Midwest Regional Carbon Sequestration Partnership

DOE/NETL Cooperative Agreement # DE-FC26-0NT42589

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Mastering the Subsurface Through Technology Innovation and Collaboration: Carbon Storage and Oil and Natural Gas Technologies Review Meeting

August 16-18, 2016

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Outline

This presentation will provide a technical summary

- Project Overview
- Technical Status
  - Injection Test
  - Modeling
  - Monitoring
  - Regional Assessment
  - Outreach
- Accomplishments
- Synergy Opportunities
- Project Summary

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Benefit to the Program

MRCSP supports DOE Program Goals

DOE Program Goal	MRCSP Approach/Benefit
Predict CO_2 storage capacity in geologic formations to within ±30%	Correlate geologic characterization and reservoir models with monitoring and regional mapping.
Demonstrate that 99% of CO_2 remains in the injection zones	Account for CO_2 during EOR operations Assess monitoring options for tracking and imaging CO_2 plume, storage and retention
Improve reservoir storage efficiency while ensuring containment effectiveness	Test in EOR fields in various life cycle stages and examine strategies for utilizing the pore space created by the oil and water production
Development of Best Practices Manuals (BPMs)	Contribute to BPMs through large-scale test and regional analysis across MRCSP

Project Overview

Michigan Basin Large-Scale Test Goals and Objectives

RCSP Goal	MRCSP Approach and Success Criteria
***Goal 1** – Prove Adequate Injectivity and Available Capacity*	• Injecting 1 million metric tons of CO_2 in CO_2-EOR fields within permitted reservoir pressures • Pressure analysis and modeling used to evaluate capacity
***Goal 2** – Prove Storage Permenence*	• Site selection to include impermeable caprock, geologic structure • Seismic and well data used to evaluate storage mechanisms and containment • Monitoring wells used to measure containment over time within the reef and immediate caprock
***Goal 3** – Determine Aerial Extent of Plume and Potential Leakage Pathways*	• Monitoring portfolio employed to understand migration • Using monitoring data to compare to and validate plume models

Project Overview

Michigan Basin Large-Scale Test Goals and Objectives

RCSP Goal	MRCSP Approach and Success Criteria
Goal 4 *– Develop Risk Assessment Strategies*	• Risk assessment for events, pathways, and mitigation planning • Comparing predicted to actual field experience for all stages of the project
Goal 5 *– Develop Best Practices*	• 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
Goal 6 *– Engage in Public Outreach and Education*	• Appropriate outreach efforts for both Phase II and Phase III sites as well as technology transfer and information sharing with stakeholders

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Project Overview

MRCSP scope of work is structured around six tasks

Task 1	Regional Characterization: Develop a detailed actionable picture of the region's geologic sequestration resource base
Task 2	Outreach: Raise awareness of regional sequestration opportunities and provide stakeholders with information about CO_2 storage
Task 3	Field Laboratory Using Depleted EOR Field: Pressurize a late-stage EOR field with CO_2 injection to test monitoring technologies and demonstrate storage potential
Task 4	CO_2 Storage Potential in Active EOR Fields: Monitor CO_2 Injection and recycling in active EOR operations with different scenarios
Task 5	CO_2 Injection in New EOR Field(s): Monitor CO_2 injection into an oil field that has not undergone any CO_2 EOR to test monitoring technologies and demonstrate storage potential
Task 6	Program Management

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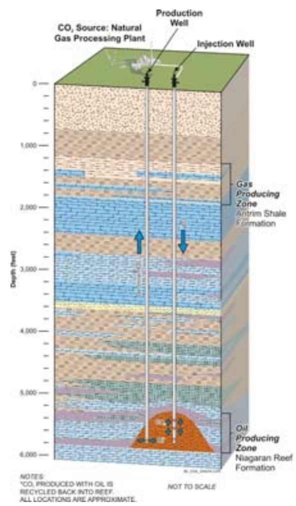
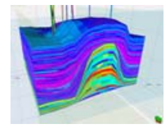
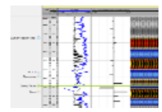
Technical Status

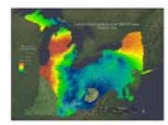
Technical updates grouped into five categories

1. Injection Test
2. Modeling
3. Monitoring
4. Regional Characterization
5. Outreach









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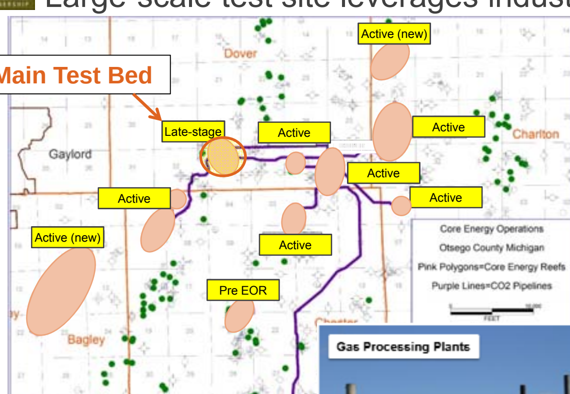
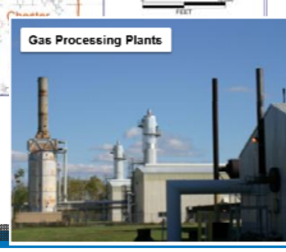
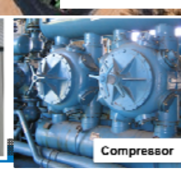
Injection Test Status – EOR Life-Cycle

Large-scale test site leverages industrial EOR operations







Natural gas processing is the source of **the CO_2** →

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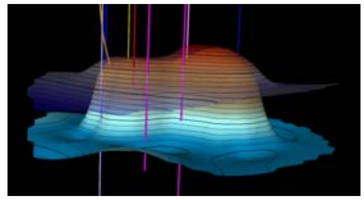
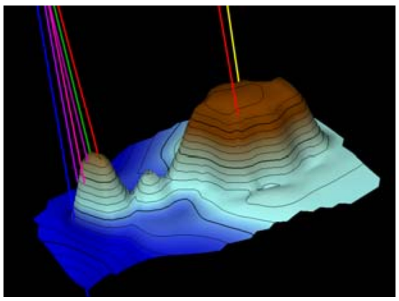
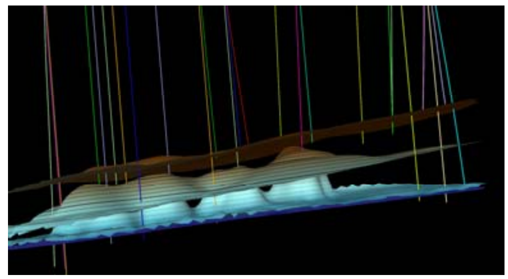
Variations in reef characteristics

- # of compartments, compartmentalization
- Lithology – dolomite vs limestone, Anhydrite
- Availability of core, seismic, well log data
- Presence of salt plugging







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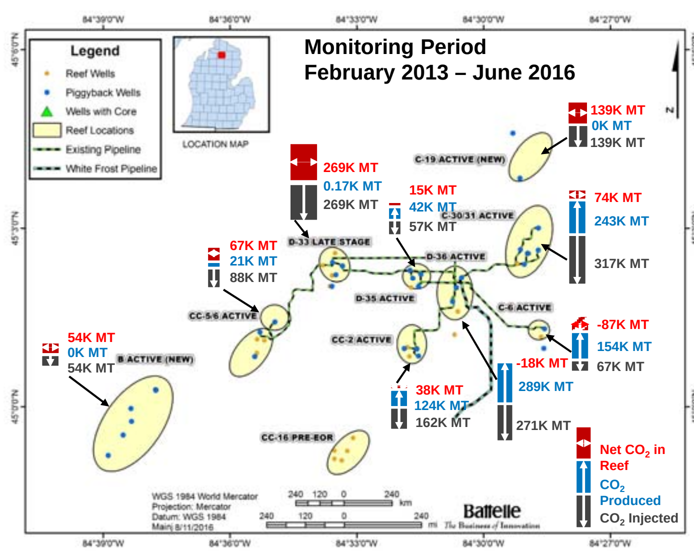
Injection Test Status – Accounting for CO_2

- Nine reefs in Northern Michigan [Otsego County]
- All in various stages of EOR
- ~570K MT net injection in nine reefs during monitoring period (Feb. '13 – July '16)
- EOR still ongoing, with a new reef (CC-16) being added



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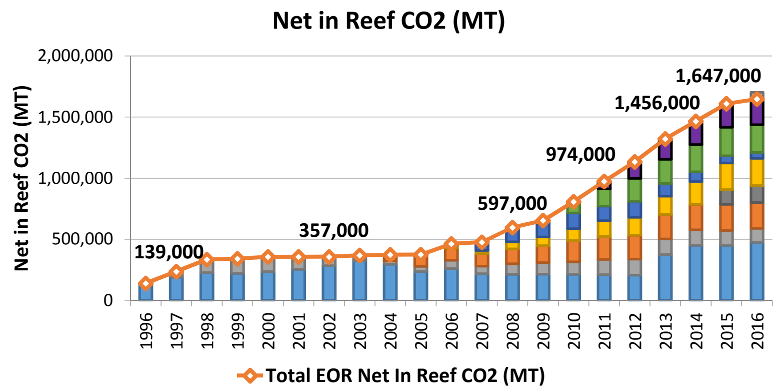
Injection Test Status – Cumulative Storage

Accounting – Incidental storage over EOR lifetime

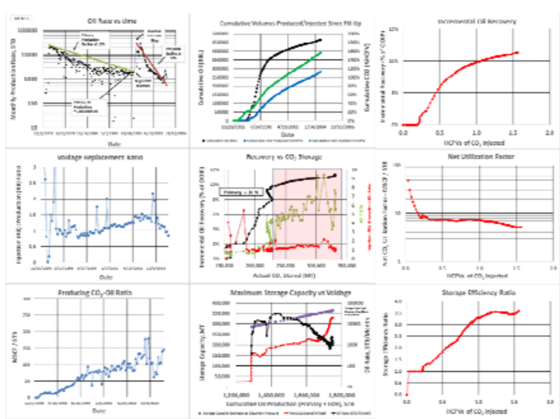


- >1.6 million metric tons of CO_2 stored over the 20 Years lifetime of EOR operations with 77% since new operator took over in 2005

Injection Test – Performance Metrics

A Dashboard to Manage Storage and EOR

Dashboard Panel for late stage reef



- 9-panel dashboard of key metrics used to track performance
- Understanding of CO_2-flood maturity, EOR and storage performance trends, and storage capacity
- Example: Beyond 80% by HCPV of CO_2 injection, incremental oil recovery began plateauing and reef entered the late stages of EOR

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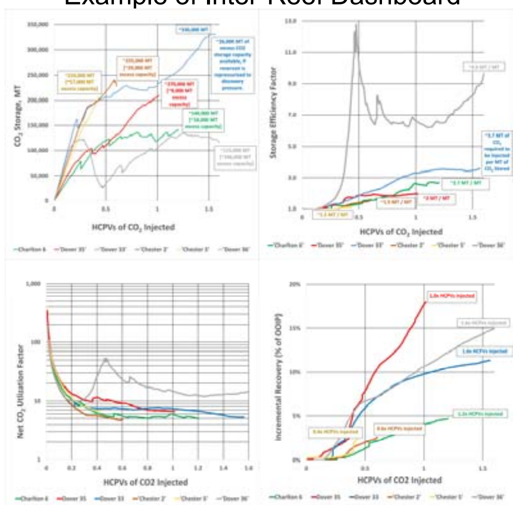
Injection Test – Performance Metrics

Comparison Across Fields

- 4-panel dashboard used to compare storage and recovery performance across all reefs
- Normalized to %HCPV (hydrocarbon pore volume) injected
- After CO_2-EOR, around ~45% of oil still remains unrecovered in the reservoirs
- D-35 is the best performing reef by oil recovery performance, and likely will have most incidental CO_2-storage at the end of CO_2-EOR

Example of Inter-Reef Dashboard



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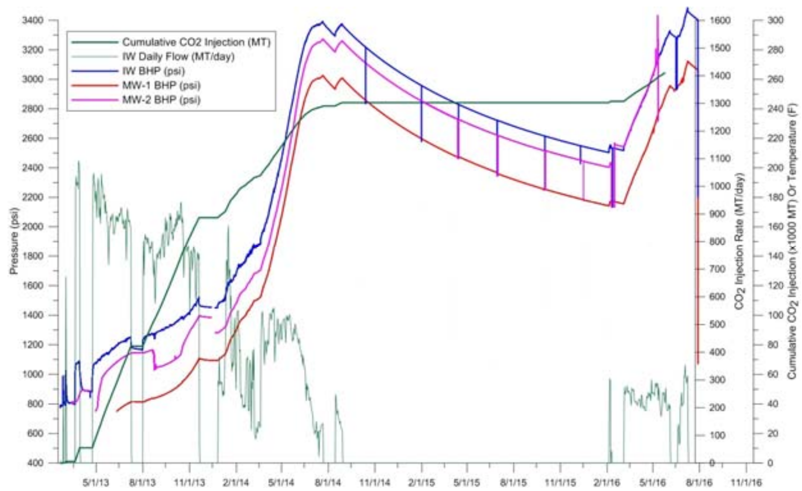
Injection Test – Storage Capacity Limits

Pressure response in Late-Stage during injection



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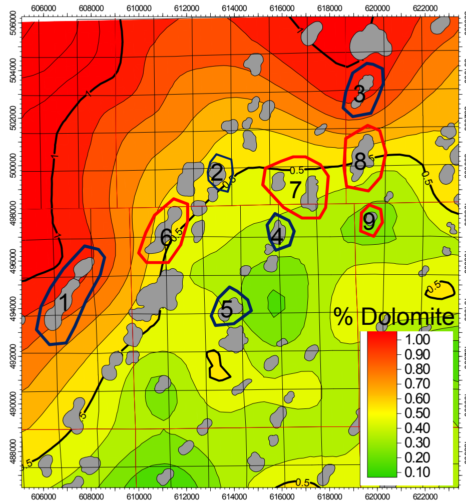
MRCSP

Geologic Modeling - Static Earth Models

Characterization of Diverse Michigan Niagaran Reefs

- Niagaran reefs effectively used for EOR
- Diverse geology of reefs makes characterization and SEMs challenging
- Key issues include:
  - Limestone vs dolomite
  - Salt plugging
  - Multi-pods
  - Diagenesis
  - Data availability
  - Geologic heterogeneity



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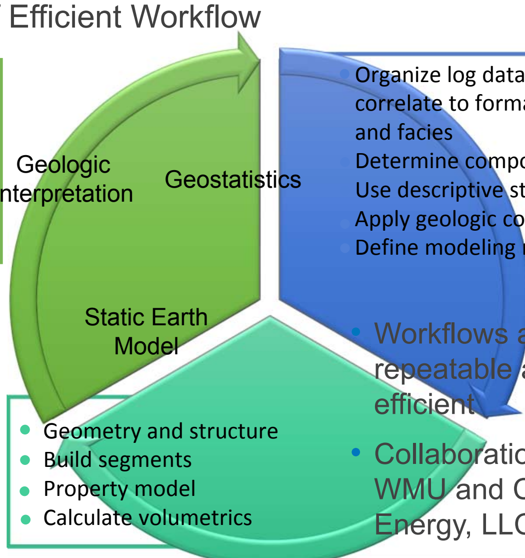
MRCSP

Geologic Modeling - Static Earth Models

Development of Efficient Workflow

- Formations and facies
- Define zones
- Calculate petrophysical properties
- Analyze whole core
- Depositional model



- Organize log data and correlate to formations and facies
- Determine components
- Use descriptive statistics
- Apply geologic concepts
- Define modeling rules

- Geometry and structure
- Build segments
- Property model
- Calculate volumetrics

- Developed approach to integrate data and to simplify SEMs

- Workflows are repeatable and efficient
- Collaboration with WMU and Core Energy, LLC

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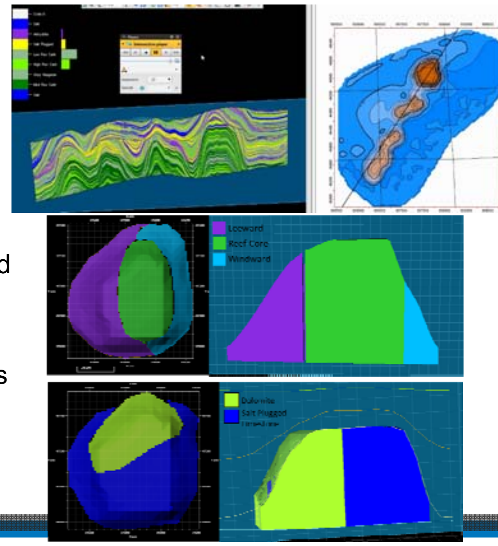
Geologic Modeling - Static Earth Models

New Insights into Michigan Niagaran Reefs

- Salt plugging can be extensive and traceable
- Definition of reef geometry with 3D seismic is critical
- Geostatistics can assist with modeling decisions and be used to predict electrofacies
- Increased dolomitization often leads to better quality reservoirs



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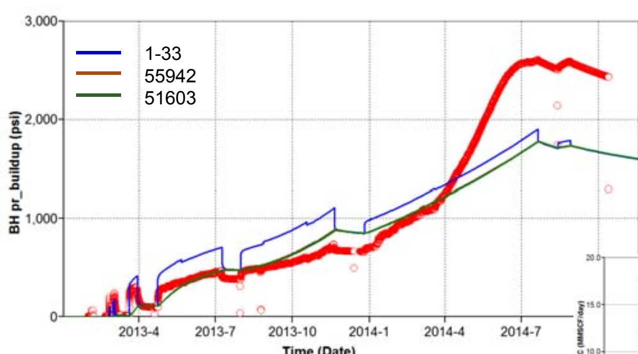
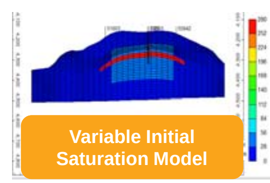
Dynamic Modeling - Injection Response Validation

Equivalent Homogeneous Compositional Reservoir Model





Injection Schedule

- Reasonable match except near the end of injection
- Further model calibration is in progress

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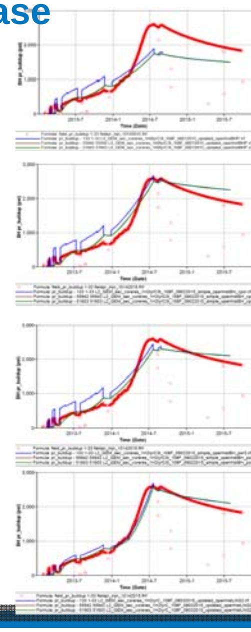
Dynamic Modeling - Injection Phase Pressure Buildup

Scenarios to explain pressure response

- Tighter Rock:
  - Lower rock compressibility
  - Tighter (i.e. less permeable flanks)
- Smaller pore volume for HC fluids-in-place and CO_2:
  - Lower model pore volume
  - Higher water saturation outside the core reservoir in the flanks
  - Amount of CO_2 present in the system



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Dynamic Modeling – Fundamental Approaches

Using Synthetic Models

- Use numerical model representing typical depleted reef reservoir with simulated primary production followed by CO_2 injection (but no production)
- Create synthetic datasets for analyzing pressure fall-off response and injectivity at injection well:
  - Pressure falloff data ⇨ Horner analysis to estimate reservoir properties and identify boundaries
  - Injectivity index (injection rate normalized by pressure buildup) ⇨ commonly-used oil-field metric of well performance
- [Q] What to expect in a multiphase environment?

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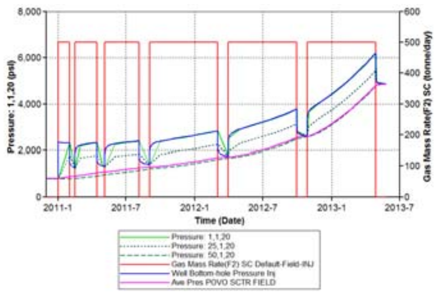
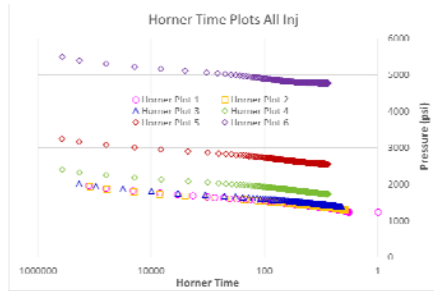
Dynamic Modeling - Synthetic Models

Fall-off Pressure Response



- Upward shift in time-lapse Horner plots confirms evidence of boundary effects



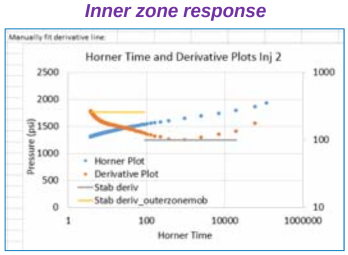
- Pressurization in closed reservoir evident in falloffs after injection periods 4-6

[Q] Does CO_2 injection into an oil-gas system create a multi-bank (composite) system with different near-field and far-field characteristics?

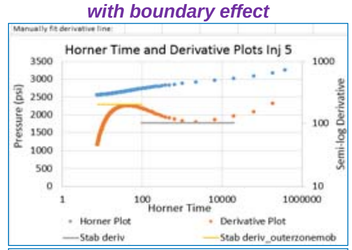
Dynamic Modeling - Synthetic Models

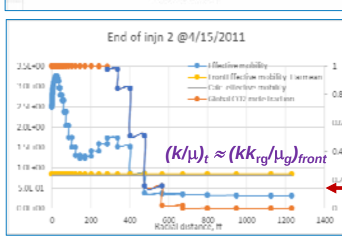
Pressure Derivative Analysis

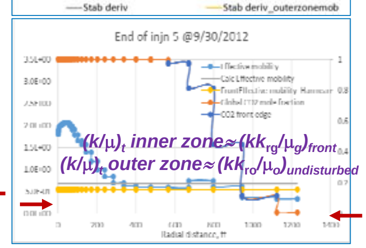
Inner zone response



Inner and outer zone responses with boundary effect



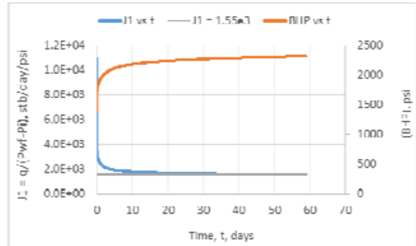


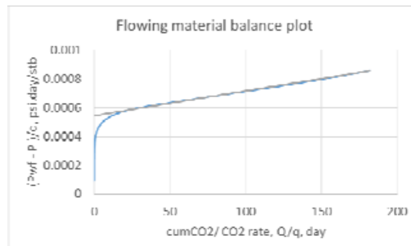


Dynamic Modeling - Synthetic Model

Injectivity Index for Well Performance:

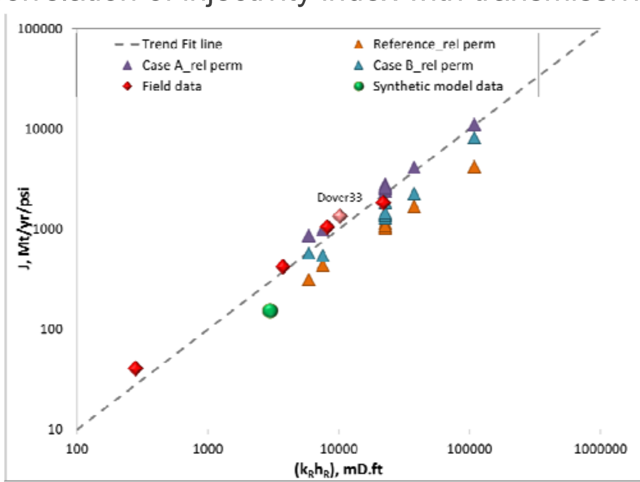
- [J] = Ratio of injection rate [q] to pressure buildup [P_{wf}-P_i]
- Useful metric for comparing well performance over time or comparing formations
- Transient period ⇨ plot of [J] versus [time] shows stabilization
- Pseudo-steady-state period ⇨ plot of [1/J] versus [Q/q]:
  - Intercept ⇨ 1/J
  - Slope ⇨ 1/($V_p c_t$)





Dynamic Modeling - Injectivity Index

MRCSP and other field and model data show correlation of injectivity index with transmissivity



Modeling Status: Synthetic modeling

Key Points

- Inner zone total mobility (permeability divided by viscosity) related to gas-phase mobility in the vicinity of CO_2 front
- Outer zone total mobility related to oil-phase mobility in the undisturbed reservoir
- Cannot determine absolute permeability from mobility, due to unknown multiphase viscosity
- Injectivity index behavior during transient and boundary dominated periods different
- Empirical correlation found between injectivity and permeability-thickness product (helpful for screening analysis and quick-look estimation of absolute permeability)

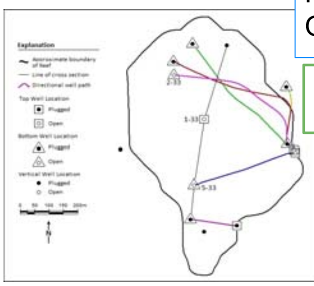
Monitoring Status – Late Stage Reef

Currently in After Injection Monitoring Stage

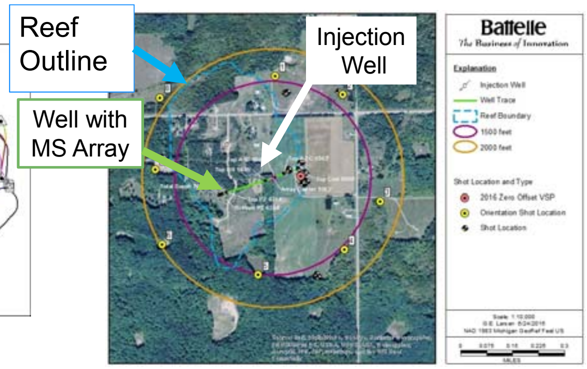
Activity	Before Injection	Early Injection	Mid Injection	Late Injection	After Injection
CO_2 flow accounting		X	X	X	X
Pressure and temperature		X	X	X	X
PNC logging	X		X		Aug 2016
Borehole gravity	X				Aug 2016
Fluid sampling	X		X		X
Vertical seismic profile	X				Sep 2016
Microseismic	X			X	
InSAR (Satellite radar)	X	X	X	Complete	
Characterization Well Drilling					Sep 2016

Monitoring – Microseismic

Microseismic performed during final injection at Late-Stage Reef above discovery pressure



Well Map

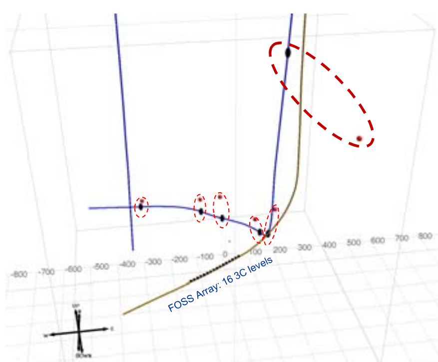


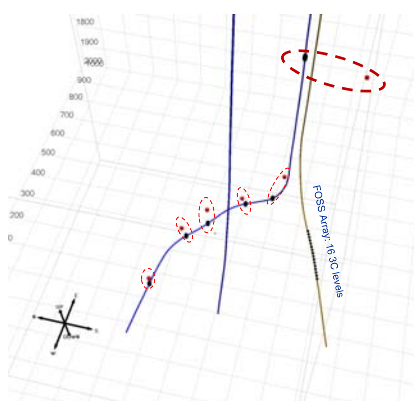
Monitoring performed by Paulsson Geophysical, Inc.

Monitoring Status

String shots in off-set well used to “calibrate” microseismic

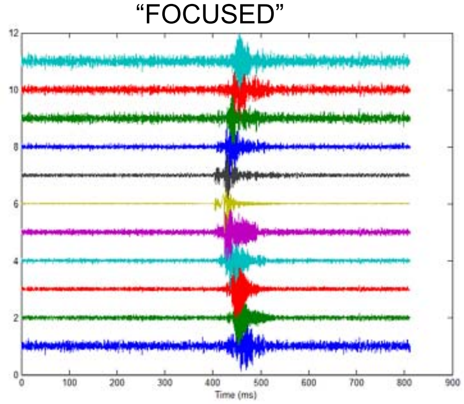
- 5 of 6 string shots located with “good” accuracy

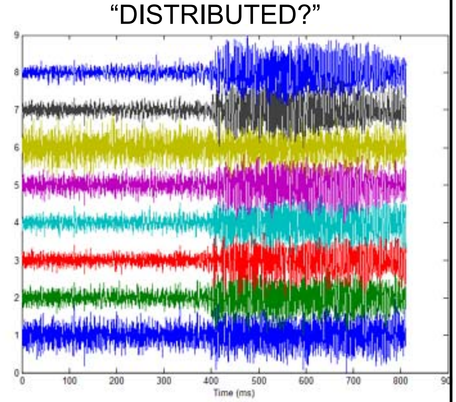




Monitoring Status

Two types of microseismic events detected





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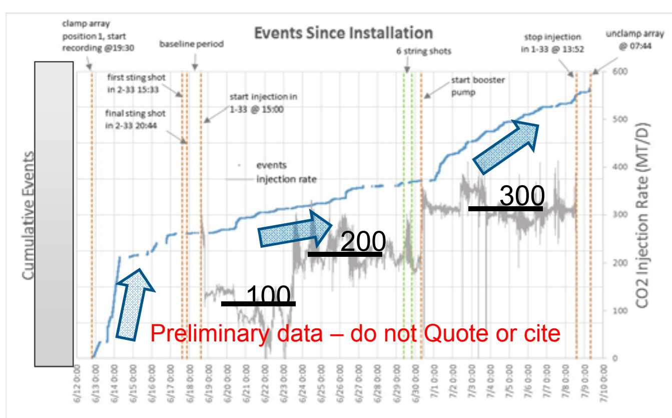
Monitoring Status

Injection Rate vs Detected Events

- 28 day injection following 6-day installation and baseline monitoring
- Step increase in injection
- ~7,000 events during initial installation and Zero-offset OVSP
- Steady frequency during initial injection
- Increased frequency after booster pump started



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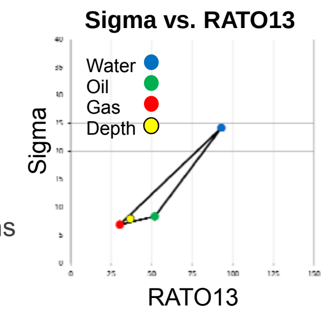
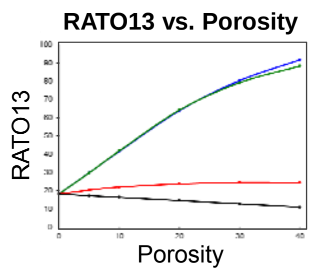
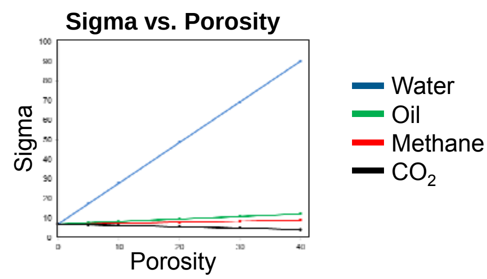
Monitoring Status

Pulsed Neutron Capture (PNC)

- New triangulation model developed to provide better resolution and better estimations of gas, water, and oil saturations



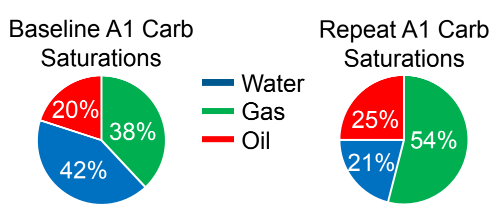


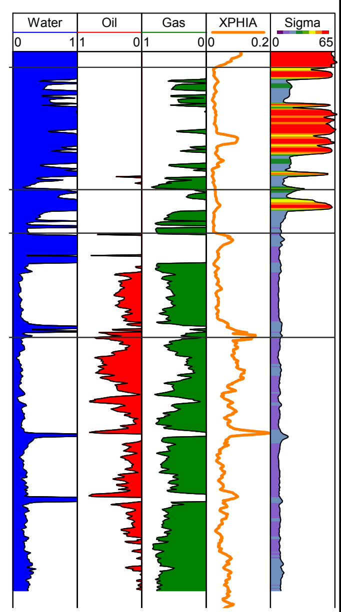


Monitoring Status

Saturation Estimation Analysis

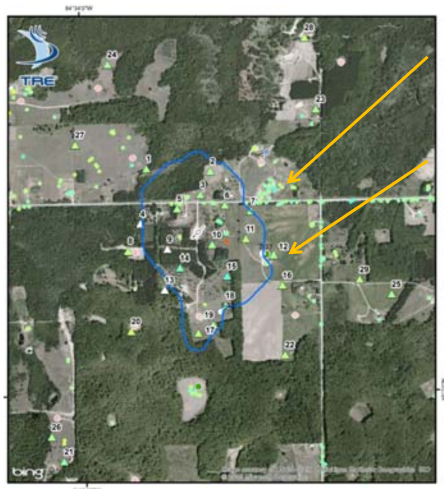
- Water, oil, and gas saturations are of interest for CO_2 EOR and CO_2 storage
  - Better estimations of saturations using triangulation method
  - Baseline and repeat logging show changes in saturations





Monitoring Status – INSAR Results

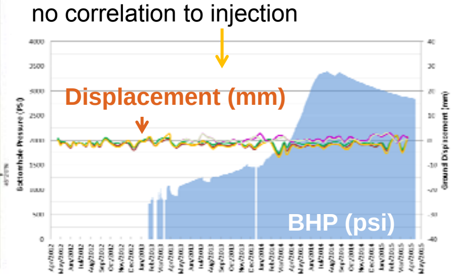
No Meaningful Displacement Observed



Vegetation and snow are challenging for radar, but there were a reasonable number of natural reflectors

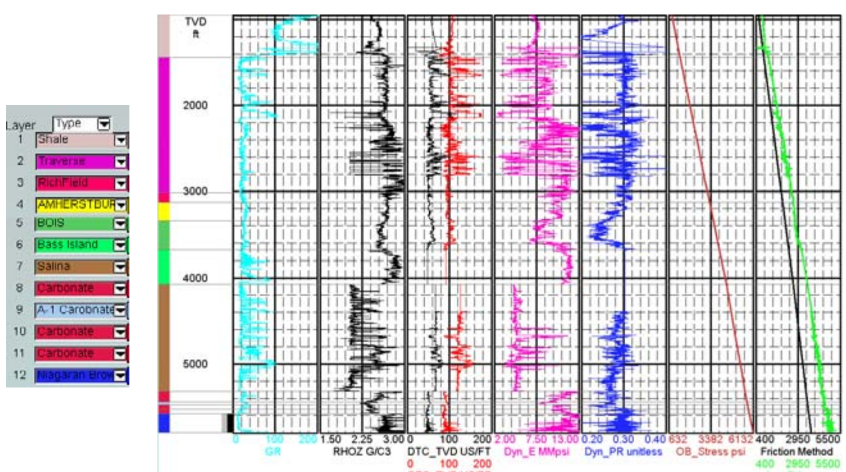
Artificial reflectors augmented the data for injection monitoring

Time series displacement data show no correlation to injection



Monitoring Status

Geomechanical modeling to validate INSAR results

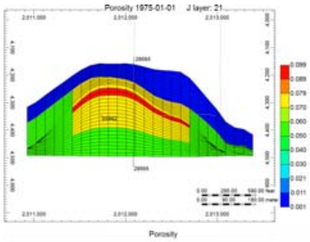


Average Dynamic Young Modulus and Poisson Ratio transferred to D-33

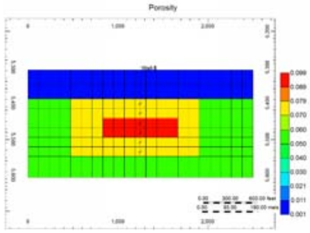
Monitoring Status

Geomechanical modeling, multi-phase fluid flow

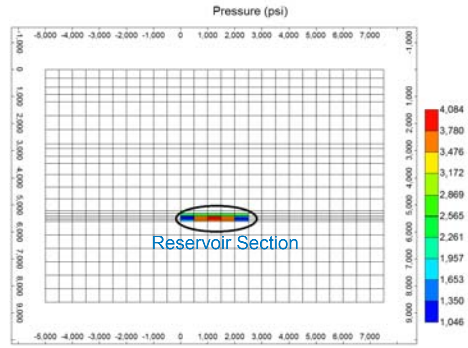
Complex Model



Simple Model



Simple model including overburden

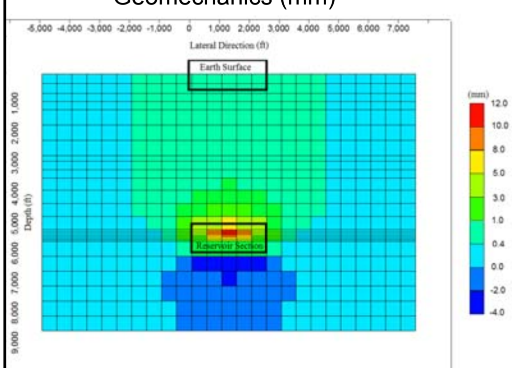


- Bulk volume, pore volume, porosity, and permeability for each sector same as complicated model: Reservoir Flank, Aquifer, A1 Carb., Core Reservoir.

Monitoring Status

Geomechanical modeling agreed with INSAR results

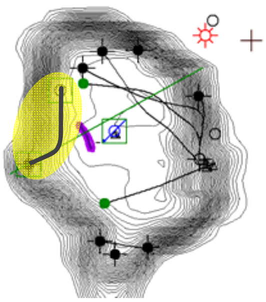
Top Vertical Displacement from Geomechanics (mm)

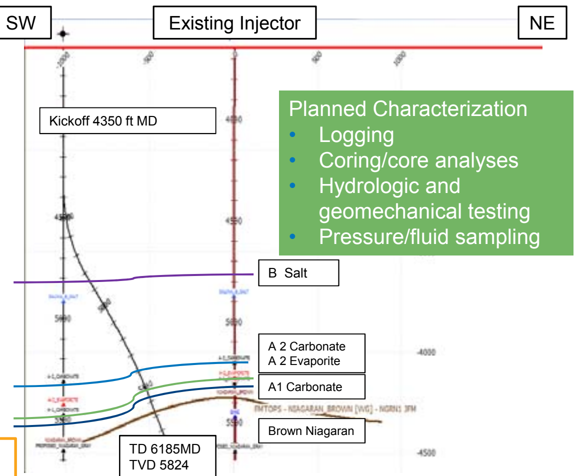


- Predicted surface displacement is less than 1 mm - insignificant
- Agreement among model and field observations

What's Next – Characterization Well

A new well in late-stage reef will provide key data





Planned Characterization
- Logging
- Coring/core analyses
- Hydrologic and geomechanical testing
- Pressure/fluid sampling

These data will improve static and dynamic reservoir models

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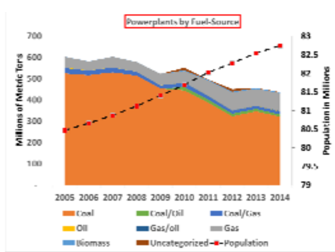
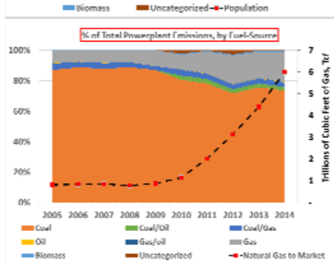
Regional Assessment Status

Emissions from Power plants in the MRCSP region





- Population growth has not been accompanied by an increase in emissions from power plants.
- Declining market-share of coal.
- Increased availability of cheaper gas has led to more power plants switching out of coal into natural gas.

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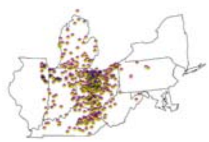
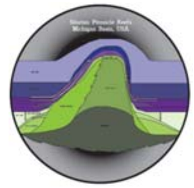
Regional Assessment Status

MRCSP 10-State team conducting regional studies



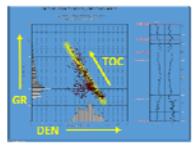
Cambro-Ordovician Storage Potential
Led by Indiana

East Coast Offshore and Onshore Storage Targets
Led by Rutgers

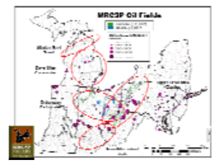


Silurian Pinnacle Reef Reservoirs
Led by W. Michigan University

CCUS Opportunities in Appalachian Basin
Led by Pennsylvania



Storage and Enhanced Gas Recovery for Organic Shale
Led by Kentucky



Reservoirs for CO_2-EOR, EGR, and other Commercial Uses
Led by West Virginia

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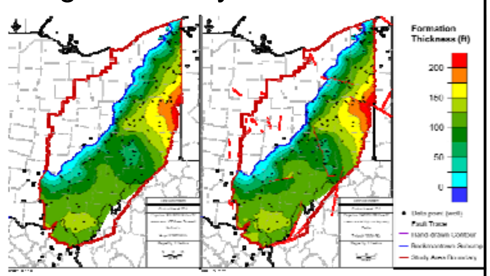
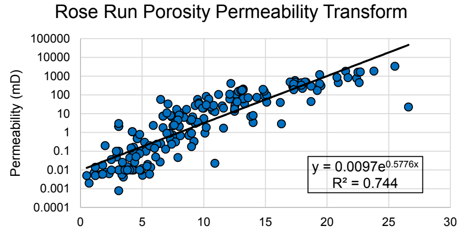
Regional Assessment – Upper Ohio Valley

Use of Multiple Datasets for Regional Analysis

- Dataset varies throughout the region, formation by formation:
  - Basic and advanced wireline data synthesis
  - Core analysis for geomechanical, petrophysical, and porosity-permeability assessment
  - Facies analysis using petrophysical and statistical methods
  - Depth, structure, isopach, thickness, and porosity map generation by formation
  - Regional formation assessment for storage potential



Rose Run Porosity Permeability Transform



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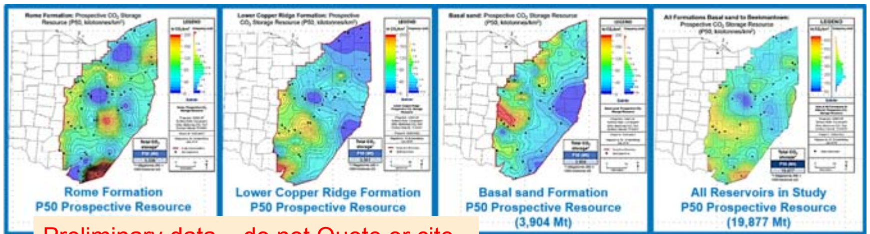
Regional Assessment Status

Calculation of Prospective Stacked CO_2 Storage Resource



Preliminary data – do not Quote or cite

Formation	Mt CO2 /km3 Pore Volume			Total Prospective CO2 Storage Resource (Mt)					ESaline Depositional Environment (CO2-SCREEN; IEAGHG, 2009)
	P10	P50	P90	P10	P50	P90	Theoretical Max.	Esaline P50 (avg.)	
Beekmantown	5	18	43	652	2,137	5,227	97,207	2.20%	Dolomite: Unspecified
Rose Run	5	20	61	188	757	2,305	30,320	2.50%	Clastics: Peritidal
Upper Copper Ridge	5	18	42	436	1,462	3,498	66,236	2.21%	Dolomite: Unspecified
Copper Ridge B	5	18	42	205	674	1,634	30,776	2.19%	Dolomite: Unspecified
Lower Copper Ridge	5	17	42	1,090	3,561	8,637	163,846	2.17%	Dolomite: Unspecified
Kerbel Sandstone	6	22	63	134	505	1,464	18,610	2.71%	Clastics: Delta
Conasauga	5	17	42	393	1,321	3,194	29,480	4.48%	Dolomite: Unspecified
Rome	5	18	42	1,639	5,556	13,281	250,824	2.22%	Dolomite: Unspecified
Basal Sandstone	6	24	70	990	3,904	11,348	130,915	2.98%	Clastics: Shallow Shelf

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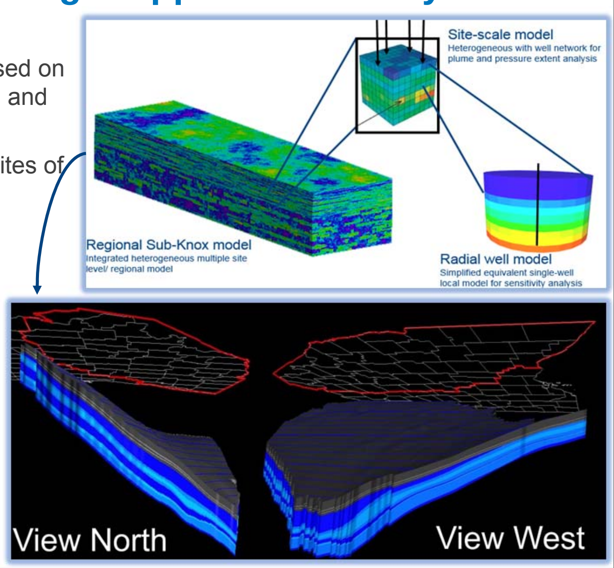
Geologic Modeling – Upper Ohio Valley

Multiple Scales

- Regional structural model based on geologic data, regional maps, and available seismic data
- Local scale assessments at sites of interest
- Dynamic modeling of CO_2 scenarios at local scale
- Analysis of image and acoustic log data with core data for analysis of mechanical properties
- Static and dynamic modeling of geomechanical caprock behavior
- Fracture analysis and modeling of behavior



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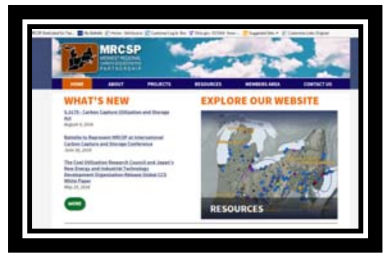
Outreach Status

Technology transfer is a growing focus

- Convening/participating in the Outreach Working Group
- Communicating results to a broad audience via site visits, fact sheets, conference and meetings, and the website
- Topical highlights:
  - CO_2 accounting in closed reservoirs
  - Performance Measures
  - Numerical Modeling
  - Monitoring-Modeling Loop
  - Regional Storage Opportunities



www.mrcsp.org

- MRCSP website moving to a mobile friendly platform (transitioning in August)

Accomplishments

MRCSP positioned for developing its storage potential

- ~575,000 metric tons injected across all reefs (ongoing)
- Completed injection at main test bed
  - Performed microseismic monitoring in final injection stage
  - Post-injection PNC, microgravity, and VSP underway
- Developed performance metrics to assess storage capacity
- Advancements in static and numeric modeling processes
- Collaborative team for regional assessments across ten states
- Technology transfer is focus of outreach

Synergy Opportunities

Research is complementary to the RCSP projects

- Knowledge share with Plains CO_2 Partnership on closed reservoirs modeling and monitoring
- Knowledge share with other RCSPs on monitoring technologies and depleted oilfield modeling
- Testing NRAP models and CO_2Screen tools
- Collaboration with international projects on modeling and CO_2 EOR to Storage transitions
- IEAGHG monitoring/Modeling Network
- Input to DOE Best Practices Manuals

Project Summary

Key Findings and Lessons Learned

- MRCSP Large-Scale Test ~60% 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 CCUS
- Results will contribute to developing standards and best practices, NRAP tools, CO_2 capacity estimate tools

Project Summary

Future Plans

- Completing post-injection monitoring and data analysis for late-stage field
- Drilling a new characterization well in late-stage field post-injection, applying results to validate/improve models
- Implementing metering improvements for MVA
- Applying methodologies and lessons to new EOR reefs
- Extending findings to the entire Michigan reef trend
- Expanded technical outreach

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

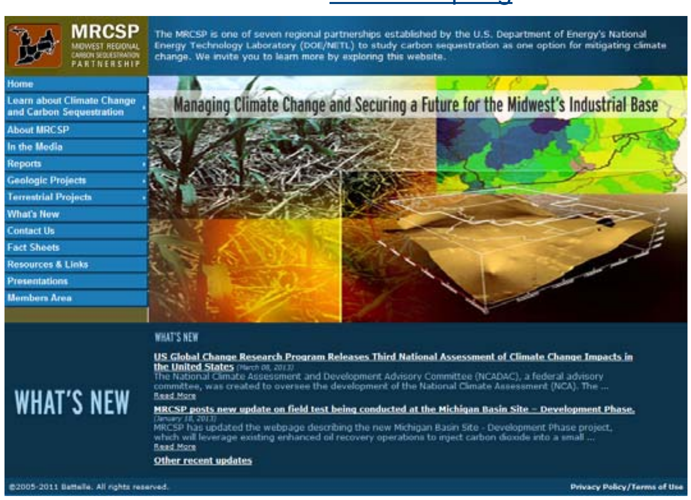
MRCSP's technical **partners, sponsors, and host sites**

The MRCSP Region's State **Geology Surveys and Universities**

Contributions From Partners Have Helped Make MRCSP Successful

Questions?

Please visit www.mrcsp.org



BACK UP SLIDES
Midwest Regional Carbon Sequestration Partnership

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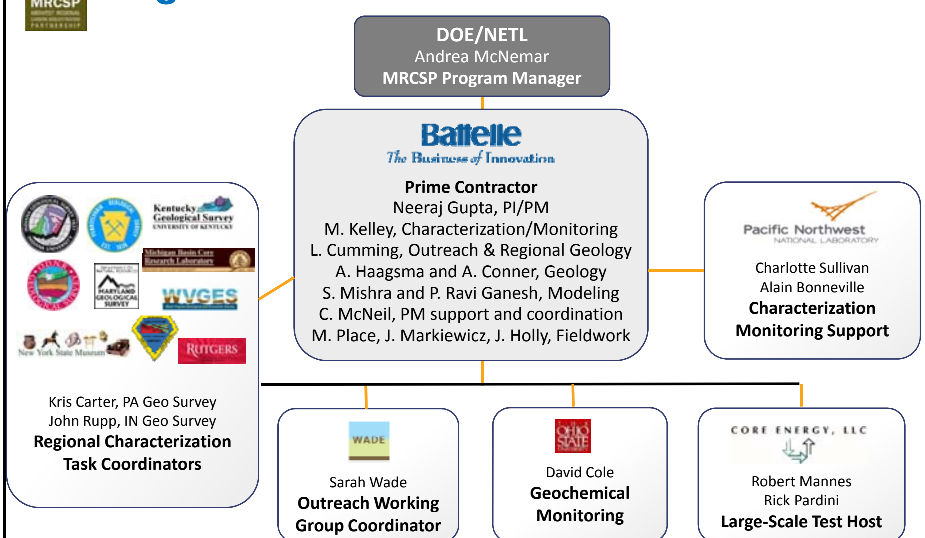
Organization Chart



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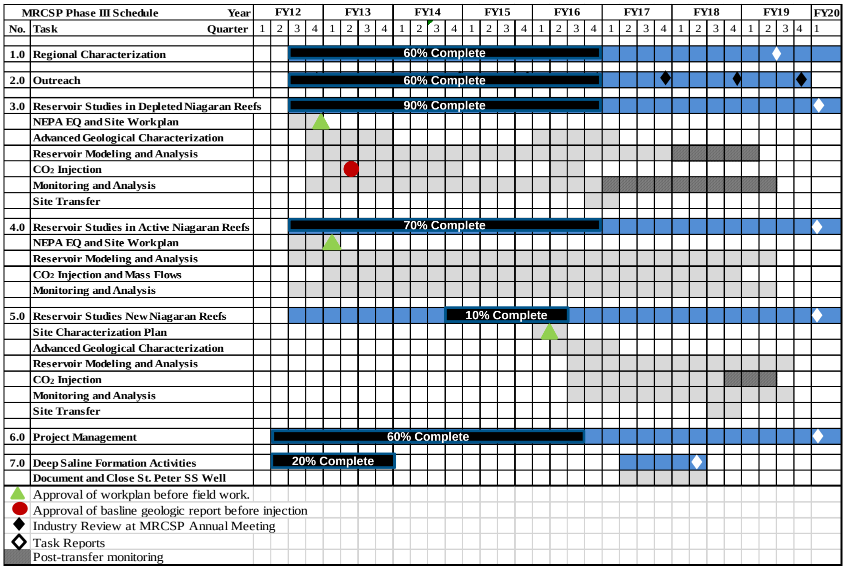
MRCSP Task Schedule



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