which emitters have the best emissions to successfully be sequestered into a local oil field sink. Using this methodology of evaluation and mapping we can minimize the distance CO_2 is transported and determine the best sources prior to any construction or long term investments.

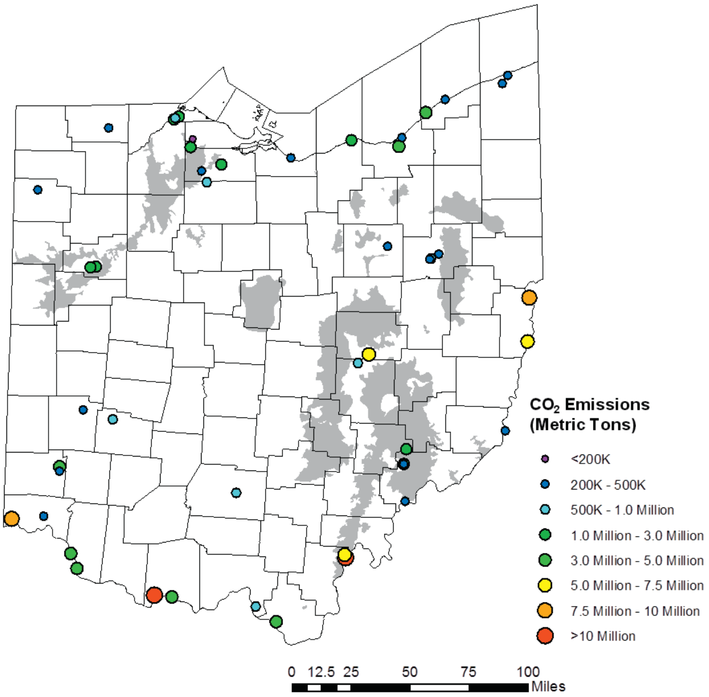

Figure 2. Location of the top 50 direct emitters of CO_2 in Ohio juxtaposed with the location of major depleted oil fields.

4. Production History Assessment

The production history assessment began with conducting an inventory of depleted oil fields in Ohio. The State of Ohio Geologic Survey of the Ohio Department of Natural Resources (ODNR) maintains oil and gas field, formation, and production data in two databases: the Tertiary Oil Recovery Information System (TORIS) database and the Production of Oil and Gas in Ohio (POGO) database. The TORIS database contains information collated by oil and gas field, including field size, reservoir information (e.g., average true vertical depth, net pay, average porosity, and initial and current temperature and pressure), and fluid information (including the formation value factor, API oil gravity, molecular weight of the C5+ fraction in the crude oil [$MWC5^+$], original oil in place [OOIP], field-wide cumulative production, and initial and current water, oil, and gas saturation). The Production of Oil and Gas in Ohio (POGO) Database (version 2.3), on the other hand, has monthly, yearly, and cumulative production of oil, gas, and brine water for over 80,000 wells throughout Ohio.

Figure 2 shows the locations for each of the 30 fields in the TORIS database. The majority of the fields are in the eastern half of the Ohio; however, two large fields are located in the northwestern corner of the state.

5. Selection of Candidate Fields for Detailed Modeling

An important consideration for enhanced oil recovery is whether a field is considered miscible, meaning the injected CO_2 is miscible with the oil in-place in the formation at the reservoir temperature and pressure. The highest efficiencies for CO_2-oil displacement are attained when CO_2 is miscible with the oil. The defining field characteristic that determines its miscibility (in additional to the oil composition) is true vertical depth (TVD), which affect the underlying reservoir pressure and temperature. Fields less than 1,800 ft. below ground surface (bgs) are considered technically infeasible because the reservoir pressure is generally lower than the minimum miscibility pressure, fields between 1,800 and 2,500 ft. bgs are considered immiscible, and fields greater than 2,500 ft. are considered miscible. **Figure 3** is a plot of minimum miscibility pressure and initial formation pressure over average TVD for each of the fields in the TORIS database. Of the 30 fields in the TORIS database, 16 fields had a TVD that placed them in the miscible range (**Figure 3**). These fields have been selected for further evaluation.

From these 16 fields, two were selected for initial analysis – the East Canton Consolidated oil field and the Morrow consolidated field. The former produces from the Clinton sandstone, the latter produces from the Trempleau, a Knox dolomite formation. Both fields have sufficiently high cumulative production, fall within the miscible range, and have sufficient coverage of oil and gas wells with available wireline logs. In addition, these fields were determined to be the best candidates for further study based on professional experience and judgment, which was informed by the size of the fields, the relative ease of working with the few oil companies that own the majority of wells in these fields, and the current limited evaluations of the potential for carbon capture storage and enhanced oil recovery.

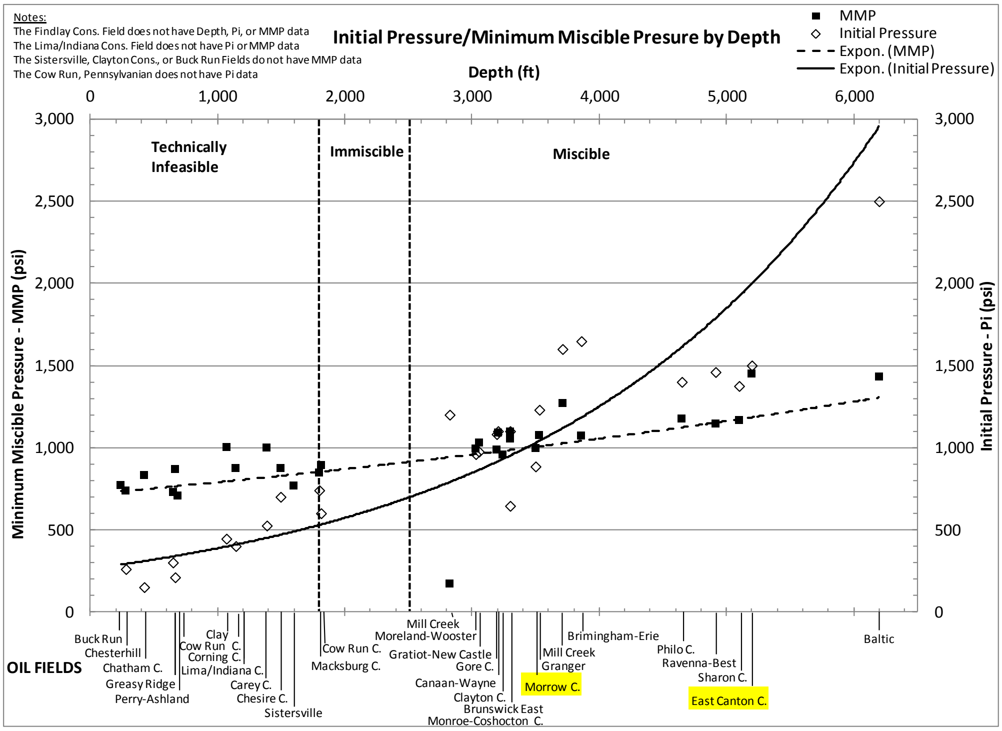

Figure 3. Initial pressure and minimum miscibility pressure of the 30 oil and gas fields included in the TORIS Database.

Next the POGO Database was used to determine the production of oil, gas, and brine water at each well for the two selected fields. Less than half of the wells included in the POGO database were assigned to a specific oil and gas field. Because over half of the wells had no field assigned, it was necessary to assign them by field footprint. To do this, shape files for the two selected fields were loaded into ArcMap® along with the spatial coordinates and API (American Petroleum Institute) numbers for all of the oil and gas wells in the POGO database. Wells were selected by footprint of each field using the "select by location" tool in the program. Selected wells were used to obtain production information for all wells in the entire field. The integrated field-wide production information from the TORIS and POGO databases is shown in **Table 1**. These field-wide data will be used to evaluate the potential for each formation to be used in carbon capture storage and enhanced oil recovery scenarios. **Figure 4** shows per-well production decline curves from the Morrow Consolidated and East Canton Consolidated oil fields. These plots show that the average well is rapidly approaching a nominal economic limit of ~50-100 STB/year [7]

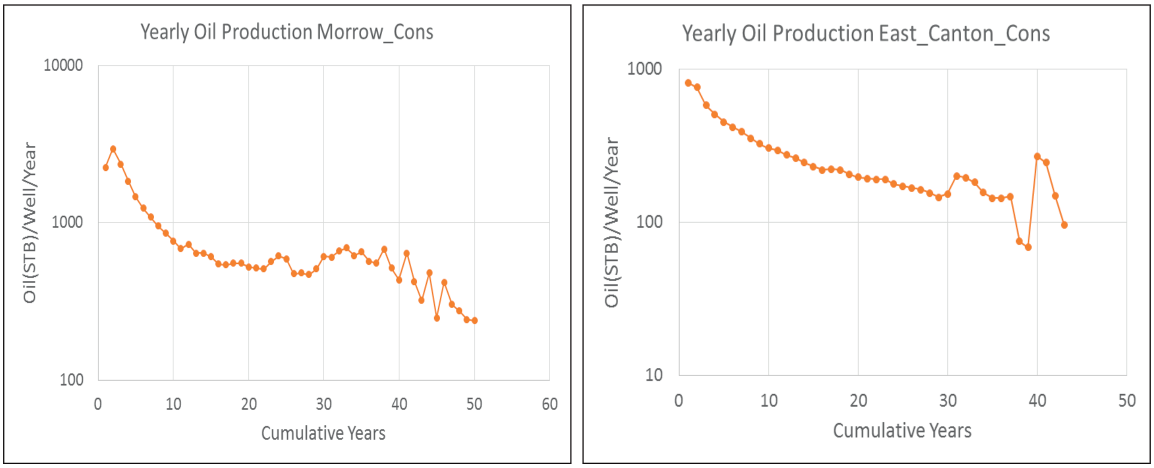

Figure 4. Per-well historical production decline trends from Morrow Consolidated field (left panel) and East Canton Consolidated oil field (right panel).

6. Reservoir Characterization

A subset of the 30 Ohio oil and gas fields in the TORIS database was selected for reservoir characterization based on the availability of data. Two databases were used for this effort. A database of all of the oil, gas, and injection wells drilled in Ohio was obtained from the ODNR Division of Oil and Gas: The Risk-Based Data Management System (RBDMS). The database includes, among other data subsets, information about well location, drilling and logging dates, and the types of logs available for up to 265,000 wells in Ohio. In addition, shape files for oil and gas fields within Ohio were obtained from the ODNR Division of Geologic Survey. The POGO database, described earlier was also used in this effort.

Maps showing wells drilled after January 1, 1985 (selected to filter out older, unusable logs) with triple combos and/or advanced logs were created to assist geologic characterization efforts in each oil and gas field. To do this, the RBDMS wells (with information about the drilling date and the types of logs available) and the ODNR oil and gas well shape files were loaded into ArcMap (ver. 10.1). After the wells were assigned to the fields, wells drilled to total depth by January 1, 1985 were selected. Of these wells, those with triple combo logs (gamma ray, resistivity and bulk density/neutron) were selected for further analysis. Wells with advanced logs (image logs, sonic logs, and nuclear magnetic resonance logs) were also noted on the resulting maps. Wells drilled to total depth before January 1, 1985 and wells without triple combo logs were shown on the maps as legacy wells. Maps showing the cumulative production from the POGO database at each of the selected wells were also created. **Figure 5** shows the spatial coverage of log information for the Morrow Consolidated field. Based on this information, a representative sub region for each field with good production history and good log coverage will be selected for detailed geologic characterization and reservoir modeling of CO_2 injection.

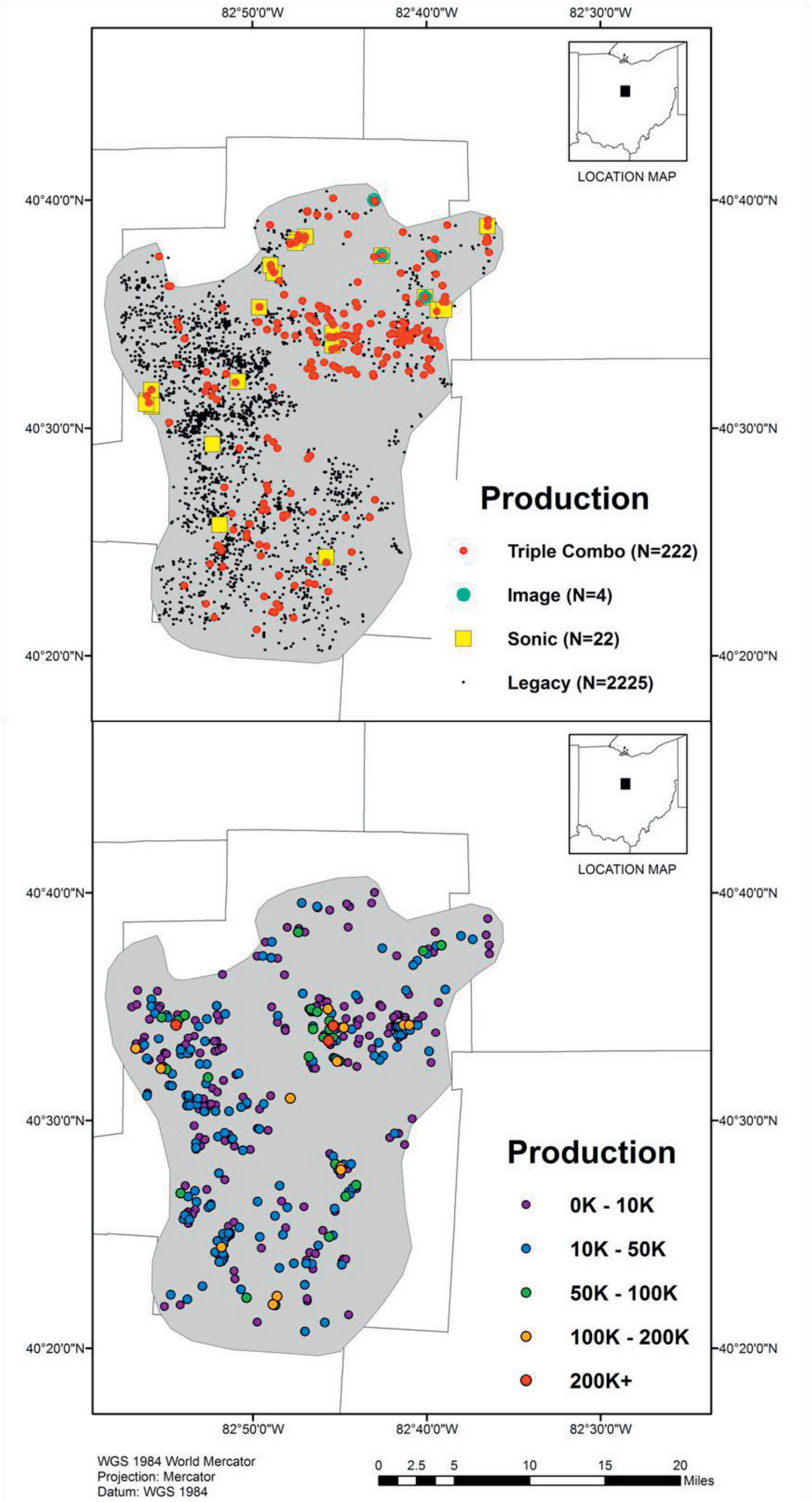

Figure 5. Spatial coverage of well-log data and corresponding production history for the Morrow Consolidated oilfield.

7. Fluid Property Characterization

Pressure-volume-temperature (PVT) relationships for crude oil–brine–CO_2 systems are essential for numerical modeling of CO_2 injection into depleted oil fields and saline aquifers, which require knowledge of formation volume factor, viscosity, gas solubility (or gas deviation factor), and isothermal compressibility. Often, these properties are not measured in the laboratory for a variety of reasons (the most important of which is cost), and have to be developed from empirical correlations. Several such correlations have been described in the petroleum literature and form the basis for this analysis [8].

Figure 6 shows examples of how these properties vary with pressure for a typical Ohio oil field containing light oil of 42 degree API gravity at 100 degree F. These correlations have been implemented in an Excel® spreadsheet to facilitate the rapid computation of fluid properties required as inputs to fluid flow simulators. We are also evaluating several correlations that characterize the mixing behavior between CO_2 and oil, i.e., CO_2 formation volume factor, viscosity and compressibility, oil swelling, and oil viscosity reduction [9].

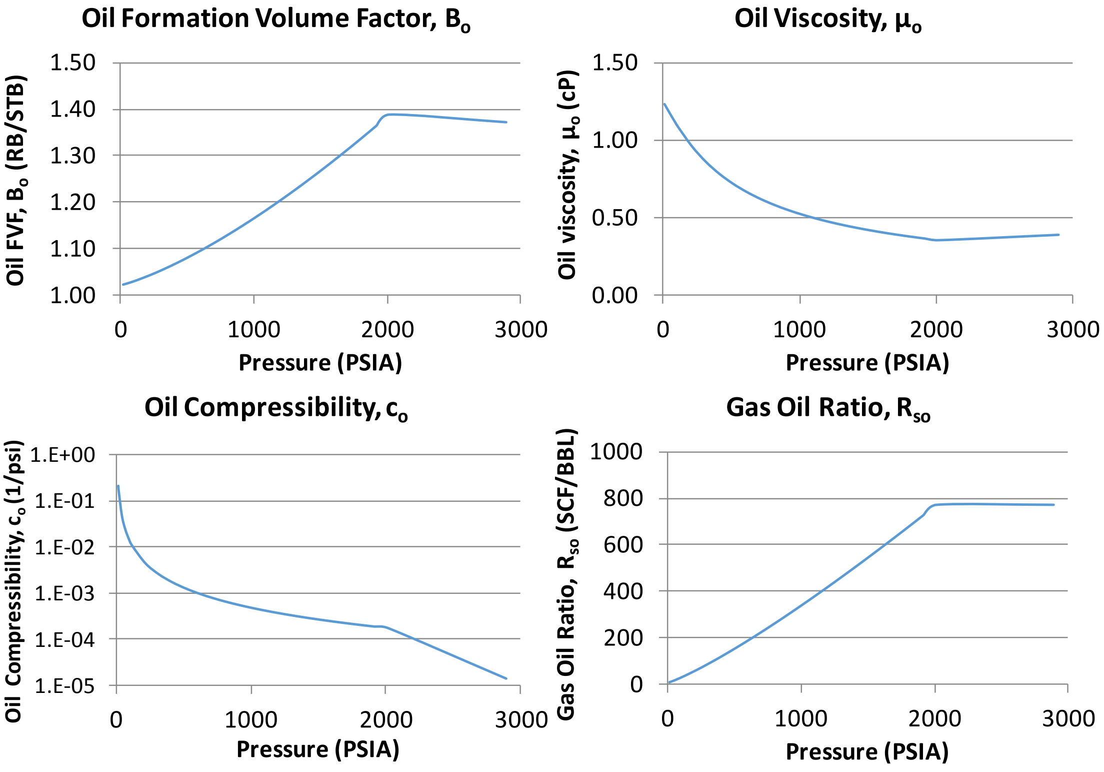

Figure 6. Example calculation of oil PVT properties using selected correlations

8. Reservoir Simulation

Simulations of CO_2-oil-brine interactions within a reservoir generally require a compositional simulator, where detailed information is required regarding oil characteristics. Typically, this compositional information is expressed using an Equation-of-State formalism, where a cubic equation state is used to describe the phase behavior between all of the components present in the system [10]. Often, such information is not available, and it may be useful to consider alternatives such as a pseudo-miscible model or a K-values based model – as described below.

In a pseudo-miscible model, the simulation of gas or solvent injection into an oil reservoir can be modeled by approximating the phase behavior with four components – oil, water, free/solution gas, and injection gas (solvent) - as described by Todd and Longstaff [11]. The effective component properties are calculated for either gas-solvent or oil-gas-solvent miscible phases. Injected solvents are assumed to be miscible with natural gas at all reservoir pressures. Above the minimum miscibility pressure, injected solvents are fully miscible with both reservoir oil and natural gas. Based on slim tube experiments (usually between 85 and 95 percent oil recovery), a transition zone is defined from immiscible to fully miscible conditions. Effective fluid densities and viscosities are calculated using the approach of Todd and Longstaff [11].

An alternative is a K-values based approach, where the K-value (equilibrium ratio between liquid and gas phases) is calculated from experimental data or correlations, and replaces the need for detailed equation of state based flash calculations [12]. Such an approach can also be a cost-effective alternative to a fully compositional model, as it does not require the specification of complete compositional information for the reservoir oil/gas system. We are currently evaluating various commercial and public domain reservoir simulators with respect to data needs, computational requirements and accuracy for modeling CO_2 injection into depleted oil fields.

9. Concluding Remarks

The goal of this project is to develop process understanding and evaluate technical and economic feasibility of CO_2 utilization and storage in Ohio. Our focus will be on depleted oil fields in the Clinton sandstone in eastern Ohio at depths ranging from 3400 to 5000 ft. and the Knox dolomite in North-Central Ohio at depths ranging from 3000 to 8000 ft. Depleted oil fields located within these formations appear to be promising candidates for CO_2-assisted EOR because of poor primary recovery efficiency that leaves behind ~80–90% original oil in place. A systematic assessment of enhanced recovery and co-sequestration potential in these under-pressurized low-permeability depleted oil fields is being carried out, which includes source –sink matching, production history assessment, reservoir characterization, fluid property correlations, and reservoir simulation. One project outcome will be the development of characterization and modeling protocols suitable for depleted oil fields in Ohio, which will assist geologic characterization, reservoir modeling, and economic studies.

The results of this study will be used to guide the selection of fields for carrying out CO_2 injectivity testing in individual wells to develop a better understanding on injectivity and in-situ CO_2-oil mixing characteristics. Development of the knowledge-base needed to support implementation of CCUS in Ohio will pave the way for commercialization of this technology, ultimately reduce greenhouse gas emissions from coal fired power plants in Ohio and allow additional production and revenue from Ohio’s oil fields.

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Table 1. Cumulative oil production, OOIP, and % oil Produced for the 30 fields of interest.
Data comes from the TORIS and POGO Database

Field	**Cumulative Oil Production (MMBbls)**	**OOIP (MMBbls)**	**% Oil Produced**
Baltic	0.94	98.9	<1%
Birmingham-Erie	1.40	2.85	49%
Brunswick East	0.41	5.71	7.2%
Buck Run	2.17	14.0	16%
Canaan-Wayne	5.80	56.2	10%
Carey Consolidated	30.0	87.0	34%
Chatham Consolidated	12.2	282	4.3%
Chesire Consolidated	5.10	179	2.8%
Chesterhill	4.26	21.4	20%
Clay	0.77	5.42	14%
Clayton Consolidated	13.0	197	6.6%
Corning Consolidated	3.60	61.1	5.9%
Cow Run Consolidated – Berea	0.42	3.23	13%
Cow Run Consolidated – Pennsylvania, Undiff	2.50	24.7	10%
East Canton Consolidated	86.5	1,537	5.6%
Findlay Consolidated	380	1,900	20%
Gore Consolidated*	33.5	413	8.1%
Granger	3.30	68.0	4.9%
Gratiot-Newcastle	33.5	575	5.8%
Greasy Ridge	0.37	3.13	12%
Lima/Indiana consolidated	485	1,213	40%
Macksburg Consolidated	5.70	54.7	10%
Mill Creek – Clinton	4.58	55.3	8.3%
Mill Creek – Oriskany	0.26	1.05	25%
Monroe-Coshocton Consolidated	21.8	232	9.4%
Moreland-Wooster	7.00	86.9	8.1%
Morrow Consolidated	37.7	177	21%
Perry-Ashland	2.50	11.2	22%
Philo Consolidated	17.9	326	5.5%
Ravenna-Best	13.1	958	1.4%
Sharon Consolidated	2.00	50.5	4.0%
Sistersville	16.6	150	11%

*Contains TORIS fields Bremen-New Lexington and Union-Furnace Consolidated. These were consolidated with the Gore Consolidated in 2004.