Presentation Outline

• Introduction

• Technical Status
  – Characterization
  – Monitoring
  – MRV and Life-Cycle Analysis
  – Modeling
  – Outreach status

• Summary
  – Accomplishments
  – Lessons Learned
  – Synergy Opportunities
MRCSP Goals and Objectives

Primary goal: execute a large-scale CO₂ injection test to evaluate best practices and technologies required to implement carbon sequestration

Objectives: Advance operational, monitoring, and modeling techniques needed to:
- Develop infrastructure for wide-scale CO₂ sequestration deployment
- Address public concerns such as leakage and long-term storage security
- Address other topics such as cost effectiveness and CCUS practicability

Project updates and results can be found at www.mrcsp.org
Large-Scale Injection Test

Geologic Setting in Michigan’s Northern Niagaran Pinnacle Reef Trend
Injection Test Status Update

• ~1.1 MT tons CO\textsubscript{2} in net storage under MRCSP research
• >2 MT associated storage in 10 reefs over EOR lifetime since 1996

*Net-in-reef CO\textsubscript{2} stored represents difference between CO\textsubscript{2} injected and CO\textsubscript{2} recycled at 10 active EOR reefs.
Large-scale Injection Test

Key Reefs Vary in Setting and Operational History

Late-Stage Reef: Dover 33

1 Lobe
Operational since 1974
Primary Production + CO₂-EOR
MRCSP CO₂ Injection since 2013
1 CO₂ Injection Wells
2(+1) Monitoring/ Production Wells

Chester 16

2 Lobes
Operational since 1971
Primary Production + Water EOR
MRCSP CO₂ Injection since 2017
1 CO₂ Injection Well
1 Monitoring Well

Charlton 19

2 Lobes
Operational since 1988
Primary Production
MRCSP CO₂ Injection 2015-2017
1 CO₂ Injection Wells
2 Monitoring Wells
Currently in CO₂-EOR

Bagley

4 Lobes
Operational since 1973
Primary Production only
MRCSP CO₂ Injection only since 2015
3 CO₂ Injection Wells
4 Monitoring Wells
Characterization and Monitoring Program

- 10 reefs various stages of EOR
- All reefs monitored for CO₂ injection and reservoir pressure
- Additional monitoring on selected reefs
- Characterization (logs, cores, testing) in new wells

![Image of a map with various monitoring technologies indicated: VSP, Geochemistry, INSAR, Microseismic, Borehole, Gravity, PNC, DAS VSP, DTS, PNC.]

Legend:
- Reef Wells
- Piggyback Wells
- Wells with Core
- Reef Locations
- Existing Pipeline
- White Frost Pipeline
- Highways
- Secondary Roads

Supplemental monitoring:
- Basic monitoring
- PNC Geochemistry
- VSP Geochemistry
- INSAR
- Microseismic
- Borehole
- Gravity
- PNC

Well characterization data

Map of locations with various symbols indicating different monitoring techniques and locations.
Monitoring Objectives

- Operational accounting for CO$_2$ during EOR
- Monitoring options to track and image plume
- Ensuring containment effectiveness by monitoring CO$_2$ storage integrity and retention

Higher confidence in CO$_2$ migration pathways through project life

Examples presented
Borehole Gravity Monitoring

- Late Stage Reef
- Three surveys completed
  - Baseline – Pre-MRCSP CO₂ (Jan 2013)
  - First Repeat – 270K tonnes CO₂ (Sept 2016)
  - Second Repeat – 130K tonnes CO₂ (July 2018)
- 2016 data shows 90 µGal (0.05 g/cm³) increase at top of reservoir – consistent with the mass of CO₂ injected
- Processing of 2018 survey underway
New EOR Reef 1: Chester-16

Advanced Monitoring - Distributed Fiber Optic Systems

*Injection started in Jan 2017*
DTS Temperature Monitoring

- New Reef
- Temperature data recorded continuously with DTS
- Injection well and monitoring well
- Cooling in injection well indicates injection intervals.
- Cooling in monitoring well shows CO\(_2\) breakthrough

One of the first examples of CO\(_2\) breakthrough using temperature data
DTS Monitoring (cont’d)

*Warmback & Differential Temperature Analysis*

- “Warmback” analysis – how quickly formations warm back to reservoir temp after injection stops
- Differential temperature analysis – with some reference depth-temperature
- Identify perforated zones which received CO$_2$

Blue color (cooling) during shut-in periods provides more reliable indicator of which perf zones took CO$_2$
Dynamic Modeling of CO$_2$ Injection (Chester-16)

- Model successfully reproduced reservoir behavior during primary and waterflood production.
- Pressure response at monitoring well during CO$_2$ injection adequately replicated.
Using Model to Evaluate Alternate Engineering Solutions to Improve CO$_2$ Injectivity

- Increasing the number of perforations provides only marginal improvement
- Drilling radial “tunnels” is more effective; performs similar to a horizontal well

Radial Tunnels are small open boreholes drilled laterally from existing well
New EOR Reef 2: Bagley

*Pressure Data Analysis to Infer Complex Reef Hydraulic Properties*

- Reef with 3 to 4 partly connected lobes having multiple CO₂ injection and monitoring wells
- Suite of basic and advanced monitoring deployed
- Continuously monitored pressure data subjected to hydraulic interference analysis to estimate inter-lobe connectivity
Pressure Interference Analysis

- Evident hydraulic communication between multiple lobes in the reef
- Analysis of delay time and well spacing allows calculation of reservoir diffusivity and permeability

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Pressure in middle lobe injection well showing effect of injection in northern lobe
Geochemical Monitoring: Visualization of pore-scale CO₂ behavior

One XCT shows the formation of complex secondary mineralization within a rhombohedral-shaped vug (black) in dolomite (light gray groundmass).

“Early Dol” is primary rock matrix; “Late Dol” is secondary pore-filling mineral.

Black is pore space; granular and splinter materials are secondary minerals

Microanalysis of individual crystals with SEM (EDX) reveals sylvite (KCl), calcium chloride, anhydrite (CaSO₄), and barite (BaSO₄). In addition, a low-Mg-Ca carbonate is observed in SEM as a pore-filling material.
Monitoring, Reporting & Verification (MRV) Plan

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Draft MRV Plan (Subpart RR, EPA):

- Project Description
- Delineation of Active & Maximum Monitoring Area
- Evaluation of Leakage Pathways
- Monitoring Baselines
- EPA Mass Balance Equations
Life Cycle Assessment of CO$_2$-EOR

- Provide a data-based estimate of the net CO$_2$ emissions associated with CO$_2$-EOR
- Applies to Core Energy’s infrastructure
- Gate-to-gate direct & indirect CO$_2$ emissions
- Report expected in 2018
- Using PCOR approach as starting point
Improving Workflows for Reliable Geologic Modeling

- Robust integrated workflow to better characterize pore space
- Higher confidence in CO₂ storage estimates and potential migration pathways
Expanding Geologic Characterization to Entire NPRT

- Building off of individual reef characterizations to >800 reefs in NPRT
- Comprehensive database of reefs, wireline logs, core, production, etc.
- Develop reef types to better estimate resources and feasibility in the region

NPRT = Northern Pinnacle Reef Trend
Establish fundamentals for CO₂ storage within the ten-state region and to qualify what volumes, how and where

– Assess the potential reservoirs and seals in the region, including offshore
– Determine the type of storage (saline, EOR or EGR reservoirs)
– Quantify the potential storage resources
– Generate products essential for siting, performance modeling, MVA
Regional Characterization Task

- Establish fundamentals for CO$_2$ storage within the ten-state MRCSP region and to qualify what volumes, how and where
- Assess the potential reservoirs and seals in the region, including offshore
- Determine the type of storage (saline, EOR or EGR reservoirs)
- Quantify the potential storage resources
- Generate products essential for siting, performance modeling, MVA
MRCSP Outreach
Sharing Lessons Learned to Foster CCUS Development

Stakeholder Meetings

Conferences and Papers

www.mrcsp.org

Factsheets and BPMs

Message Mapping
MRCSP Outreach
FY2018 Highlights

- Highly attended MRCSP Annual Meeting in Washington DC
- Participated in major conferences and workshops
  - Mexico EOR Conference
  - AIChE Conf. on regional carbon storage resource assessment
  - Harrisburg Univ. of Science and Technology CCUS meeting
  - Joint IEA/KAPSARC meeting on CO₂ EOR
  - CO₂ GeoNet program workshops and Tech Savvy conference
  - 3rd International Workshop on Offshore Geologic CO₂ Storage
  - IEAGHG Modelling and Risk Management Network Meeting
  - SPE/AAPG Regional Meetings
- Provided input into Permitting and Standards
  - DOE/EPA UIC meeting about permitting under MRCSP and related projects.
  - International Standards Organization (ISO) meetings
  - SPE SRMS System and Guidance Document
MRCSP Outreach

Next steps

MRCSP 2018 Meeting and Offshore Workshop, Annapolis, Nov 14-15

• Complete monitoring, including DAS-VSP and DAS-cross well surveys
• Final report – document lessons learned
• Series of topical reports and papers
• Outreach summary for policy makers
• Information sharing meetings with stakeholders
• Develop an extensive bibliography of papers and materials
• Facilitate public access to technical and scientific information using DOE’s EDX and/or other tools
  – Phase II data already loaded on EDX
Accomplishments to Date

All Critical Milestones and Objectives On Track

- >1,100,000 metric tons net stored under MRCSP monitoring
- >2.4 M metric tons stored since start of EOR in 1996
- Completed injection at main test bed in late-stage reef
  - Performed microseismic monitoring in final injection stage
  - Post-injection PNC, microgravity, and VSP completed
  - Post-injection test well drilled and characterized
  - Returned to normal EOR operations, with continued accounting and pressure monitoring
- Added new EOR reefs with complex geology to monitoring
- Drilled new wells and initiated advanced fiber-optic monitoring
- Advancements in static and numeric modeling processes
- Developed performance metrics to assess storage capacity
Project Summary

- MRCSP Large-Scale Test >80% completed with diverse EOR field setting and variety of monitoring options
- Multiple monitoring options are being tested
- Both monitoring and modeling are essential for understanding performance – imperative to be able to do much with limited data
- Regional characterization helping identify new storage zones and estimate storage resources – setting stage for commercial scale CCS
- Results will contribute to developing standards and best practices, NRAP tools, CO₂ capacity estimation tools
Lessons Learned

- CO₂ measurement/accounting can be performed with high level of confidence in an inter-connected multi-field EOR complex.
- Storage potential in closed reservoirs evaluated, after active EOR ends – EOR to storage transition.
- Geologic complexity within and across reefs affects CO₂ injection, migration, and storage.
- Pressure monitoring remains the mainstay for managing injection operations and monitoring reservoir response.
- Advanced monitoring technologies still require testing/validation for confident assessment of plume development.
- Characterization-monitoring-modeling loop requires more research for cross-validation over the life-cycle.
- A well developed CO₂-EOR regulatory/policy framework with financial incentives essential for enhanced associated storage.
Synergy Opportunities

- Geomechanical Stress Assessment (FOA1829)
- CarbonSafe Phase I (Ohio, Michigan, Nebraska) and Phase II (Nebraska, Kansas) projects
- Mid-Atlantic Offshore storage assessment
- Well integrity and risk management
- Brine disposal and induced seismicity research
- Knowledge share with RCSPs on monitoring and modeling
- Testing NRAP models and CO₂ Screen tools
- Collaboration with international projects - South Africa, China, Mexico, Indonesia, Spain
- IEAGHG monitoring/Modeling Networks
- Input to DOE Best Practices Manuals
International Capacity Building – Extending MRCSP’s Value

MRCSP experience used in local capacity building in international CCS projects with multilateral funding
Acknowledgements

*Battelle’s MRCSP Current Contributors* – Mark Kelley, Srikanta Mishra, Matt Place, Lydia Cumming, Sanjay Mawalkar, Charlotte Sullivan, Priya Ravi Ganesh, Autumn Haagsma, Samin Raziperchikolaeae, Amber Conner, Glen Larsen, Joel Main, Jacob Markiewicz, Isis Fukai, Ashwin Pasumarti, Manoj Kumar Valluri, Andrew Burchwell, Jackie Gerst, Rod Osborne, and others

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Ohio Development Services Agency’s *Ohio Coal Development Office*

MRCSP’s technical *partners, sponsors, and host sites since 2003*

The MRCSP Region’s State *Geology Survey and University team members*
Partners over 15 years have helped make MRCSP successful
Appendix
Benefit to the Program

**MRCSP Approach/Benefit**

- Geologic characterization, reservoir assessment and models correlated with field monitoring combined with MRCSP regional mapping.
- Operational accounting for CO$_2$ during EOR
- Monitoring options to track and image plume, and monitor CO$_2$ storage and retention
- Test in EOR fields in various stages of their life cycle and examine effective strategies for utilizing the pore space created by the oil production
- Contribute to BPMs through large-scale test and regional analysis across MRCSP

**DOE Program Goal**

- Predict CO$_2$ storage capacity in geologic formations to within ±30%
- Demonstrate that 99% of CO$_2$ remains in the injection zones
- Improve reservoir storage efficiency while ensuring containment effectiveness
- Development of Best Practices Manuals (BPMs)
Project Overview

Goals and Objectives

• Describe the project goals and objectives in the Statement of Project Objectives.
  – How the project goals and objectives relate to the program goals and objectives.
  – Identify the success criteria for determining if a goal or objective has been met. These generally are discrete metrics to assess the progress of the project and used as decision points throughout the project.
MRCSP Basin Large-Scale Injection

- Objective – Inject/monitor 1 million metric tons of CO₂ in collaboration with EOR operations.
- Evaluate CO₂ injectivity, migration, containment
Project Overview
Goals and Objectives

RCSP Goal

Goal 1 – Prove Adequate Injectivity and Available Capacity

Goal 2 – Prove Storage Permanence

Goal 3 – Determine Aerial Extent of Plume and Potential Leakage Pathways

MRCSP Success Criteria

• Success measured by injecting 1 million tonnes of CO₂ in CO₂-EOR fields within permitted pressures
  • Pressure analysis and modeling used to evaluate and validate capacity

• Seismic and well data used to evaluate storage and containment zones
  • Monitoring wells used to measure containment over time within the reef and immediate caprock
  • Reservoir modeling to evaluate storage mechanism

• Monitoring portfolio employed to image and track the lateral and vertical plume migration. Success measured by using monitoring data to compare to and validate plume models
Project Overview
Goals and Objectives

RCSP Goal

Goal 4 – Develop Risk Assessment Strategies

Goal 5 – Develop Best Practices

Goal 6 – Engage in Public Outreach and Education

MRCSP Success Criteria

• Risk assessment for events, pathways, and mitigation planning
• Success will be measured by comparing predicted to actual field experience for all stages of the project

• Phase III builds on Phase II best practices in siting, risk management, modeling, monitoring, etc.
• Key emphasis is on operation and monitoring and scale-up to commercial-scale

• Extensive outreach efforts for both Phase II and Phase III sites as well as technology transfer and sharing
• Phase III lessons learned contribute directly to the RSCP Best Practice Manual updates
**MRCSP Scope of Work**

**Structured Around Six Six Tasks**

| Task 1 | Regional Characterization: Develop a detailed actionable picture of the region’s geologic CO₂ storage resource base |
| Task 2 | Outreach: Raise awareness of regional CO₂ storage opportunities and provide stakeholders with information about CO₂ storage |
| Task 3 | Field Laboratory Using Late-Stage EOR Field: Pressurize a depleted oil field with CO₂ injection to test monitoring technologies and demonstrate storage potential |
| Task 4 | CO₂ Storage Potential in Active EOR Fields: Monitor CO₂ Injection and recycling in active EOR operations with different scenarios |
| Task 5 | CO₂ Injection in New EOR Field(s): Monitor CO₂ injection into an oil field that has not undergone any CO₂ EOR to test monitoring technologies and demonstrate storage potential |
| Task 6 | Program Management |
Gantt Chart

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Legend:
- Approval of workplan before field work
- Approval of baseline geologic report before injection
- Industry Review at MRCSP Annual Meeting
- Task Reports
- Post-transfer monitoring
Recent and upcoming publications and presentations:


Recent presentations:


• Mawalkar, S., Kelley, M., Gupta, N., Place, M., Mansouri, M., Pardini, R., and Shroyer, B., 2017, Distributed Temperature Sensing (DTS) in a CO₂-EOR Complex, Poster Presented at Mastering the Subsurface through Technology, Innovation and Collaboration DOE NETL meeting, Pittsburgh, PA.

• Haagsma, et al., 2017, Regional Variability of Michigan Niagaran Reefs and the Impact on CO₂ Storage Resources, Poster Presented at Mastering the Subsurface through Technology, Innovation and Collaboration DOE NETL meeting, Pittsburgh, PA.

• Cumming, L., Place, M., Hare, J., Black, A., Gupta, N., Modroo, A., and Pardini, R., 2017, Field testing the applicability of borehole gravity for monitoring geologic storage of CO₂ within closed carbonate reef reservoirs, Poster Presented at Mastering the Subsurface through Technology, Innovation and Collaboration DOE NETL meeting, Pittsburgh, PA.

• Kelley, M., Miller, D., Modroo, A., and Gupta, N., 2017, Baseline DAS VSP of the Chester 16 field (reef), Michigan, Poster Presented at Mastering the Subsurface through Technology, Innovation and Collaboration DOE NETL meeting, Pittsburgh, PA.

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- Along with nine Poster Presentations accepted to be presented at the 14th International Conference on Greenhouse Gas Control Technologies (GHGT-14), Melbourne, Australia.
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