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Editorial

Forecasting CO_2 Sequestration with Enhanced Oil Recovery

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1. Introduction

Over the years, naturally occurring CO_2 has been used in many enhanced oil recovery (EOR) projects in the United States. There is opportunity to supplement and gradually replace scarce and regionally limited natural CO_2 sources with anthropogenic sources, giving incentive for operators to become involved in the storage of anthropogenic CO_2 within partially depleted reservoirs. Aside from the incremental produced oil revenues, incentives include a wider availability of anthropogenic sources in regions distant from natural CO_2 sources, and a reduction in emissions to meet regulatory requirements, tax incentives, and favorable public relations. The US Department of Energy through its Carbon Storage Program has sponsored several Regional Carbon Sequestration Partnerships (RCSPs) that have conducted field demonstrations for both EOR and saline aquifer storage. This Special Issue highlights some of the observations and lessons learned through one of these RCSP programs, that of the Southwest Regional Partnership on Carbon Sequestration (SWP). This Special Issue includes scientific output from the RCSP program on key topics related to CCUS including reservoir characterization, simulation, monitoring, verification and accounting (MVA), and risk assessment.

This Special Issue reports some of the work performed by the Southwest Regional Partnership on Carbon Sequestration (SWP) as part of the United States Department of Energy (DOE) National Energy Technology Laboratory (NETL) Regional Carbon Sequestration Partnerships (RCSPs) Phase III demonstration project. The ultimate goal of the RCSPs was to support the development of regional infrastructure for carbon capture and storage (CCS). The program had three phases: characterization (Phase I), validation (Phase II), and development (Phase III). The primary focus of Phase III was on large-scale field laboratories in saline formations and oil and gas fields, with a target of injecting at least 1 million metric tons (MMT) of CO_2 per project. For the SWP, the Phase III project's objective has been to characterize and evaluate an active commercial-scale carbon capture, utilization and storage (CCUS) operation, and demonstrate the associated effective site characterization, MVA, and risk assessment techniques. In sum, this project contributes to the development of future commercial CCUS projects in the United States by demonstrating all aspects of an actual commercial CCUS field operation, including effective reservoir engineering, characterization, monitoring, and simulation technologies.

In our introduction, we briefly describe Phase I and II findings, set the stage for our Phase III project, and summarize the papers included in this Special Issue.

2. Phase Summary

2.1. Phase I: Summary

The SWP commenced work on Phase I in 2003 [1]. The main objective of the SWP Phase I project was to evaluate and demonstrate the means for achieving an 18% reduction in carbon intensity by 2012. Many other goals were accomplished on the way to this objective, including (1) analysis of CO_2 storage options in the region, including characterization of storage capacities and transportation options, (2) analysis and summary of CO_2 sources,

(3) analysis and summary of CO_2 separation and capture technologies employed in the region, (4) evaluation and ranking of the most appropriate sequestration technologies for capture and storage of CO_2 in the Southwest region, (5) dissemination of existing regulatory/permitting requirements, and (6) assessing and initiating public knowledge and acceptance of possible sequestration approaches.

Results of the Southwest Partnership's Phase I evaluation suggested that the most convenient and practical "first opportunities" for sequestration would lie along existing CO_2 transportation networks in the region. From this study, six Phase II validation tests in the region were developed, with a portfolio that included four geologic pilot tests distributed among Utah, New Mexico, and Texas, along with a regional terrestrial sequestration pilot program focused on improved terrestrial monitoring, verification, and accounting (MVA) methods and reporting approaches specific for the Southwest region. Phase II also included a local-scale terrestrial sequestration pilot study using desalinated water from one of the pilot tests to restore.

2.2. Phase II Validation: Summary

The SWP carried out five field pilot tests in its Phase II Carbon Sequestration Demonstration effort [2]. Field-testing demonstrated the efficacy of proposed sequestration technologies to reduce or offset greenhouse gas emissions in the region. Risk MVA protocols and effective outreach and communication were additional critical goals of these field validation tests. The program included geologic pilot tests located in Utah, New Mexico, and Texas, and a region-wide terrestrial analysis. Each geologic sequestration test site was planned to be injected with a minimum of 75,000 tons/year CO_2, with a minimum injection duration of one year. These medium-scale validation tests were sited in sinks that have the capacity for possible larger-scale sequestration operations in the future. Tests demonstrated a broad variety of carbon sink targets and multiple value-added benefits, including the testing of enhanced oil recovery and sequestration, enhanced coalbed methane production, and a geologic sequestration test combined with a local terrestrial sequestration pilot.

2.3. Phase III Demonstration: Summary

In Phase III, the SWP's work was more closely focused on a single field laboratory sited in the Farnsworth Unit (FWU) Field, a mature active oilfield in Ochiltree County in the far northeastern Texas panhandle. The site operator began injection of anthropogenic CO_2 in the field in late 2010, starting with several five-spot well patterns with the intent to add several more each year, up to a total of 25. Planned net CO_2 injection at Farnsworth was 10 MMscf/D (million standard cubic feet per day), ~190,000 tons/year, not including recycled CO_2. The actual delivered volumes averaged slightly less, ~9.3 to 9.4 MMscf/D. The SWP began working at this site in 2013, establishing baselines for surface and subsurface metrics, drilling, logging, and coring three science wells, collecting a variety of 2D and 3D seismic data, and devising long-term monitoring protocols. The field operator allowed access to a wealth of legacy data and the SWP was able to evaluate surface and subsurface areas of the field with varying degrees of CO_2 exposure, from none to 22 months at project inception. The access to data and continued monitoring efforts have been maintained for almost nine years to date of this publication, providing an unprecedented look at an active commercial CCUS project. The ability to compare regions with and without CO_2 exposure provides an invaluable opportunity for the calibration of tools and techniques.

The injection target at FWU is the informally named Morrow B sandstone, a regionally important rock unit that has produced more than 100 million barrels of oil and 500 billion cubic feet of gas [3]. Several regional and local studies [3–6] provided excellent baseline information; however, few have been specifically concerned with using the sandstone as a target of CO_2-EOR or storage and none have had the rich and deep dataset afforded by this project.

3. Summary of Publications

This Special Issue presents work accomplished as part of the Phase III of the SWP project at the FWU field site. The work presented can, in some cases, be used as a guideline for what would need to be carried out for any successful CCUS project. Selected publications include those on site characterization, simulation, monitoring, verification, and accounting (MVA), and risk assessment. The project utilized the FWU as the study site and, unless noted, all papers relate to this area. The Special Issue also received an additional publication presenting aspects of CO_2 storage in Poland which was included as relevant.

3.1. Characterization

Cather et al. [7] present a geological description of the rocks comprising the reservoir that is a target for both oil production and CO_2 storage, as well as the overlying units that make up the primary and secondary seals. Core descriptions and petrographic analyses were used to determine depositional setting, general lithofacies, and a diagenetic sequence for reservoir and caprock at FWU. This paper synthesizes multiple studies conducted to determine the FWU capacity and suitability for long-term carbon storage. A rich dataset including core data and core descriptions, petrographic analyses, petrophysical and geomechanical data from the core, legacy logs from 149 wells, and a very complete suite of modern logs for three characterization wells, as well 2D and 3D seismic survey data, were all used in this effort.

Van Wijk et al. [8] report on the analyses of natural, geologic CO_2 migration paths in and near the FWU on the western flank of the Anadarko Basin. The paper interprets 2D and 3D seismic reflection datasets from the study site and compares seismic interpretations with results from a tracer study. The authors conclude that CO_2 escape in Farnsworth Field via geologic pathways such as tectonic faults is unlikely. Analysis of 2D legacy and 3D seismic datasets do reveal depth and thickness variations of the Morrow B reservoir rock; the interpretation is that they are related to erosional events and the creation of paleotopographic features that underlie the Morrow sandstone and are unlikely to be faults or fractures within the reservoir.

To assess the multiscale sealing integrity of the caprock system that overlies the Morrow B sandstone reservoir, Farnsworth Unit (FWU), Texas, USA, Trujillo et al. [9] combine pore-to-core observations, laboratory testing, well logging results, and noble gas analysis. A cluster analysis using many parameters defined lithologic classes within the upper Morrow shale and Thirteen Finger limestone caprock units, and geomechanical properties were calculated for each class. Several lines of evidence indicate that the overlying shale and limestone seal rocks have excellent sealing capacity with both strength and elasticity. The Morrow B sands are weaker than the overlying lithologies and any fracture initiation around the injection well would not be expected to propagate into the overlying sealing units. Noble gas analysis from fresh core shows that the caprock lithologies show no degree of leakage from historical water and CO_2 flooding in the FWU, whereas the Morrow B sandstone shows an impact from historical EOR activities.

Asante et al. [10] present probabilistic methods to estimate the quantity of CO_2 that can be stored in a mature oil reservoir and analyze the uncertainties associated with the estimation. The results of the estimation of the CO_2 storage capacity of the reservoir are presented with both an expectation curve and log probability plot. From the probabilistic output generated by both techniques, at least 7.68 MMtons can be stored, 17.79 MMtons of CO_2 can probably be stored, and it may be possible to store as much as 40.58 MMtons of CO_2 in the Morrow B reservoir. From the relative impact plot, the net thickness, storage efficiency factor, and area contributed about 95% to the total uncertainty for both techniques. Any further estimation of the storage capacity of the Morrow B reservoir should focus on reducing the uncertainty of these parameters.

3.2. Simulation

Relative permeability curves assumed for simulations can introduce a large source of uncertainty, significantly impacting forecasts of all aspects of the reservoir simulation, from CO_2 trapping efficiency and phase behavior to volumes of oil, water, and gas produced. Moodie et al. [11] evaluate the impacts on CO_2-EOR model forecasts of a wide range of relevant relative permeability curves, from the near linear to highly curved. Small variations in the shape of the relative permeability curve have a significant impact on the model forecasts; thus, selecting an appropriate relative permeability curve for the reservoir of interest is critical for CO_2-EOR model design. If measured laboratory relative permeability data are not available or limited for the study domain, the relative permeability curve should be considered a significant source of model uncertainty and accounted for as part of the simulation effort.

Sun et al. [12] present a hybrid numerical machine-learning workflow to solve various optimization problems. By coupling the expert machine-learning proxies with a global optimizer, the workflow successfully solves the history-matching and CO_2-water-alternative-gas (WAG) design problem with low computational overheads. The history-matching work considers the heterogeneities of multiphase relative characteristics, and the CO_2-WAG injection design takes multiple techno-economic objective functions into account. This work trained an expert response surface, a support vector machine, and a multilayer neural network as proxy models to effectively learn the high dimensional nonlinear data structure. The selection of the machine-learning algorithm may comprehensively consider the dimension of the problem and the demand of error margin. The RSM, SVM, and MLNN are suitable for different types of datasets and a wise choice of method could essentially enhance the prediction performance of the proxy model. The Pareto front optimum protocol provides an alternative way to address multiobjective optimization problems.

Kutsienyo et al. [13] assess the fate and impact of CO_2 injected into the Morrow B sandstone in the Farnsworth Unit (FWU) through numerical non-isothermal reactive transport modeling, and compare the performance of three major reactive solute transport simulators, TOUGHREACT, STOMP-EOR, and GEM, under the same input conditions. Model results show several broad similarities, such as the pattern of reservoir cooling caused by the injected fluids, a large initial pH drop followed by gradual pH neutralization, the long-term persistence of an immiscible CO_2 gas phase, the continuous dissolution of calcite, very small decreases in porosity, and the increasing importance over time of carbonate mineral CO_2 sequestration. The results of the study show the usefulness of numerical simulations in identifying broad patterns of behavior associated with CO_2 injection, but also point to significant uncertainties in the numerical values of many model output parameters.

3.3. MVA

Will et al. [14] present the current status of time-lapse seismic integration at the FWU. The efficacy of seismic time-lapse monitoring depends on a number of key factors which vary widely from one application to another. Most important among these are the thermophysical properties of the original fluid in place and the displacing fluid, followed by the petrophysical properties of the rock matrix, which together determine the effective elastic properties of the rock fluid system. They present a systematic analysis of fluid thermodynamics and the resulting thermophysical properties, petrophysics and rock frame elastic properties, and elastic property modeling through fluid substitution using data collected at FWU. The resulting fluid/rock physics models are applied to the output from the calibrated FWU compositional reservoir simulation model to forward model the time-lapse seismic response. Modeled results are compared with field time-lapse seismic measurements and strategies for numerical model feedback/updates are discussed.

Morgan et al. [15] analyze greenhouse gas (GHG) emissions related to FWU's EOR operations through a gate-to-gate life cycle assessment (LCA). The analysis yielded a net negative (positive storage) of 1.31×10^6 tonnes of CO_2 equivalent, representing 79% of purchased CO_2. An optimized 18-year forecasted analysis estimated 86% storage of the forecasted 3.21×10^6 tonnes of purchased CO_2 with an equivalent 2.90×10^6 tonnes of crude oil produced by 2038. The work presented provides a potential roadmap to others for performing these assessments and, in this case, indicates that the integration of CO_2-EOR and carbon storage is a valid approach to minimizing net GHG emissions.

3.4. Risk

Lee et al. [16] summarize the risk assessment and management workflow developed and used at the FWU. The SWP employed quantitative methods of risk analysis including the Response Surface Method (RSM), Polynomial Chaos Expansion (PCE), and National Risk Assessment Partnership (NRAP) toolset. Tools and workflows used provided useful methods of risk quantification. However, simulation processes (especially geological ones) inherently contain aleatory uncertainty. Thus, it would be most helpful to correctly define the ranges and distribution of uncertain parameters to significantly reduce the uncertainty.

Wei at al. [17] present a simplified model used to screen representative cases from many mineral reactive surface area (RSA) combinations to reduce computational cost. Three selected cases with low, mid, and high RSA values were used for the FWU model. Results suggest that the impact of RSA values on CO_2 mineral trapping is more complex than it is on individual reactions. The impact of mineral RSA values on CO_2 mineral trapping, on the whole, is more complex than it is on individual geochemical reactions. Additionally, the presence of hydrocarbons affects geochemical reactions and can lead to net CO_2 mineral trapping, whereas mineral dissolution is forecasted when hydrocarbons are removed from the system.

Xiao et al. [18] present a quantified risk assessment case study of the FWU that identifies water chemistry indicators for early leak detection and includes the use of response surface methodology (RSM) to quantify potential risks of CO_2 and brine leakage to the overlying USDW quality. Salient findings include: (1) with a leakage flux up to 0.4% of injected CO_2 and brine from a conceptual leaky well with failure, it is likely that the impacted area is limited to within 50 m from the well after 200 years; (2) toxic trace metals may be considered an insignificant long-term concern because of clay adsorption; (3) site-specific, no-impact thresholds could be a preferable reference for groundwater quality evaluations; and (4) pH is suggested as a likely geochemical indicator for early detection of a leakage, due to its easy testing and sensitivity aspects.

3.5. Other

Slota-Valim et al. [19] provide the first study of a Polish oil reservoir as a potential candidate for CCUS. Capacity and integrity were examined using numerical methods that combined geomechanical and reservoir fluid flow modelling with a standard two-way coupling procedure. The long-term simulations resulted in a comprehensive assessment of the total amount of CO_2 leakage as a function of time and the leaked CO_2 distribution within the caprock.

4. Conclusions

The storage of CO_2 as an incidental byproduct of EOR projects has been happening in the U.S. for almost fifty years with related research going back about a century. The first CO_2-EOR projects used exclusively anthropogenic CO_2, but as demand far outpaced anthropogenic sources in the Permian Basin, natural CO_2 became the dominant source of CO_2. With increasingly urgent demands to reduce GHG emissions, as well as new incentives offered by tax credits and incremental oil recovery, there is renewed interest in using depleted reservoirs for carbon storage. Carbon storage can be a bridge between a carbon-based energy economy and a renewable low-carbon energy economy. The experience and data collected from EOR projects are vital to the further development of a viable carbon storage industry. The body of work presented in this Special Issue provides a real-world example of the techniques and methodologies used to develop and execute a successful CCUS project.

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