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The CO_2 Capture Project Phase 2 (CCP2) Storage Program: Progress in Geological Assurance in Unmineable Coal Beds

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Abstract

The CO_2 Capture Project's (CCP) Phase 2 program made significant progress addressing issues to facilitate assurance of the safety and security of geological storage of CO_2. This work included stakeholder assurance of CO_2 storage in unmineable coal beds. Simulation studies of CO_2 injection into coal beds were designed to identify operating conditions that will minimize leakage of CO_2 and maximize production of methane. Geophysical models were used to simulate gravity and electromagnetic responses from coal beds containing CO_2. Hyperspectral remote sensing was evaluated for its ability to detect leakage of CO_2 and CH_4 to the surface.

Keywords: CO_2; coal bed; ECBM; monitoring; EM; gravity; MASTER; remote sensing

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1. Introduction

The CO_2 Capture Project (CCP), started in 2000, is an international consortium intended to address the issue of reducing CO_2 emissions resulting from the combustion of fossil fuels. The CCP seeks to develop new technologies to reduce the cost of capturing CO_2 from combustion sources and safely store it underground. The objective is to reduce the impact of continued fossil energy use by implementing these new technologies while cleaner energy sources are being developed.

The CCP Phase 1 Storage, Monitoring, and Verification (SMV) program developed a program consisting of more than 30 projects distributed over four technical themes (Integrity, Optimization, Monitoring, Risk Assessment)

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designed to identify efficiencies and reduce uncertainties associated with geologic CO_2 storage. Upon completion of CCP1 in 2004, technical issues in geologic CO_2 storage assurance that remained to be addressed were identified. An SMV program was developed for Phase 2 of the CO_2 Capture Project (CCP2) which began in 2004 and is scheduled to conclude in April 2009 to address these issues. One of the issues identified was stakeholder assurance of the safety and security of CO_2 storage in unmineable coal beds. Three critical areas identified that required further study were (1) the integrity of coal bed methane geologic and engineered systems, (2) the optimization of the coal bed storage process, and (3) reliable monitoring and verification systems appropriate to the special conditions of CO_2 storage and flow in coals.

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2. Discussion

To address specific issues regarding stakeholder assurance of CO_2 storage in unmineable coal beds, CCP2 and the U.S. DOE co-funded a project consisting of three tasks:

- Simulation of coal bed methane (CBM) and CO_2 enhanced coal bed methane (ECBM) recovery processes and operating practices that could lead to leakage of methane or CO_2
- Modeling the resolution of inexpensive non-seismic geophysical monitoring tools to detect gas movement within coal zones and in the subsurface in general
- Direct, remote detection of methane and CO_2 leakage from a coal (mining, CBM or CO_2 ECBM) or other geologic storage

The objectives of the three tasks were to establish CO_2 injection and methane (CH_4) production procedures in deep, unminable coals that would avoid CO_2 and CH_4 leakage and to develop more cost-effective technologies to monitor the movement of CO_2 and CH_4 gases in subsurface coals and at the surface. All three tasks addressed the behavior of CH_4 in addition to CO_2 since a substantial leakage of CH_4 would negate the climate benefits of CO_2 storage.

2.1. Simulation of CBM and CO_2 ECBM recovery processes and operating practices

CBM and CO_2 ECBM recovery processes and operating practices were simulated using Computer Modeling Group's state of the art GEM simulator to simulate (1) injection of CO_2 into a coal bed and (2) the upward migration of CH_4 and CO_2 from coal deposits toward the surface of the Earth. A Southeastern Regional Carbon Sequestration Partnership (SECARB) small scale injection (900 tonnes) of CO_2 into the Deerlick Creek coal field was used as a test case for the simulations [1].

Methane is produced from the Pratt (427 – 457 m), the Mary Lee (579 – 609 m), and the Black Creek (732 – 762 m) coal groups in the Deerlick Creek test area. The 4 acre test site includes a planned single injection well (J. D. Jobson 24-14 #11). The pilot injection schedule will involve injection of approximately 300 tonnes into each of the three coal zones. Initially, 35 tonnes CO_2 will be injected into each zone followed by a 16 day pressure stabilization period, after which the remainder of the CO_2 will be injected. Injection will be into the Black Creek zone first followed by injection into the two shallower zones.

A simplified model of the Deerlick Creek test area was constructed to investigate CO_2 injection into the three coal seams. The model was expanded from the one injection well of the test site to include nine wells. The model included 27 layers, 14 coal seams in the Pratt, Mary Lee, and Black Creek groups, and thirteen intervening shale layers. Data for model construction was obtained from logs obtained from M J systems and the State Oil and Gas

Board of Alabama. A reasonably good history match of the cumulative water and gas production from the field and the water and gas production rates was obtained by adjusting the fracture permeability and porosity and the original gas-in-place to include drainage from outside the coal model area.

The planned SECARB test injection schedule and longer term CO_2 injection schemes were simulated using the simplified model. With the test schedule, CO_2 injection into all three zones was successful and in no case did the pressure increase significantly or did CO_2 break through to a producing well. The distribution of adsorbed CO_2 in the Pratt layer is shown in Figure 1. The areal extent of the CO_2 plumes in the Mary Lee and Black Creek zones was less.

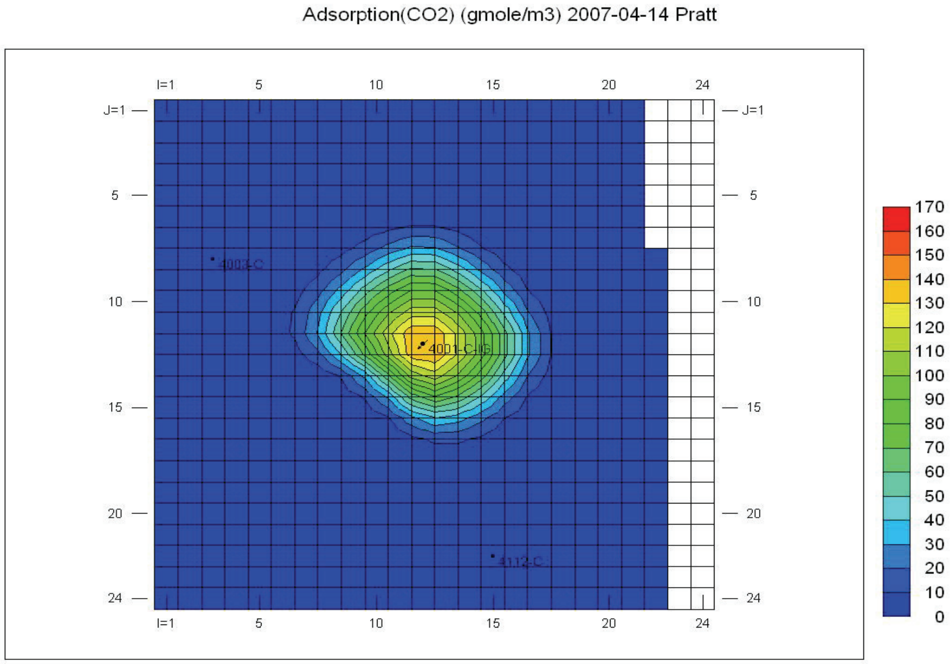


Figure 1. Distribution of adsorbed CO_2 in Pratt zone (gmole/m^3)

The longer term CO_2 injection scenarios studied included

1. A base case with no CO_2 injection.
2. Continuous CO_2 injection for 10 years with continuous operation of production wells.
3. Continuous CO_2 injection for 10 years with production wells shut-in after CO_2 breakthrough.
4. Continuous CO_2 injection for 13 years, production wells shut-in, CO_2 injection continued for an additional 20 years.
5. Continuous CO_2 injection for 13 years, production wells shut-in, CO_2 injection continued for an additional 16 years at a higher injection rate.

Simulation results, shown in Table 1, showed CO_2 sequestration amounts ranging from 85,000 to 400,000 tonnes for the various injection schedules used. For the model area of 1.44 km^2, this translates to storage capacities ranging from 59,000 to 279,000 tonnes/km^2. This range is somewhat less than the 390,000 tonnes/km^2 sequestration capacity predicted for coal in the area [2]. The lower sequestration capacities are most likely due to (1) uneven pressure distribution throughout the model area following CO_2 injection and (2) incomplete water displacement from the coal cleats.

Table 1. Simulation Results

Scenario	Cumulative CH_4 Produced (10^6 m^3)	Cumulative CO_2 Injected (10^6 m^3)	Cumulative CO_2 Produced (10^6 m^3)	Net CO_2 Sequestered (10^3 tonnes)
1	87.3	0	0	0
2	75.7	45.5	0	85
3	73.3	54.9	0	103
4	83.5	177.4	11.1	308
5	83.5	186.5	9.1	402

Simulation results showed that a decline in CH_4 recovery accompanied CO_2 injection for all cases studied. The largest declines were observed for those cases (2 and 3) with only 10 years production versus 33 years for the base case. The other main contributing factor was the high primary production achieved in the base case which was due in large part to the relatively high cleat permeability.

A model with 786 layers that included the coal seams and overburden was constructed to simulate leakage of CO_2 from the coal seams into shallower formations and possibly to the surface. The overburden layers were identified from logs obtained on the Research Waste Disposal #1 well located in section 3, township 21 S, range 9W. The Deerlick Creek test site is located in section 24, township 20, range 9W. The model goes from the surface to the base of the Black Creek coal and was constructed with 2 m thick layers and one layer for each coal zone. A run was set up with CO_2 injection to 2030 followed by a 70 year shut-in period. The run showed some leakage of CO_2 out of the coals and into the sand but by the end of the 70 year shut-in period, CO_2 had migrated at most 10 m from the coals.

2.2. Non-seismic geophysical monitoring tools

An analysis of the applicability of electromagnetic (EM) and gravity monitoring techniques was conducted using the Deerlick Creek pilot area as a case study. A previous analysis of the spatial resolution and detectability limits of non-seismic geophysical techniques for monitoring CO_2 injection was carried out in CCP1 [3,4]. The results from that study showed that EM and gravity measurements could, under certain circumstances, be used as a lower cost alternative to seismic geophysics. However, the reduction in cost is accompanied by a reduction in spatial resolution so the utility of non-seismic techniques will be site dependent.

This work involved integrating results from rock-properties, flow simulation, and geophysical modeling. The flow simulation model constructed for the Deerlick Creek pilot was used to provide reservoir pressure, temperature, and fluid saturations as a function of time. These were converted to geophysical parameters using a rock properties model developed using laboratory measurements of acoustic velocity, shear wave velocity, density, and electrical resistivity obtained on a horizontal coal core plug from the upper Cretaceous Ferron Sandstone member of the Macos Shale (“A” coal bed, Ivie Creek #11, footage 293’4” to 294’0”, Loc Sec 20 T 235 R6E Salt Lake Meridian), Utah. The rock properties model provides the link between reservoir properties and geophysical measurements.

A sensitivity study was conducted to assess the ability of gravity and EM techniques to detect the small volumes of CO_2 to be injected in the Deerlick Creek pilot. Increasing the CO_2 saturation reduces the bulk density of the coal layer, causing a decrease in the gravity response. Decreased brine saturation resulting from CO_2 injection should lead to a change in the electrical resistivity of the reservoir rock. Simplified models were constructed for the sensitivity studies using log data provided by the Alabama Geological Survey for a deep disposal well drilled a couple of miles from the pilot area.

Simulation results predicted that the gravity response for each coal layer measured independently would be at or below the detection threshold. However, the three layers together would produce a detectable gravity response. Inversion of gravity data is very important, since construction of density contrast models significantly increases the amount of information that can be extracted from the gravity data [5]. The inversion of gravity data located the CO_2

plume correctly (Figure 2) although with the smoothing constraint of the inversion, the area was slightly overestimated, resulting in an underestimated value of density change.

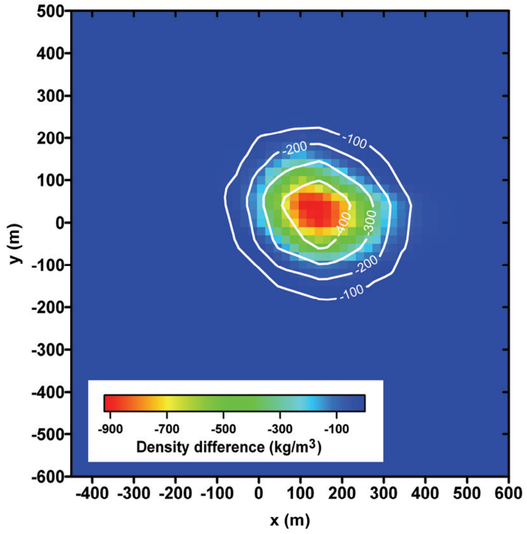
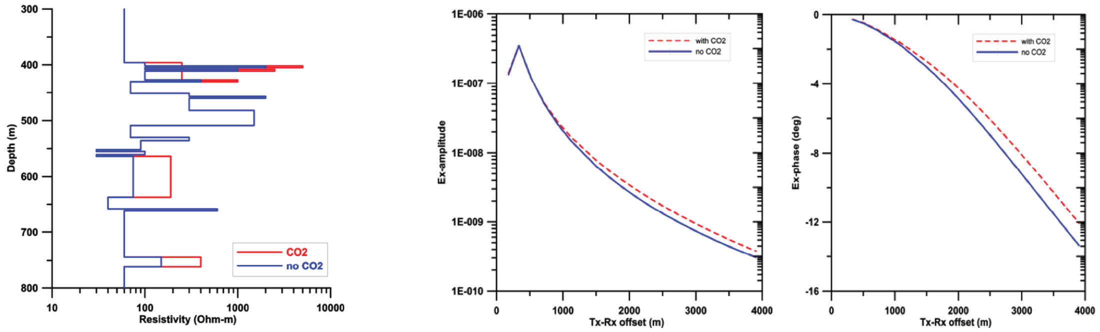


Figure 2. Gravity inversion – density change (kg/m^3) as a function of x and y coordinates. True model is shown with white contours.

For the EM technique, simulation results indicated that the electric field response from an EM survey would not detect 300 tonnes CO_2 injected into a single coal zone, but the response from injecting a total of 900 tonnes into three separate zones would be detectable. A resistivity model with and without CO_2 present is shown in Figure 3a, while the amplitude and phase response is shown in Figure 3b.



(a) (b)

Figure 3. (a) Resistivity log with and without CO_2, (b) amplitude and phase response to the model.

Synthetic time-lapse seismic Amplitude vs. Angle (AVA) analysis showed that by inverting seismic and EM data jointly much better estimates of CO_2 saturation can be obtained compared to those obtained from the inversion of seismic data only.

2.3. Direct, remote detection of CO_2 and CH_4

Aerial hyperspectral detection of CO_2 and CH_4 seepage was investigated as a low cost alternative to conventional monitoring techniques. Airborne and satellite remote sensing are unique in their ability to monitor large land-surface areas and would eliminate the need for extensive ground based monitoring infrastructure, thereby significantly reducing operational costs. Hyper-spectral sensors are defined as those that can record data from greater than 100 independent and usually contiguous bands. Previous work conducted for CCP1 used Visible-Shortwave hyperspectral imagery to detect gas emissions and their environmental proxies [6]. The previous work has been extended into the Thermal InfraRed (TIR) where unique spectral absorption features of gaseous CH_4 and CO_2 facilitate direct detection.

The MASTER (MODIS/ASTER Airborne Simulator) instrument, developed by the NASA Ames Research Center in cooperation with the Jet Propulsion Laboratory and operated by Airborne Sensor Facility, was selected for use for detection of both CH_4 and CO_2. The MASTER system acquires data from the 0.4 to 13 µm spectral range in 50 channels (bands). Significant CO_2 and CH_4 absorption wavelengths and their corresponding MASTER bands are given in Table 2. This work focused on the CO_2 absorptions at 2.06 and 4.3 µm and the CH_4 absorption at 2.4 µm because they had the desired combination of measurable absorptions at the concentrations of interest and minimal interference from other species.

Table 2: CO_2 and CH_4 absorption wavelengths and their corresponding MASTER bands

Molecule	Absorption Wavelength	MASTER Band (Band Center Wavelength)
CO_2	1.63 µm	Band 12 (1.6060 µm)
	2.06 µm	Band 20 (2.0806 µm)
	4.3 µm	Band 34 (4.3786 µm)
	9.4 µm	Band 45 (9.7004 µm)
CH_4	1.7 µm	Band 14 (1.7196 µm)
	2.4µm	Band 24 (2.3284 µm)
	7.4-7.58 µm	Band 41 (7.7599 µm)

On August 3, 2006, MASTER was flown over the Rocky Mountain Oil Field Testing Center NPR#3 (RMOTC), a 10,000 acre, operating oilfield with approximately 1,200 well bores and 600 producing wells established in 1993 by the U.S. DOE as a testing ground for new energy-related technologies. A Sky Cessna Caravan carrying the modified MASTER payload and flying between 1000 and 2000 m above ground level imaged the RMOTC site in nine complete and overlapping flight-lines. The flight path roughly followed a ‘virtual pipeline’ set up by RMOTC for previous remote sensing studies. Seven experimental leak sites were set up along the ‘virtual pipeline’ for this study. Natural gas from the RMOTC gas plant and CO_2 tanks were used to simulate the leaks. The type of gas released at each site along with the targeted and actual leakage rates are identified in Table 3.

Table 3. Gas Leak Rates

Leak Point ID	Gas Leak Type	Intended Release Rate (cmh)	Actual Release Rate (cmh)
P5	CO_2	8	6
04	CO_2	23	566
P1	CO_2	142	113
2E	CH_4	3	3
P3	CH_4	8	12
01	CH_4	23	23
05	CH_4	142	161

Using the 1976 Standard Atmospheric profile and inputting site specific parameters, MODTRAN (moderate spectral resolution atmospheric transmittance algorithm and computer model) was used to predict transmittance at the RMOTC site. Little change in transmittance for different CO_2 concentrations was predicted. Changes in transmittance with increasing CH_4 concentrations, although still small, were more significant, especially at the lower levels evaluated.

To test MASTER's ability to detect CO_2 through very small changes in transmittance measured in pixels near the leak source, a 'pixel subtraction' method was developed where background pixel spectra were subtracted from the leak source pixel. Background pixels were selected from a line of pixels running north to south across the leak source. The ideal output from the 'pixel subtraction' method would be a series of negative numbers occurring in the MASTER channels sensitive to the absorption bands of the target gas.

Results from the pixel subtraction technique applied to the transmissions measured at the Site 4 CO_2 leak site are shown in Figure 4. Site 4 was the highest rate CO_2 leak. All of the background pixels indicate a drop in transmission in band 35 which covers a CO_2 absorption at a slightly longer wavelength than 4.3 µm. Absorption at this wavelength is less intense than at 4.3 µm and differences due to changing CO_2 concentrations are easier to detect. The result at Site 4 indicates that the method can work for larger leaks. However, inconsistent results were obtained at the other CO_2 leakage sites and at some of the CH_4 leak sites. In addition, the response for CH_4 is a couple of orders of magnitude less than for CO_2 meaning that noise may be an issue in interpreting the CH_4 data. Topography may have played a role in some of the anomalous results obtained since higher than expected gas concentrations may have resulted from gas pooling in low lying areas.

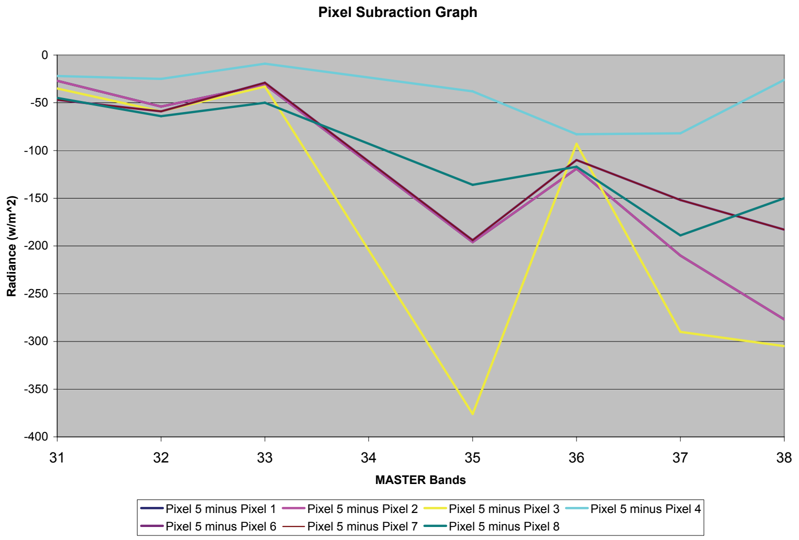


Figure 4. Site 04 pixel subtraction graph. Line 'Pixel 5 minus Pixel 1' is overlain by line 'Pixel 5 minus Pixel 2'. Line 'Pixel 5 minus Pixel 6' is overlain by line 'Pixel 5 minus Pixel 7'.

3. Conclusions

The CCP2 Storage program successfully addressed some of the remaining assurance issues related to the safe and secure storage of CO_2 in coal beds. Simulation results based on the planned CO_2 injection into the Deerlick Creek test site should not lead to large pressure increases. Longer term simulations predict storage capacities ranging from 59,000 – 279,000 tonnes/km^2 with minimal leakage of CO_2 from any of the coal seams. Migration of injected CO_2 through natural fissures to the surface is highly unlikely, even over centuries. Lower cost alternatives to seismic measurements for monitoring CO_2 movement in coals may be applicable under certain circumstances. Simulation results indicate that even the small volumes (900 tonnes) of CO_2 injected into coal seams as planned for a field test in the Black Warrior basin should be detectable using gravity or EM monitoring techniques. Furthermore, inverting seismic and EM data jointly may yield much better estimates of CO_2 saturation. Results obtained from the evaluation of remote, hyperspectral monitoring for direct detection of CO_2 and CH_4 leaks showed the MASTER instrument to be unsuitable as it is currently configured. However, the MASTER instrument may be useful for detecting large-scale CH_4 ground leaks. In general, the MASTER spectral resolution is too broad, and the spatial resolution too coarse to confidently detect and map variations of greenhouse gas releases.

4. Acknowledgments

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5. References

1. J. C. Pashin, P. E. Clark, R. A. Esposito, M. McIntyre, and G. Koperna, 2008, Sequestration in Mature Coalbed Methane Reservoirs of the Black Warrior Basin, in *Proceedings of the Seventh Annual Conference on Carbon Capture and Sequestration*, May 5 – 8 , 2008, Pittsburgh, PA.

2. Pashin, J. C., Carroll, R. E., Groshong, R. H. Jr., Raymond, D. E., McIntyre, M. R., and Payton, J. W., 2004, Geologic screening criteria for sequestration of CO_2 in coal: quantifying potential of the Black Warrior coalbed methane fairway, Alabama: Final Technical Report, U. S. Department of Energy, National Technology Laboratory, contract DE-FC26-00NT40927.

3. G. M. Hoversten and E. Gasperikova, 2005, Non-seismic Geophysical Approaches to Monitoring, in *Carbon Dioxide Capture for Storage in Deep Geologic Formations – Results from the CO_2 Capture Project, Vol. 2: Geologic Storage of Carbon Dioxide with Monitoring and Verification*, S. M. Benson (ed), 1071 – 1112, Elsevier, New York.

4. E. Gasperikova and G. M. Hoversten, 2006, A Feasibility Study of Non-seismic Geophysical Methods for Monitoring Geologic CO_2 Sequestration, *The Leading Edge*, **25**, 1282 – 1288.

5. E. Gasperikova and G. M. Hoversten, 2008, Gravity monitoring of CO_2 movement during sequestration: Model Studies, *Geophysics*, **73** (in press).

6. W. L. Pickles and W. A. Cover, 2005, Hyperspectral Geobotanical Remote Sensing for CO_2 Storage Monitoring, in *Carbon Dioxide Capture for Storage in Deep Geologic Formations – Results from the CO_2 Capture Project, Vol. 2: Geologic Storage of Carbon Dioxide with Monitoring and Verification*, S. M. Benson (ed), 1045 – 1170, Elsevier, New York.