Monitoring a large volume CO$_2$ injection: Year two results from SECARB project at Denbury’s Cranfield, Mississippi, USA

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1. Abstract

The Southeast Regional Carbon Sequestration Partnership (SECARB) early project in western Mississippi has been testing monitoring tools and approaches to document storage efficiency and storage permanence under conditions of CO$_2$ EOR as well as downdip injection into brine. Denbury Onshore LLC is host for the study and has brought a depleted oil and gas reservoir, Cranfield Field, under CO$_2$ flood. Injection was started in July 2008 and has now achieved injection rates greater than 1.2 million tons/year though 23 wells, with cumulative mass injected as of August, 2010 of 2.2 million metric tons. Injection is into coarse grained fluvial deposits of the Cretaceous lower Tuscaloosa Formation in a gentle anticline at depths of 3300 m. A team of researchers from 10 institutions has collected data from five study areas, each with a different goal and different spatial and temporal scale.

The Phase 2 study began at the start of injection and has been using pressure and temperature as a tool for assessing permanence mostly in the oil productive interval. Real-time read-out shows high sensitivity to distant changes in injection rate and confirms the geologic model of reservoir compartmentalization. Above-zone pressure monitoring ~120 m above the injection interval is used to test the sensitivity of this approach for documentation of integrity of the confining system in an area of numerous well completions as pressure increase is induced in the reservoir by more than 70 bar.

Monitoring of the High Volume Injection Test (HiVIT) area includes repeat measurements of aqueous geochemistry in the injection zone. Rock-water-CO$_2$ interactions in the reservoir as CO$_2$ dissolves are minimized by
mineral “armoring” by abundant chlorite cement in high permeability reservoir sandstone. Geochemical monitoring of confined freshwater aquifers at depths of 70-100 m is underway. Groundwater analysis focuses on assessment of the sensitivity of this method to detect leakage above background variability. A repeat seismic survey of the HiVIT is planned for late 2010 to assess saturation change especially in downdip brine-only areas.

A study focused on feasibility of monitoring the shallow subsurface to separate leakage from normal complex surface fluxes is underway at an monitoring array installed in October 2009 to assess the interactions of recharge, soil gas, and shallow groundwater aquifers. Recent well re-entry and tracer injection will provide further information to interpret observed elevated deep-sourced methane.

The Detailed Area Study (DAS) is collecting dense time-lapse data from closely-spaced three well array of an injector and two observation wells. The observation wells were completed with fiberglass casing to facilitate electrical resistance tomography (ERT) measurements, and a diverse array of instrumentation was both cemented behind casing and suspended on tubing. Injection started at the DAS December 1, 2009. We have measured pulsed neutron and resistivity via wireline, downhole and above-zone pressure, distributed temperature, and fluid chemistry including introduced pulses of perfluorocarbons, noble gases, and SF₆ as tracers. Between wells, time-lapse crosswell seismic and electrical resistance tomography (ERT) are used to measure saturation change. The goals are to measure changes as fluids evolve from single phase (brine) to two phase (CO₂–brine) in order to document linkages between pressure and sweep efficiency. A time-lapse VSP survey bridges the vertical resolution and areal coverage between cross-well and surface seismic. The repeat surveys for many tools are scheduled for September, 2010.

Reservoir characterization based on cores, historic and new wireline log data, production history, hydrologic tests, fluid analysis, and a three-D seismic survey have been used in multiple numerical models to predict reservoir response in order to design effective monitoring strategies and optimize deployment. History matching of observed response to predicted response is used to interpret results and improve confidence in conceptual models and numerical approaches. Probabilistic methods have been used to assess the significant uncertainties resulting from reservoir heterogeneity.

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2. Introduction

The US Department of Energy has funded seven Regional Carbon Sequestration Partnerships (RCSP) across the United States and portions of Canada and charged them to conduct small- to moderate-scale field tests during the phase 2 validation (2005-2010) and the phase 3 large-scale (defined as one million metric ton) tests during deployment stages of the program. The Southeast Regional Carbon Sequestration (SECARB) partnership led by Southern States Energy Board has four phase 2 tests at or nearing completion and two phase 3 tests underway. This paper provides a progress update and early review of results from a phase 2 and phase 3 test led by the Bureau of Economic Geology and linked to a new CO₂–EOR project conducted by Denbury Onshore LLC at Cranfield Field in western Mississippi.

The injection target at Cranfield Field comprises fluvial sandstones of the Cretaceous lower Tuscaloosa Formation at depths of 3300 m which form a simple anticline with a northwest trending crestal graben. The injection interval is the “D” and “E” sandstones. These units were deposited as part of a coarse grained fluvial complex and are amalgamated to form an internally complex but relatively laterally continuous 6- to 26-m-thick, overall fining-upward zone. Chlorite cement is pervasive in the “D-E” sandstones, and plays a significant role in preserving high porosity and an average 100mD permeability. Red terrestrial mudstones of variable thickness locally isolate the “D-E” units from the overlying less aerially continuous “A” through “C” sandstones. Dark marine mudrocks and fine sandstones of the middle Tuscaloosa are more than 60 m thick and serve as the lowest regional confining system. Thin and aerially extensive marine sandstones form the upper Tuscaloosa and Eutaw formations. A 3-m-thick sandstone with zones of 100 mD permeability are used as the above-zone monitoring interval (AZMI). Below the basal Tuscaloosa unconformity are the marine mudstones and fine-grained, thin sandstones of the Washita-Fredericksburg Formation. Freshwater resources occur in Tertiary clastic units to depths of more than 600 m and
are sparsely used for water supply. The deeply dissected surface is mantled with loess, and used for timber, farming, and gravel production.

Tuscaloosa oil and gas production at Cranfield started in 1944 with drilling of wells in the oil rim below a large gas cap at the top of the structure (Mississippi Oil and Gas Board, 1966). Gas recycle was used to manage pressure until 1959, when the gas cap was produced, decreasing pressure and ending production. By 1966, nearly all the wells were plugged and abandoned and the Tuscaloosa reservoir was idle and in pressure recovery until Denbury began injection for the EOR project in July 2008.

CO₂ injection at Cranfield provides a strong platform for transferable research and technology demonstration related to geologic storage for five reasons:

1) Injection is into porous and permeable sandstones with mudstone confining systems, a typical setting for the Gulf Coast region, so that results can be applied widely.

2) Large volumes of CO₂ are commercially available, so that tests can be conducted to support regulatory and policy development now underway.

3) Denbury’s commercial experience and logistical support in the form of CO₂ handling best practices, pipeline transport, permitting, and liability management has allowed a strong focus on novel and research-oriented tests.

4) Via SECARB-Denbury cooperation, wells were placed further downdip than normal (below the oil-water contact) and injected at higher rates than normal, providing experimental sites with conditions similar to those that will be used for brine storage. The numerous penetrations in the oil rim provide access points for intensive monitoring and are used to assess methods by which permanence can be assured in an EOR setting.

5) Staging the test at the start of the tertiary recovery program has provided information with broad relevance to other sites. In particular, prior to initiation of the CO₂ flood in 2008, the prolonged period of reservoir shut-in allowed recovery of reservoir pressure to near original pressure and fluid reequilibration. Most other EOR fields begin CO₂ flooding directly after secondary and/or other tertiary recovery, which creates a complex environment with respect to pressure and fluid distribution at the start of CO₂ injection. In contrast, CO₂ injection at Cranfield started into a near hydrostatic pressure regime, which is the common initial condition that will be encountered in CO₂ projects that inject into non-productive brine-bearing formations.

3. Statement of research problems

The programmatic objective of RCSP field tests is to demonstrate the ability to inject CO₂ safely and economically into geologic formations where it will be permanently stored in preparation for the commercialization of geologic sequestration. For the tests at Cranfield this goal is divided into three sub-goals (table 1): (1) effective environmental assurance monitoring, (2) extent of CO₂ plume migration in the injection interval predicted, and (3) magnitude and extent of pressure increase resulting from injection predicted. For each of the sub-goals, a hypothesis is set forth to be tested though a series of field experiments. In addition, a number of supporting theories and lab tests are recognized that are out of the scope of this project but can be accessed through collaboration with other projects. For example, we are collaborating on advanced simulation of multiphase fluid flow with the DOE Basic Energy Sciences funded UT Center for Frontiers of Subsurface Energy Security (CFSES) (http://www.utcfses.org).

Table 1. Goals of Phase 3 SECARB research at Cranfield.

| Commercialization goals | Effective environmental assurance monitoring | Extent of CO₂ plume predicted | Magnitude and extent of pressure increase predicted |
|-------------------------|---------------------------------------------|-----------------------------|--------------------------------------------------|
| Hypothesis tested ⇝     | CO₂ is retained in-zone: documentation of no leakage to air & no damage to water | Observed CO₂ saturation is correctly predicted by flow modeling | Observed pressure distribution is correctly predicted by model |
| Field experiments ⇝     | Surface monitoring: verification of groundwater and soil gas approaches. | Bounding uncertainty in reservoir characterization; CO₂ saturation and extent rigorously measured using time-lapse 4-D surface | Measure pressure changes over time and area; Microseismic test |
Above-zone monitoring: pressure, temperature, composition, seismic, VSP, and cross-well seismic, ERT; RST; Dissolution and saturation measured via tracer chromatography.

**Theory and lab**
- Sensitivity of tools; saturated-vadose modeling of flux and tracers.
- Lab-based geophysics under various saturations.tracer performance. Advanced flow simulation with multiphase fluid.

Advanced simulation of reservoir pressure field.

To coordinate the SECARB field experiments with Denbury’s commercial flood, the project was staged in five areas (figure 1) each along it’s own time line.

![Figure 1: Five study areas of the SECARB experiments at Cranfield superimposed on a structure contour of the field](image)

The Phase 2 (Phase II in Figure 1) monitoring program is focused on CO₂ injected into the oil-bearing zone in the northern part of Cranfield and began at the start of injection in July, 2008. The use of pressure response, the “work horse” of commercial field management, was evaluated in the context of sequestration monitoring. A dedicated observation well in the center of the Phase 2 area was completed with a permanent digital bottom hole pressure gauge in the reservoir zone perforated in the Tuscaloosa “D-E.” A second completion with similar gauge was produced by perforating casing at the upper Tuscaloosa monitoring sandstone and was isolated by packers and tubing from the injection zone. In addition to the continuous measurements from gauges, bottom hole pressure was periodically collected from other wells in the Phase 2 region as injection advanced and was used for calibration of a numerical model (Nicot and others, 2009). Schlumberger’s cased-hole, pulsed-neutron reservoir saturation tool (RST) was used to measure change in near well saturation in the Phase 2 area, however it could only be run in a few wells. Lack of “rat hole” below the reservoir and damaged casing prevented access for the long tool string across the perforated interval. In addition, lack of modern log suites limited quantitative assessment options. Injection profiles were used to augment the RST.

Injection of 1 million metric tons/year at 200 bar injection pressure though normal well tubing was predicted to require four to eight widely spaced wells. The area required for this injection is known as the High Volume Injection Test (HiVIT). Monitoring the HiVIT started in April 2009, and includes three test elements (1) repeat 3-D seismic (2) geochemical monitoring of the injection interval fluids though producers, and (3) groundwater quality monitoring. One research question addressed is the extent to which CO₂ migration is limited by formation dip and by pressure sinks at production wells. The repeat 3-D seismic will be used to assess saturation change in the downdip brine areas, as well as observe any changes in gas saturation that result from CO₂ injection in the areas with residual gas. Geochemical monitoring tracks injected CO₂ via its distinctive carbon isotopes and reaction of dissolved CO₂ with rocks. Semi-annual ground water quality monitoring of the HiVIT and Phase 2 area is conducted
using new water wells installed to provide a local water supply at each newly drilled well. These wells provide
excellent access to the shallow confined sandstone aquifers (70-100 m deep) over the injection area. In addition
water supply wells provide more distant access to deeper aquifers. Samples of the shallow aquifers from a coring
program conducted by the University of Mississippi and a stratigraphic study using collected wireline logs provide
inputs to the hydrogeologic model. These data provide needed inputs to assessment of risk to water should CO₂
escape into the aquifer, as well as inputs to sensitivity studies of the value of monitoring aquifers to document
retention.

Effective environmental assurance monitoring is a highly valued component of a monitoring program. We
hypothesize that because of the depth and numerous confining zones, the CO₂ will be retained in the subsurface and
that neither leakage to air nor damage to water will occur. However, without a leakage signal, it is difficult to
determine if the monitoring program is effective. We therefore set out a high resolution array of soil gas instruments
to assess the variability of the natural system and its interaction with the engineered system including well pads,
mud pits, and plugged and abandoned (P&A) well. In reference to a co-assessment of plants, pit, P&A well, and
pad, this array is called the P-site. We used an area of soil gas anomaly identified in a pre-injection soil gas survey,
and started collecting data in late 2009 as CO₂ moved into the reservoir 3000 m beneath the site.

In order to correctly predict the ultimate extent of the two-phase plume, CO₂ saturation must be rigorously
measured and correctly predicted by flow modeling. The Detailed Area Study (DAS) is collecting dense time-lapse
data from an array of three closely-spaced wells. The goal is to measure changes as fluids evolve from single phase
(brine) to two phase (CO₂–brine) flow system and document linkages between rock properties, pressure, gravity, and
sweep efficiency. Injection in the DAS started on December 1, 2009 with time-lapse repeat survey for many tools
scheduled for September, 2010.

The first step to developing a flow model is deterministic and probabilistic characterization of the reservoir using
available data. Data in the project are diverse and abundant, and include four cores with many types of analyses:
historic and new wireline log suites, production history, hydrologic tests, fluid analysis, and baseline cross-well and
three-D seismic survey. A pattern of cross-cutting channel geometries showed significant inter-well variability with
at least one locally continuous fine-grained zone at the DAS wells. These data have been used in multiple numerical
models and represent the reservoir at several scales and with various types of interpolation. Model results predict
reservoir response to injection, which was in turn used to design monitoring strategies that are sensitive to
uncertainties. We selected subsurface instrument deployments that could measure many different types of reservoir
response. A closely spaced array comprising an injector with two down-dip observation wells along the 112 m
(DAS) provided a “window” into a section of the evolving two-phase plume. Observation wells were completed
with fiberglass casing across the reservoir and had many types of installed instrumentation deployed on casing, on
tubing, and through tubing. Wireline deployed tools included Schlumberger RST, resistivity, and borehole gravity
(BP experiment). Casing deployed above-zone pressure and distributed temperature were used to measure in-zone
retention. Fluid chemistry was sampled with the LBNL U-tube and USGS Kuster sampler to recover introduced
pulses of perfluorocarbons, noble gases, and SF₆ tracers. Between wells, time-lapse cross-well seismic and LLNL
electrical resistance tomography (ERT) are used to measure saturation change. The tools are designed to measure
changes as fluids evolve from single-phase (brine) to two-phase (CO₂–brine) in order to document the relationship
between pressure and sweep efficiency. Large uncertainties exist in quantifying two-phase flow within a
heterogeneous reservoir. High quality measurements can be used to constrain and model this uncertainty so that the
error in plume-size estimate can be more confidently expressed. A time-lapse VSP survey bridges the vertical
resolution and areal coverage between cross-well and surface seismic.

This project should not be used as a general model for a commercial test plan. The design was developed in
research mode to test conceptual and numerical modeling approaches and monitoring tools to support future
commercial monitoring projects, but it is itself not a commercial monitoring program. It is noted that the complex
installations used in the experiment had a number of instrument failures. In a research environment the value of data
makes the risk of some data loss acceptable. However, in a regulated environment such failures might have a
negative impact on performance metrics. The test plan focuses resources on obtaining in-depth information from
specific locations at the DAS and P-site rather than documenting retention over the whole field. By test end, it is
hoped that results will provide guidance on how to deploy and sequence monitoring approaches. For example some
types of measurements can be used as flags for possible non-conformance; other types of measurements are then
deployed to assess possible issues should a non-conformance flag require it. In addition, the measurements selected
for the Cranfield experiment were limited to those that could be effectively tested and were pragmatically possible at this site. Some important tests could not be conducted at the site. For example, the post-injection stabilization of the plume will not occur until after the cessation of the EOR project and therefore is not part of this test.

4. Overview of early results of the monitoring program

Injection was started in July 2008. Injectors were active first, then as pressures in the reservoir increased, production started. The early stages of the project are therefore not influenced by production and are identical to a solely sequestration project. As production increases, the pressure sinks around producers become more important, which is a less direct analog for a solely sequestration scenario. Because the field was developed in stages, the early injection-only stage of the project is repeated as each section is brought under flood. Injection is now occurring at rates greater than 1.2 million tons/year though 23 wells, with cumulative injected mass, as of August, 2010, of 2.2 million metric tons. In August 2009 recycle made up less than 5% of the CO2 but has increased until the percentage of field-wide recycle average is approaching 30%.

Injection at four brine-leg Phase 3 wells was increased to attain the 1-million tonnes per year rate in mid December, 2009. Field-wide pressure in the reservoir has increased 50 to 100 bars from initial 311 bars. At the DAS, initial injection rates were kept modest, 180kg/min at the start of injection, and stepped up incrementally to observe reservoir response. Opening the valves at wellhead to near full field pressure (200 bar) produced a pressure increase at bottom hole to 413 bars. However, pressure stabilized well below fracture pressure, suggesting that the reservoir was not at a limit and could accept a higher injection rate if surface pressure was increased or larger diameter tubing installed.

The Phase 2 program is nearing completion. High resolution pressure data from reservoir at the dedicated observation well has been used to observe reservoir response to increased injection rate over 1 km distances, which shows that although the fluvial reservoir is stratigraphically complex with multiple incised channels, pressure communication is good (Meckel and others, 2009). Injection profiles and RST logging show a pattern of preferential CO2 flow into different reservoir intervals within the “D-E” reservoir interval, confirming a model of reservoir complexity. CO2 migration to the dedicated observation well was slower than modeled. CO2 arrived in July 2010, two years after the start of injection ~220 m away. More analysis is underway to attempt to separate possible factors causing slow response, which include interaction of reservoir complexity with two-phase flow and injection and production patterns. Lack of response to pressure changes across the northeast fault offsetting the reservoir interval confirms the characterization model of reservoir compartmentalization. This demonstration shows the value of the pressure approach to establish compartment boundaries in future sequestration reservoirs without production history.

Above-zone pressure monitoring is being used to test the sensitivity of this approach for documentation of integrity of the confining system in an area of numerous well completions. As pressure in the reservoir was increased by more than 70 bar by injection, a subdued and delayed <7 bar response in the above-zone monitoring interval is interpreted in several ways, with slow local behind-casing flow considered the most likely (Meckel, in prep). Repeat downhole fluid sampling will be used to evaluate this hypothesis and determine if the hydraulic connectivity is sufficient to transmit CO2. Complex dual completion of the 60 year old remediated observation well adds engineering-related complexities to pressure signals that are difficult to interpret uniquely.

A deterministic model of the Phase 2 area using the GEM simulator and early characterization data has been used to obtain a good history match with pressure observations at time steps (Nicot and others, 2009). Other model options are under consideration to integrate the data collected in this area.

In the HiVIT, produced fluids have been sampled to assess the results of more than a year of CO2-rock-water reaction, and additional sampling is planned. Isotopic composition of gases in produced fluids show an evolution from minor dissolved CO2 in native brine to dominantly injected CO2. Change in major and minor elements, pH, and alkalinity are small even in samples with dominantly injected CO2 (Thordsen and others, 2010). Minimum rock-water reaction is tentatively interpreted as the result of preservation of permeability by grain-rimming chlorite cement, which has slow reactivity with dissolved CO2. Calcite and siderite cements are observed in cores from the reservoir, but these cements may have occluded permeability and removed rocks containing them from active flow. Laboratory batch reaction of reservoir rocks in fluids at pressure is underway at National Energy Technology Laboratory. Noble gas research underway at University of Edinburgh (Stuart Gilfillan, 2010, personal
communication) will be used to further assess rock–water reaction. The final element of the HiVIT monitoring program will be collection of a repeat 3-D seismic survey in fall of 2010 to assess the areal changes in gas distribution.

Dense data collection at the DAS followed the start of injection in December, 2009 and data collection to complete the cross well and VSP program is planned for fall, 2010. Good hydrologic connection (average of 100 mD over 20 m perforated zone) between the F1 injector and the F2 and F3 observation wells was observed during the pre-injection water production and reinjection test program. In addition, pressure response to start of injection at distant wells shows that the DAS area is hydrologic well connected to the rest of the area; this supports the use of open boundary conditions for fluid flow simulation. Pre-injection modeling using multiple probabilistic realizations of small scale heterogeneities related to fluvial channel geometries produced a wide range of migration paths for CO₂, including realizations that CO₂ injected at F1 would by-pass the closer F2 well and arrive first at the F3 well. Fluid sampling with the U-tube sampler documented first arrival for CO₂ (breakthrough) at the F2 well by day 9 of injection, at the early end of the predicted arrival times. CO₂ was then detected by day 13 at the F3 well, documenting very fast transport and non-radial flow. As injection rate was increased to 500 kg/minute, near the maximum that the injection tubing would accept at field pressure, tracer arrival became faster at the F3 well. This response is interpreted as indicative of a heterogeneous flow system in which complex behavior from changes in relative permeability and capillary pressure as fluid saturations change. Significant information about the development of the flow system and rate of CO₂ dissolution derived from exsolution of dissolved methane from formation water as CO₂ dissolved. An overall decrease in methane shows that the pore fluids are depleted of methane over a period of months, but pulses of increased methane in the overall decreasing trend document that CO₂ is accessing new rock volumes and developing new flow paths.

Electrical resistance tomography (ERT) was successfully deployed for the second time in a CO₂ setting and for the first time at these depths. Initial inversions of daily cross well surveys showed apparently meaningful changes in fluid resistivity as low-conductivity, free-phase CO₂ displaced high conductivity brine. In the observation field between the F2 and F3 wells, a low-conductivity tongue was initially observed low in the profile from the F2 (injection side) that advanced slowly between the wells. A second low-conductivity area, not connected to the first, was then observed in the upper part of the flow field, intersecting the F3 well. Accepting the inversion as a correct map of the approximate distribution of CO₂ between wells suggests that this geometry was the cause for fast CO₂ arrival at the F3 well. A favorable sinuous flowpath in the upper part of the injection zone diverted flow around the F2 well to intersect the F3 well. The ERT inversion also showed an area of increased resistivity appearing soon after the start of injection above the reservoir near the F2 well. Additional analysis of diverse data is needed to determine if this is an indication of out-of-zone migration. Other features such as a persistent high-conductivity plume require further work to separate signal from possible numerical artifacts.

Logging with the Schlumberger reservoir saturation tool (RST) and interpretation of tool response shows patterns of saturation change similar to the ERT across the reservoir interval with increase in CO₂ concentrated low in the perforated interval in the F2 well and high in the F3 well. In addition, change in near-wellbore fluids is seen along much of the perforated interval. This change is tentatively interpreted as invasion of permeable sandstones from CO₂ inside the well bore flowing out through the perforations.

Upcoming work at the DAS includes repeat cross-well seismic that is designed to be co-interpreted with the ERT constrain the spatial distribution of CO₂ and attempt to increase the accuracy of saturation estimates. A VSP survey includes a walk-away and areal distribution of shot points to attempt to resolve the geometry of the plume in down-dip settings. This will complement and increase in-zone resolution of the repeat surface seismic.

The P- (pit-pad-plant)-site study is designed to investigate the interactions of natural CO₂ sources with constructed features typical of sequestration sites, including gravel well pads and pit excavations formerly used to handle drilling mud. The site selected for follow-up was one in which anomalously elevated methane and CO₂ concentrations were detected during reconnaissance of areas near plugged and abandoned (P&A) wells. Detailed sampling of soil-gas and near-surface water showed that the anomaly (as much as 34% methane and 45% CO₂) was persistent over an area of the pad near but not directly over the P&A well (Romanak and others, 2010). δ¹³C and δD isotopic signature of gasses is consistent with a deep source for methane (not microbially produced at the pit or within the vadose zone) and CO₂ derived from biodegradation of thermogenic methane in the near-surface. No salinity anomaly suggestive of leakage of fluids from depth was detected. The P&A well was re-entered and
remediated as a producer in July 2010. Tracers were emplaced into the lower Tuscaloosa through old perforations prior to cementing and recompletion with perforations in a deeper interval. Observation of near surface fluids at this site will continue after well remediation to look for tracer signal or change in methane concentration or isotopic composition. An assessment is underway to determine the sensitivity of geochemical response of the aquifers to any possible leakage events. Complexity because of past oilfield activities, composition and seasonal variability of groundwater, and the impact of carbonate-poor aquifer host sediment are under consideration.

5. Summary

The staged field tests monitoring high volume injection at Cranfield are increasing confidence in monitoring and modelling techniques that can be used in-zone, above zone, and near surface. The goals of this study are to develop and test monitoring strategies (1) for effective environmental assurance, (2) for predicting and monitoring the extent of CO₂ plume migration in the injection interval, and (3) for predicting and monitoring the magnitude and extent of pressure increase. Diverse approaches have been tested with a research focus on intensive and detailed deployments. Early successful measurements include documentation of the details of two-phase flow in a complex fluvial channel setting. High frequency geochemical measurements of methane exsolution and of introduced tracers show non-radial flow through preferential intervals that evolve through time and with changes in injection rate. A preliminary interpretation of cross-well ERT yields complementary and corroborating measurements of sinuous localized flow paths. Other tests to show retention of CO₂ in zone are awaiting further data collection in upcoming repeat sampling trips and additional joint analysis with data already collected. Several more years of observation and analysis at this site are planned.

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