Charged Wellbore Casing Controlled Source Electromagnetics (CWC-CSEM) for Reservoir Imaging and Monitoring: FE0028320

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U.S. Department of Energy
National Energy Technology Laboratory
CO2 Capture Technology Project Review Meeting
August 13-17, 2018
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Presentation Outline

• Project Overview
• Methodology
• Current Status
• Accomplishments
• Lessons learned
• Summary
Project Overview

Production-scale verification of CWC-CSEM as MVA technology

• Multi-phase system, fluid content change alters electrical conductivity
• Dynamic system with CO₂ injection, time-lapse monitoring
• Cost-efficient monitoring through use of existing wellbores

Integrated reservoir MVA

• Coupled simulation
• Constrained inversion
• History matched with time-lapse CWC-CSEM and production data
• Collaboration with site operator - Denbury Resources, Inc.

Field site: Bell Creek, Montana
Methodology: Underlying Method

Charged wellbore casing controlled source electromagnetics

1. Electrical conductivity tied to reservoir fluid phase (oil / CO₂ / water)
2. Development and maturation at active CCS-EOR project
3. Constrained inversion using data from existing characterization
4. Static near-surface correction from transient EM data
5. Integration with reservoir simulation
6. History matching for validation
Methodology: Workflow

- Reservoir model (relative permeability, porosity, hysteresis, saturations)
  - Initial build
  - History matching

- CWC-CSEM data acquisition (Time-lapse monitoring)

- Near-surface EM survey
  - Statics

- Constrained and coupled EM inversion (electrical conductivity, saturations)
  - For coupled inversion
  - Structural constraints

- Seismic imaging
- Production data
- Archie’s law
Methodology: CWC-CSEM Principle

- CSEM transmitters inject current through legacy borehole casings deep into subsurface
- Current flows around resistive bodies (CO\textsubscript{2})
- Surface measurements of E and B fields
- Time-lapse measurements to observe changes
- 4D inversion of electrical conductivity

No internal borehole access!
Methodology: CWC-CSEM Basis

Archie’s Law \( R_t = a \phi^{-m} S_w^{-n} R_w \)

Waxman-Smits \( \phi^m S_w^n \left( \frac{1}{R_w} + \frac{BQV}{S_{wt}} \right) \)

- \( R_t \) saturated rock resistivity
- \( a \) tortuosity factor
- \( \phi \) porosity
- \( m \) cementation factor
- \( S_w \) saturation of water
- \( R_w \) brine resistivity
- \( S_{wt} \) saturation of water

- Conductivity changes have been shown to be effective in mapping saturation in CCS settings (Yang et al., 2014)
- Archie’s law and similar empirical relationships map resistivity to saturation
- Crosswell ERT requires dedicated wellbore jewelry and specialized construction

Methodology: CWC-CSEM Simulation

Resistive CO$_2$ plume near charged wellbore casing
Methodology: CWC-CSEM Simulation
Methodology: CWC-CSEM Simulation
Methodology: CWC-CSEM Simulation
Transmitter Scenario 1: Borehole to Surface

- Simplest configuration
- Only requires single borehole
- Rely on a conventional surface electrode
Methodology: CWC-CSEM Deployment

Transmitter Scenario 2: Borehole to Borehole

- Improved depth of investigation
- Current path between casings
- Less invasive, easier setup
- Requires additional access
Methodology: CWC-CSEM Deployment

Base Camp

- Established next to Electrode-A borehole
- Provides shelter for personnel and electronics
- Close to Denbury office
Methodology: CWC-CSEM Deployment

Transmitter Station

- Transmitter box, Iso-amp, Zen-receiver, Laptop
- Full transmission cycle: ~ 4-hours
- Transmission run continuously throughout each day while the receivers are moved every 4-hours to ensure that they capture a complete transmission cycle
Transmitter: Borehole Electrode

- Electrode A always
- Electrode B for borehole-borehole array
- Tx wire connected to production tubing of legacy wells
- 25 Amps; 200 Volts
- Full transmission cycle is approximately 4 hours
- Warning signs placed on the wells
- Provides direct contact with reservoir
Transmitter: Surface Electrode

- Tx Electrode – B (scenario-1)
- “Layer-cake” construction
- Alternating layers of aluminum foil, soil, and a lot of salt water
- Buried at approximately 1-ft depth
Methodology: CWC-CSEM Deployment

Receiver Box

• South-west corner of each Rx Station
• Sealed box with Zen receivers and batteries
• Connects to receiver electrodes and B-coils
• Data collected for a minimum of 4-hours for full transmission cycle
• Data downloaded with laptop before moving the Rx station to the next location
• Center electrode near the receiver box in the south-west corner
• Additional electrodes buried 100-m to the north and east of the center electrode in L-shape
• Vector E-field measurements
Receiver Sensors: B-Field

- Three sensors measuring horizontal and vertical components of the B-field
- Located near center receiver station
- Approximately 1-ft deep for horizontal components
Project Year 2017: Recap

• Significant initial developments
  – Reservoir simulation modeling
  – EM modeling codes
  – Field survey planning

• Unexpected setback
  – Loss of initially planned field site due to internal re-organization of site operator
  – Initial field survey planning and reservoir simulations no longer valid

• Project adjustment
  – New field site agreement with enthusiastic operator: Denbury Resources, Inc.
  – Algorithms and procedures from initial field site in place and ready for new site
Current Status

Current Project Year

• Budget Year coincides with calendar year; Updated PMP

• Currently eight months into BY-2

• New reservoir simulation data fully available, modeling on track

• Three field surveys since last Annual Review Meeting
  – One test survey at a local ASR site in Arvada, CO: August 2017
  – Two field surveys at new CCS-EOR site: October 2017, May 2018

• Remaining for BY-2
  – Continue reservoir and EM modeling, data integration, interpretation
  – One more field campaign in BY-2: October 2018
Accomplishments: Field Surveys

Field campaigns

- Two completed at CCS-EOR site

Site Background

- Bell Creek Integrated EOR & CO2 Storage Project
- Powder River Basin
- South-eastern Montana

https://www.undeerc.org/pcor/co2sequestrationprojects/BellCreek.aspx
Bell Creek Production

- Denbury Resources, Inc.
- 9 phases of production
- Current project is within the phase-5 production area
  - Outlined in light-green
  - Approximate 2-km x 3-km area
  - Started in Summer 2017
  - Combination of private, Denbury, and BLM lands

Accomplishments: Field Surveys
Accomplishments: Field Surveys

Phase 5 Area
Accessible lands
Non-accessible lands
CWC-CSEM Tx Boreholes [3]
Tx Wire between boreholes [2]
CWC-CSEM Rx – 2017 [18]
CWC-CSEM Rx – 2018 Extended [47]
TEM Stations [20]
Accomplishments: Field Surveys

CWC-CSEM Field Data

E-field Data, June 2018, Borehole-pair one (magenta line)
Accomplishments: Field Surveys

CWC-CSEM Field Data

E-field Data, June 2018, Borehole-pair two (magenta line)
Accomplishments: Field Surveys

TEM Data Acquisition and Inversion

- Used in static correction
- Complements induction logs, which do not cover near surface
- Fast, mature, and reliable geophysical technique
Accomplishments: Reservoir Model Properties

- Reservoir Model Properties
- Transmitter 'B' casing
- CO₂ Injection well
- Permeability
- Porosity

Permeability color scale:
- 1000.000
- 1.050E+7
- 1.100E+7
- 1.150E+7
- 1.200E+7
- 1.250E+7
- 1.300E+7
- 1.350E+7
- 1.400E+7
- 1.450E+7
- 1.500E+7

Porosity color scale:
- 0.000E+0
- 0.005E+0
- 0.010E+0
- 0.015E+0
- 0.020E+0
- 0.025E+0
- 0.030E+0
- 0.035E+0
- 0.040E+0
- 0.045E+0
- 0.050E+0
Accomplishments: Reservoir Model

Initial Simulation Results

Injection
- Single well - 2612
- Injection Rate: 2,000 MSCF/d
- Injection Time: 5 years
- Total CO₂ injected: 100,000 tons

Grid
- 174 x 188 x 14
- 411,152 active cells
Accomplishments: Reservoir Model

Initial Simulation Results
5 years CO₂ injection

Water Saturation  CO₂ Gas Saturation  CO₂ in Oil Saturation  Oil Saturation

1 mile
Accomplishments: Data Integration

Reservoir model: Expanding to conductivity for EM

TEM Inversion (red)

Well-log ILD (blue)

ILD: ohm-m

Depth: meters

Conductivity: S/m

Seismic horizons

Topography

Borehole: 97-11

Reservoir

Multiphysics integration

Multiphysics integration

Conductivity: S/m

0.0003
0.003
0.0083
0.0192
0.0515
0.0838
0.1

0.0358
0.0677
0.0838
0.1
Accomplishments: Data Integration

Reservoir model: Expanding to conductivity for EM

Archie’s law applied to reservoir simulation data at each time instance

\[ \sigma_B = \sigma_w \phi^m S^n_w \]

- Conductivity
- Temperature/TDS
- Porosity
- Water saturation
Accomplishments: Data Integration

Reservoir model: Expanding to conductivity for EM
Accomplishments: Data Integration

Reservoir model: Expanding to conductivity for EM
Accomplishments: Summary

Algorithmic and modeling developments

• All tasks on track
• Reservoir model
  – Software to link reservoir model to CWC-CSEM algorithm
  – Successful application to Bell Creek
• CWC-CSEM algorithm
  – Modified to work with new reservoir model format from above
  – EM simulation codes enhanced: flexibility and interoperability
  – User interface for CESM code made more robust and flexible
  – CESM code successfully run on high performance computing resources
Accomplishments: Summary

Dissemination of information

• Web-site development
  – multiphysics-mva.org & cwc-csem.org
  – Limited content at moment

• 2017 AIChE Annual Meeting, Presentation
  – Topical conference: Advances in Fossil Energy R&D
  – Title: Monitoring carbon sequestration using charged wellbore controlled sources electromagnetics and integrated reservoir models

• 2018 American Geophysical Union (AGU)
  – Two abstracts submitted for poster presentation
  – Reservoir simulation modeling; CWC-CSEM Field campaign at Bell Creek
Lessons Learned

– The need for efficient EM simulation algorithms
– The need for high performance computing facility

– The site access was a known risk, but the actual need to change the field site did consume time and energy

– Need site-specific relationship between reservoir parameters and electrical conductivity
Synergy Opportunities

– Bell Creek Field site serves as the field laboratory for previous SubTER seismic array presentation (EERC)
  • Joint inversion of seismic and EM datasets a natural opportunity
  • Overlapping survey areas of investigation
– EM methods can provide de-risking of exploration projects
– Monitoring of CO$_2$-EOR projects has wide application
– EM methods can enhance seismic data in karst, subsalt, and anhydrite locations where seismic interpretation may be challenging
Summary: Overall Project Status

Field site, reservoir modeling, field campaigns

- Procedures and algorithms in place for reservoir modeling and simulations
- Reservoir model expanded to electrical conductivity model
- Two field campaigns completed at Bell Creek; two remaining
- Next field data acquisition campaign: October 2018
Acknowledgements

- DOE/NETL: FE0028320
- Traci Rodosta, Kylee Rice
- Denbury Resources, Inc.
- Energy and Environmental Research Center (EERC)
Thank You!
Appendix

- Benefit to the program
- Project overview
- Methodology
- Organizational chart
- Schedule
SubTER Program Goals

1) Ensure storage permanence for injected CO$_2$
   - [AOI-1]: Deploy and validate prototype carbon storage Monitoring, Verification, and Accounting (MVA) technologies in an operational field environment.

2) Advancing state of knowledge in geothermal exploration
   - [AOI-2]: Identify and validate new subsurface signals to characterize and image the subsurface advancing the state of knowledge in geothermal exploration.
SubTER Pillars

1) Wellbore integrity - New sensors and adaptive materials are needed to ensure sustained integrity of the wellbore environment.

2) Subsurface stress and induced seismicity - Radically new approaches are needed to guide and optimize sustainable energy strategies and reduce the risks associated with subsurface injection.

3) Permeability manipulation – Greater knowledge of coupled processes will lead to improved methods of enhancing, impeding, and eliminating fluid flow.

4) New subsurface signals - DOE seeks to transform our ability to characterize subsurface systems by focusing on four areas of research: new signals, integration of multiple data sets, identification of critical system transitions, and automation.
Benefit to the Program

Project Benefits Statement

• Currently, there is a lack of cost-effective tools that are able to
  – Probe to the required depths, and
  – Be sensitive to changes in the makeup of the reservoir fluids

• Responsive technologies need to be sensitive to both
  – Distribution of CO$_2$ within reservoir, and
  – Overburden where leakage may occur

• The proposed project is designed to address these requirements
Project Benefits Statement

The project will benefit the monitoring and tracking the fate of CO$_2$ in a storage site by advancing the state of art through the following three components:

1) Time-lapse monitoring using charged wellbore casing controlled-source EM (CWC-CSEM) method
   - data are to be interpreted through constrained coupled inversions using reservoir models
   - electrical conductivity changes mapped to the reservoir properties, fluid saturations (phase)
Project Benefits Statement

The project will benefit the monitoring and tracking the fate of CO$_2$ in a storage site by advancing the state of art through the following three components:

2) Improved characterization of reservoir properties such as relative permeability and dynamic states such as fluid saturations
   – Integrate static and dynamic properties from time-lapse EM monitoring
   – Improve existing reservoir models for long-term monitoring and tracking
   – Characterize the distribution and migration of CO$_2$
Project Benefits Statement

The project will benefit the monitoring and tracking the fate of CO$_2$ in a storage site by advancing the state of art through the following three components:

3) Development of a responsive technology capable of imaging CO$_2$ migration within the whole overburden
Benefit to the Program

Project Benefits Statement

• Proposed technology relies upon
  – Legacy infrastructure
  – Minimal hardware installation

• It will be possible to install sensors permanently with minimal additional effort

• The field site was selected in order to:
  – Validate the method at a WAG site that should provide a distinct target
  – Leverage existing efforts by DOE-NETL in this area
Project Overview: Goals and Objectives

Goals

• Production-scale verification of CWC-CSEM as MVA technology
  – Three phase system, fluid content-sensitive electrical conductivity
  – Dynamic system with WAG cycles, time-lapse monitoring
  – Low cost through use of legacy wellbores

• Integrated reservoir MVA
  – Coupled simulation
  – Constrained inversion
  – History matched with time lapse CWC-CSEM and production data
Objectives

1. Develop software capabilities
   – 3D CWC-CSEM simulations at reservoir scale
   – Forward looking survey design, informed with reservoir simulations
   – Constrained 3D inversion with a priori reservoir knowledge and near surface statics

2. Development of best practice recommendations for CWC-CSEM
   – Survey frequencies
   – Data and inversion uncertainty
   – Validation through CCS-EOR production data
Charged wellbore casing controlled source electromagnetics

1. Electrical conductivity tied to reservoir fluid phase (oil / CO₂ / water)
2. Validation at active CCS-EOR project
3. Constrained inversion from existing characterization
4. Static near surface correction from TEM data
5. Integration with reservoir simulation
6. History matching for validation
Organizational Chart / Communication Plan

Colorado School of Mines
- Project lead
- Survey design
- EM inversion/modeling lead

University of Utah
- Reservoir simulation lead
- Coupled modeling

United States Geological Survey
- Field logistics lead
- Statistical data analysis

New Mexico Tech
- History matching

Communication plan
- Bi-monthly virtual meetings (GOTO Meeting, etc.)
- Annual project meetings

Project website
- http://multiphysics-mva.org
- Outreach and collaboration
Proposed Schedule

Management 1.0
  Annual Meeting

Field Work 2.0
  CSEM 2.1
  TEM 2.2

Simulation 3.0
  EM 3.1
  Reservoir 3.2
  Coupled 3.3
  Survey Design 3.4

Inversion 4.0
  TEM 4.1
  CSEM 4.2

Interpretation 5.0
  $\sigma \rightarrow S$ 5.1
  Uncertainty 5.2
  History Matching 5.3
No journal publications yet