Reducing Uncertainties in Model Predictions via History Matching of CO₂ Plume Migration at the Sleipner Project, Norwegian North Sea

Project Number (DE-FE0004381)

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Presentation Outline

• Benefits to the program
• Project overall objectives
• Technical status
• Project summary
• Conclusions and future plans
Benefit to the Program

- Develop technologies that will support industries’ ability to predict CO₂ storage capacity in geologic formations to within ±30 percent.
- Develop technologies to demonstrate that 99 percent of injected CO₂ remains in the injection zones.
- This research project develops a reservoir scale CO₂ plume migration model at the Sleipner project, Norway. The Sleipner project in the Norwegian North Sea is the world’s first commercial scale geological carbon storage project. 4D seismic data have delineated the CO₂ plume migration history. The relatively long history and high fidelity data make Sleipner one of the best places in the world to conduct multi-phase flow and reactive mass transport modeling of CO₂ migration. This work contributes to the Program’s efforts of demonstrating 99% of injected CO₂ remaining in the injected zone and ability to predict storage capacity within ±30%.
Project Overview Objectives

To assess and reduce uncertainties of model predictions of CO$_2$ plume migration, trapping mechanisms, and storage capacity estimates through history matching and long-term fate modeling of CO$_2$ through implementing rigorous chemical kinetics and through a number of bounding calculations and sensitivity analyses
Norwegian Sleipner Project

Sleipner CO₂ injection:
- World’s first industrial-scale geological carbon storage project
- In operation since 1996
- 1 million ton CO₂/year
- Storage: Utsira Formation. A saline reservoir 800-1000 meters (2600-3300ft) below the sea floor
Time-lapse seismic images of the CO$_2$ plume at Sleipner

Upper row: N-S seismic section through the plume.
Lower row: plan views of the plume showing total integrated reflection amplitude (Chadwick et al., 2010)
Statoil-IEA Benchmark Geological Model

- An area ~ 3 x 6 km
- Grid dimensions: $x = 65$, $y = 119$, $z = 43$; total 332,605 blocks
- The basic grid resolution is 50 m x 50 m.

Layer 9 = “Sand Wedge”

5 m mudstone underneath
First Attempt—Applying Permeability Anisotropy

Observed extents

Topography of the Layer 9.

GEM simulation

Cannot achieve the match by adjusting permeability anisotropy alone

Tough 2 simulations (Chadwick and Noy, 2010)
CO₂ plume thicknesses derived from reflection amplitudes (Chadwick and Noy, 2010). A thick area of CO₂ plume (red circle) is clearly shown in 2004 and 2006 map. Propose to add a second feeder to that area after year 2001.
Second Attempt--Additional Feeder with Permeability Anisotropy

Observed extents 2006

100% CO₂ volume into main feeder

85% CO₂ volume injected into the main feeder and 15% into the second feeder (the triangle) starting from 2002.

Acceptable results with the second feeder.
Comparison of Observed vs. Model Predicted CO₂ Plume Extent (Base Case)

Seismic Response

Model Prediction

1999
Comparison of Observed vs. Model Predicted CO₂ Plume Extent (Base Case)
Comparison of Observed vs. Model Predicted CO$_2$ Plume Extent (Base Case)
Comparison of Observed vs. Model Predicted CO₂ Plume Extent (Base Case)

Seismic Response  
2004

Model Prediction

INDIANA UNIVERSITY
Comparison of Observed vs. Model Predicted CO₂ Plume Extent (Base Case)
Comparison of Observed vs. Model Predicted CO₂ Plume Extent (Base Case)
Overall Comparison (Base Case)

Seismic Response

Model Prediction
Model Comparison

Seismic Response

Model Prediction

Invasion percolation migration

CO₂ Black Oil Simulator using up-scaled relative permeability curves

CO₂ Black Oil Simulator using the Vertical Equilibrium option

Singh et al. (2010) using Eclipse 100/300

This Study
Simulators used

GEM

Max. Sg=0.87 in 2006

Tough2 with the same parameters

Max. Sg=0.83 in 2006

Purple: Tough2
Red: GEM
- Model calibrated to 2008 (data available);

- Model prediction 2010 (observation data black outline)
Conclusions from Modeling Study

• Introducing permeability anistropy is necessary and justifiable based on geology

• Adding another feeder is critical in order to model the N-S extension (Chadwick and Noy, 2010; Singh et al., 2010).

• Model-predicted plume thickness, CO$_2$ saturation, fraction of dissolved CO$_2$ dissolved are comparable with those based on seismic data interpretations (with estimated mass of CO2 spilled into Layer 9);

• The model calibrated to 2008 predicted 2010 plume extent reasonably.
Accomplishments to Date

1. Acquired datasets for the Sleipner project, one of the best field dataset for U.S. scientists, engineers, and students working on CCUS. Fulfilling the international/global collaboration program need;
2. Developed a multiphase reactive flow reservoir model of Layer 9 for the Sleipner project and that successfully matched 4D plume migration in Layer 9;
3. Prepared a manuscript that has received DOE approval for publication; Multiple conference presentations.
4. Currently conducting parameter sensitivity analysis;
5. Initiated coupled reactive transport model to evaluate long-term effects on reservoir prosperities by water-rock interactions.
Summary - Key Findings & Lessons Learned

– What takes to match the 4D CO₂ plume history at Sleipner?
  • We can achieve a good match without using out of ordinary parameters or assumptions, and we used two widely available reservoir simulators.

– What model produced?
  • Approximate match with the 4D plume boundaries, via adjusting permeability & anisotropy and feeders;
  • **Predictions** (without parameter adjustments) matched well with seismic data based estimates (a) CO₂ solubility, (b) CO₂ saturation, (c) plume thickness; and by extension, (d) estimate of CO₂ spilled into Layer 9.

– **Lessons Learned**: Sleipner project is an excellent candidate for demonstration that reservoir simulation of CO₂ plume migration can be achieved with a set of reasonable parameters.
Future Plans:

1) Publish the results of plume history match modeling in peer-reviewed journals;

2) Develop coupled reactive transport model to simulate long-term CO2 fate, in anticipation of drilling and coring
   - Complete conceptual model and axisymmetric TOUGHReact modeling of Utsira Sand
   - Port the conceptual geochemistry model into the calibrated multi-phase reactive flow model Layer 9 geometry

Hypothesis: Models have over-predicted mineral dissolution – precipitation reactions. Using realistic rate laws would see much less reactions
Appendix

– These slides will not be discussed during the presentation, but are mandatory
Organization Chart

• PRINCIPAL INVESTIGATOR
  • Professor Chen Zhu
  • Indiana University
• Co-Principal Investigator
  • Professor Per Aaggard
  • University of Oslo
Gantt Chart

TASK 1.0 - PROJECT MANAGEMENT, PLANNING AND REPORTING
TASK 2.0 – DATA ACQUISITION AND INTERPRETATION
TASK 3.0 – HISTORY MATCHING OF CO₂ PLUME MIGRATION WITH A RESERVOIR MODEL
Gantt Chart

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**TASK 1.0 - PROJECT MANAGEMENT, PLANNING AND REPORTING**

**TASK 2.0 – DATA ACQUISITION AND INTERPRETATION**

**TASK 3.0 – HISTORY MATCHING OF CO₂ PLUME MIGRATION WITH A RESERVOIR MODEL**

**TASK 4.0 – MODELING LONG-TERM CO₂ FATE**
Gantt Chart

Chart 1. Timeline of the completion of the Tasks (M stands for milestones).

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- **Task 3.0** – HISTORY MATCHING OF CO₂ PLUME MIGRATION WITH A RESERVOIR MODEL
- **Task 4.0** – MODELING LONG-TERM CO₂ FATE
Bibliography

• Peer-reviewed journal articles:
• Conference proceeding papers and abstracts:
• Conference proceeding papers and abstracts (continued):