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Frio Brine Storage Experiment—Lessons Learned

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Abstract

The Frio Brine pilot is a closely monitored, small-volume (1,600 tons), short-duration experiment using injection of CO_2 into high-permeability brine-bearing sandstone to test the feasibility of geologic sequestration. The experiment differed from the geoscience and engineering community's extensive previous experience in injection of CO_2 and other fluids into the subsurface. It was, from inception to completion, focused on assessing monitoring strategies. An important objective of this study is to convey lessons learned to the next generation of developers of geologic CO_2-injection-pilot projects. For the experiment, CO_2 was injected for 10 days 1500 m below the surface. The evolution of the plume was successfully monitored with diverse tools, including downhole pressure and temperature, wireline logging, fluid sampling, cross-well techniques, and vertical seismic profiling. The injection period was brief and the formation was steeply dipping with high permeability; therefore the nineteen months since injection period takes us well into the post injection phase of monitoring. As predicted, CO_2 remains stored within the formation. Surface leak detection techniques have thus far failed to detect any clear evidence of leakage except immediately above the injection zone, probably through engineered systems.

Keywords: CO2 field test, monitoring, phase trapping,

Introduction

The Frio Brine Pilot experiment is a first-of-its-kind field investigation into the feasibility of modelling and monitoring CO_2 injected into brine-filled sandstone to assess the permanence of the storage. The project is funded by the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) and lead by the Bureau of Economic Geology Jackson School of Geosciences, The University of Texas at Austin. To provide a strong test of the capability of monitoring, we assembled a diverse team of experts including Sandia Technologies (field service provider), researchers from the GEO-SEQ consortium (Lawrence Berkeley, Oak Ridge, Lawrence Livermore National Labs), National Energy Technology Lab, U.S. Geological Survey, Schlumberger, Praxair, Paulson Geophysical, Alberta Research Council, CO_2CRC-CSIRO, Core Labs, University of West Virginia, and Department of Petroleum Engineering at the University of Texas at Austin.

The Frio Brine Pilot has four goals: (1) demonstration, in an open and rigorously monitored setting, that CO_2 can be injected into a brine formation without adverse health, safety, or environmental effects, (2) testing capabilities of diverse monitoring technologies in measure the fate of injected CO_2, (3) testing the validity of conceptual, hydrologic, and geochemical models, and (4) developing the experience necessary to optimize the next generation of larger scale CO_2 injection experiments. In this paper, I review the results of the study with the emphasis on achieving the fourth goal, providing recommendations relevant to the next generation of field tests.

Methodology

The pilot site was selected in two steps. The first selection criterion was that the site provide a pragmatic demonstration from which results could be upscaled to support very large injection projects.

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The area chosen was the Tertiary age Frio Formation of the Gulf Coast of Texas, USA; a brine-bearing formation that underlies many industrial and power plant sources of CO_2 in this region. This geology is typical of clastic wedges on the training margins of many continents. The Frio Formation has the additional advantage of being well studied as a result of a century of exploration for oil and gas and decades of successful use as a waste-injection horizon. The high-porosity (as high as 35%) regionally extensive sandstone has large capacity and has multiple shale seals to ensure permanence of storage. The second site selection criterion was to design an experiment that would maximize research benefit and minimize both health and safety hazards and the risks of experimental failure. No large volume source of CO_2 from a pipeline was available in the selected region, therefore cost, safety, and timeline considerations favoured selection of a small volume of representative sandstone for the test. Selection of a small volume also permitted data to be collected with high temporal and spatial resolution, and allowed the test to evolve rapidly from a test of injection to a test of post-injection storage. Selection of a high permeability (2.5 Darcy) sandstone unit with a steep dip (16º) forced rapid migration, also allowing post-injection migration and stabilization to occur rapidly.

Results

The project team has elsewhere presented in-depth analyses of the results of a number of tools, measurement, and monitoring conducted at the site (see reviews at www.beg.utexas.edu/mainweb/presentations/2005_presentations/2005co2seq.htm). Here, we focus on analyzing how the elements interlocked. The final project timeline is shown in figure 1.

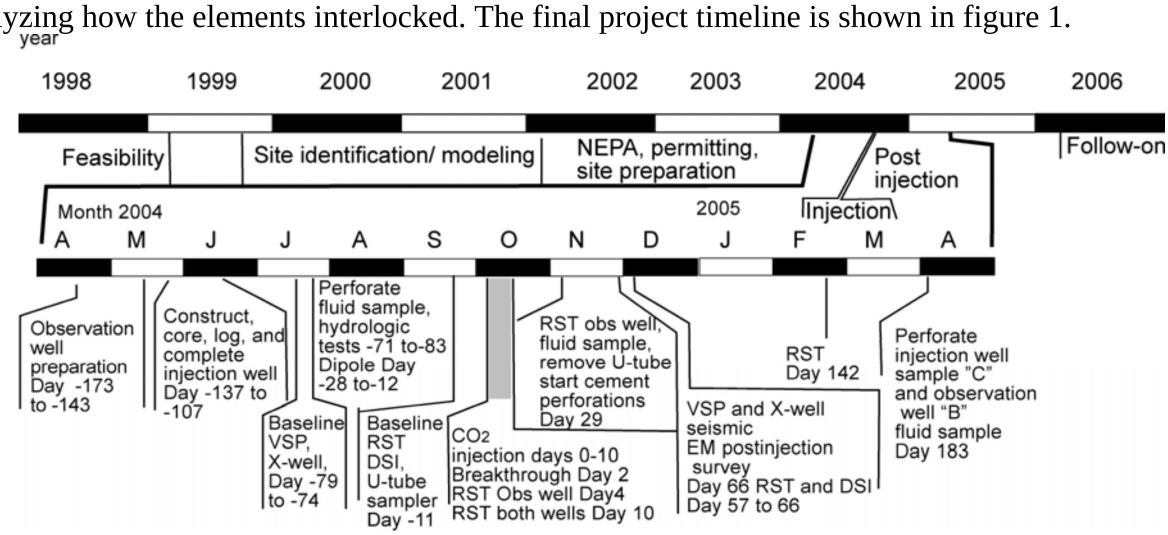

Figure 1. Frio pilot timeline

Successful strategies worthy of duplication in future demonstrations and large-scale injection are: (1) high-quality characterization prior to injection; (2) numerical modelling integrated with all phases of the project; (3) cross-comparison of multiple types of measurements; (4) use of wireline logs for monitoring plume movement; (5) data collection focused on selected azimuths; (6) above-zone monitoring for leakage; and (7) traditional groundwater monitoring for leakage. Several significant elements were selected for testing during the Frio 2 Project. This project will inject and monitor in a new sandstone interval accessed though the same wells.

High quality characterization was essential in providing qualitative data to facilitate realistic models [1,2]. We used traditional oil-reservoir and disposal-well reservoir characterization techniques extensively, for example using well logs to map high permeability fluvial channels in sandstones and interpreting the continuity of shale seals in a seismic volume. However, some innovative approaches, such as extensive preinjection hydrologic characterization [3,4] also proved informative. The storage volume was characterized with a 24 hour two-well pumping test to document sandstone permeability and continuity. In addition, a two well interference test with fluorescent water-soluble dye was used to characterize tracer performance under single phase conditions to be compared with tracer tests during

CO_2 injection using gas-soluble tracers.

Numerical modelling of flow guided site selection, well design, and tool selection and were key in designing a successful project, as well as analyzing and interpreting the results. Input of predicted reservoir conditions after injection from TOUGH2 [5,6] was used to select and stage appropriate tools. Prediction of plume thickness, saturation, and pressure change eliminated tools with low probability of success and those that could not be effectively implemented under experimental conditions and substituted tools that could accomplish required tasks. Model predictions also resulted in revisions of engineering design and experimental timelines. For example a thinner injection interval was selected and the injection well was drilled closer to the observation well after modelling predictions revealed uncertainties that the CO_2 would be recovered in the observation well with the original design.

In addition, modelling refined the parameters that were poorly known but significant in predicting CO_2 movement, which further refined experimental objectives to obtain these data.. The key uncertainly was determining the correct assumptions controlling two phase behaviour during injection and post injection migration. The pore fraction that would fill with CO_2 under open steeply dipping conditions was uncertain and would strongly influence plume thickness and rate of outward migration of the CO_2 during injection. The correct residual gas saturation during the post injection period under conditions where CO_2 was migrating updip because of buoyancy was also uncertain and was selected as an important parameter to document though post-injection observations. Modelling was also used to understand observed geochemical changes.

Cross-comparison of measurements made using different techniques provides a critical check on precision and accuracy of measurements. For example, we measured plume evolution using direct sampling of fluids [7], with a suite of gas-phase tracers having different solubilities [4], with saturation logs [8], with crosswell seismic, and wth VSP [9]. It was, however, impossible to create optimal conditions for each instrument in a single test; compromises were made, and success is dependent on making thoughtful compromises. One issue that limits data collection is space within the borehole for tubing, instruments, cabling, hangers, packers, and clearance for other downhole activities. Co-location of tests requiring formations fluids in the borehole, such as fluid sampling, tracer recovery, and pressure measurement with downhole seismic that required a full diameter of controlled borehole was also difficult, requiring numerous workovers and limiting the tools that can be emplaced. For Frio2, we have selected a smaller tool set, including an installed cross well seismic array, U-tube fluid samplers in both wells, and an RST logging program.

Wireline logging, the most standard tool for assessing fluid distribution in oil reservoirs, proved useful in monitoring evolution of the CO_2 plume along the plane of the injection and monitoring wells, which sampled one radius of the plume. Comparing changes in saturation in the observation well over time calculated from the Schlumberger RST to the modelled saturation in this same well (Figure 2) shows that by the time the first log was collected 4 days after injection, the plume was slightly better developed than had been modelled. The assumptions, simplifications, and corrections used in the calculation of saturation from RST log response are significant and are described by Sakurai and others [8] and Müller and others [10]. The CO_2 moved radially out from the injection well over the 3-m perforated interval, with fastest flow in the upper and higher permeability zones. Fluids produced by the U-tube, and downhole pressure responses from stationary transducers and logs showed that the observation well bore filled from the base of perforations to the packer with CO_2 over 15 hours following breakthough. The highest CO_2 saturation measured in both wells was on day 10, at the end of the injection period. CO_2 saturations near 100% in high permeability parts of the injection well show that drying of residual water occurred as predicted where large volumes of dry CO_2 passed thought the pore system. The largest non-correspondence between the predicted and observed CO_2 saturation is that the observed CO_2 plume moved more effectively upward through the layered muddy sandstones at the top of the “C,” showing that layering was more discontinuous than assumed in the model.

After the end of injection, saturation declined quickly as CO_2 moved updip away from the injection well. By the time the day 29 log was collected, saturation has decreased to about half its maximum

value. Only minor changes in saturation were observed in the next four months. Recent RST logging showed that saturation at the wells remains stagnant 16 months after the end of injection. This supports the model prediction that saturation will decrease until relative permeability to gas nears zero, at which point the plume will stall. This response is interpreted as suggesting that CO_2 is trapped as snapped-off bubbles and in dead-end pores. A duplicate measurement of saturation with more stable well bore conditions to optimize quantification is planned for the follow-up Frio2 test.

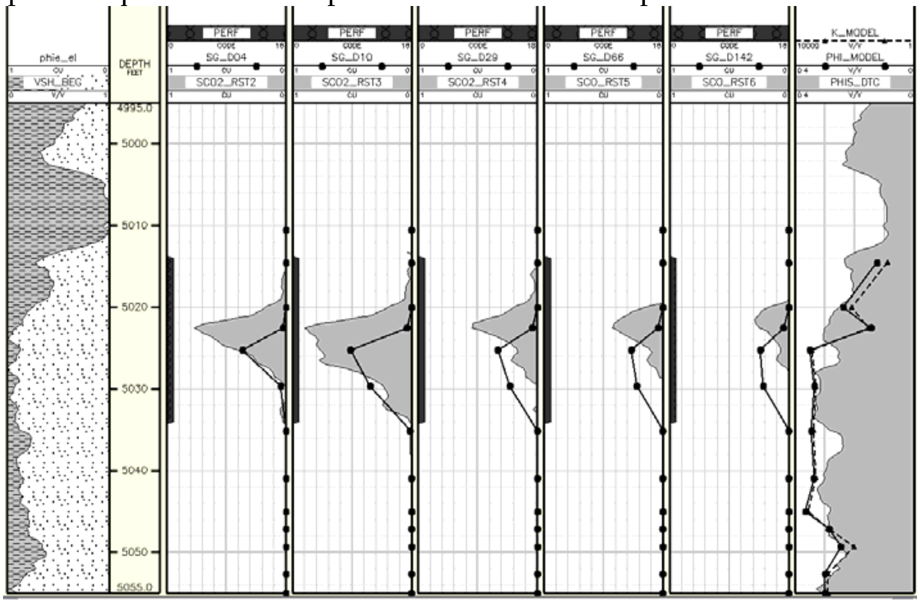

Figure 2. CO_2 saturation at the observation well calculated from RST logs (grey fill), compared with modelled changes (black dots and lines) in saturation per layer plotted at layer midpoint. Day 66 and 142 logs are corrected for borehole effects by simple subtraction of the above-background saturation, and they should be considered less quantitative. Porosity from log (left track) is compared with simplified model input porosity (right track). Depths in feet below KB datum. Figure prepared by Shinichi Sakurai with input from Christine Doughty.

To further test this conceptualization, we produced CO_2 from the injection well at month 16 after the end of injection. The top of wellbore was filled with gas-phase CO_2, with atmospheric pressure at wellhead. Below 100 m, brine filled the well, and it failed to flow when the well was opened. Swabbing the well to produce brine decreased pressure about 14 bars in the injection zone and the well produced brine under weak CO_2 lift as CO_2 expanded in the formation. The ratio of water to gas was 13,600 to 1, and CO_2 was produced at an average of 0.17 tons/hour, but the rate did not decline during the one day production period..

One choice that this study made differently than previous studies was to test downhole seismic tools and focus on high resolution data on selected azimuths of the plume rather than the a surface-collected seismic survey used for monitoring at Sleipner and Weyburn injections. Seismic monitoring was based on the difference between a pre-injection baseline and an assessment three months after injection. Vertical seismic profiling (VSP) used three sets of surface sources (explosives) on different radii of the plume and a downhole receiver string in the injection well to demonstrate a rapid and moderate cost method to show that the plume is more asymmetrical than modelled. The cross-well seismic difference tomogram showed vertical variations between the injection and observation well in impedance contrast that is inferred to represent supercritical CO_2 saturation. Cross-well tomography generally matches the RST log response and confirmed the model prediction of plume spread but showed more heterogeneity within the plume. Strong seismic signal suggests that a third time lapse repetition late in the post injection period would be successful and useful to confirm plume stabilization

One simple but innovative technology tested in this study was monitoring in the first sandstone above the injection zone. At the Frio site, this above-zone monitoring interval is the Frio "B" sandstone,

separated from the injection zone in the upper "C" sandstone by 15 m of interbedded shale and sandstone. The above-zone monitoring interval is below the regional main seal, the Anahuac Formation. Monitoring includes measuring gas saturation during the experiment using RST logging and producing fluids from the zone at the end of injection. RST logging showed no change in free gas saturation, and downhole fluid sampling [11] confirmed this result. Fluid sampling, however, detected anomalies within the "B" that suggest that contact with CO_2 had perturbed the chemistry. PFT tracers were detected [12], dissolved CO_2, alkalinity, and metals are slightly higher than baseline "C" values[11]. Additional testing is being conducted to determine if this fluid is leaking directly from the "C" into the wellbore because of failure of a cement "squeeze" to seal a perforation connecting the "C" injection sandstone to the well. Alternative leak paths are behind casing though remedial cement or though a natural flaw in the seal between the "B" and "C". In future tests, expansion of this monitoring to include pressure measurement and acoustic receivers to detect gas migration in this zone might be worthy of consideration.
Monitoring at the surface for leakage signal was not effective in detecting any leakage because the natural and induced noise was large and the pre-perturbation baseline period was short. Examples of natural variability include a high and variable water table, which resulted in poor recovery of soil gas and contamination of instruments by mud, and high natural CO_2 flux because of the swampy forest setting [13]. This warm and wet region does not have a period of quiescent biological activity during which to identify a leakage signal. Examples of perturbation include atmospheric release of tracer during sampling, and enhancement of groundwater recharge by well-site activities. Venting CO_2 during the purge cycle of the U-tube sampler released tracer to the atmosphere, which resulted in rapid tracer detection in the soils around the injection wells. This aerosol contamination obscures any leakage signal that might have formed later at other possible leak points [14]. We pioneered a test of monitoring groundwater chemistry up-gradient and down-gradient of the injection point. We expected that groundwater might serve to detect any near surface leakage via a change in pH, alkalinity, or metals. Groundwater composition changed rapidly during the monitoring period [15], with a preinjection region of high salinity migrating down-gradient across the monitoring array. We tentatively attribute these groundwater changes to improvement of the well pad and construction of a large fresh-water-filled mud disposal pit. Bicarbonate, which might serve as a leakage signal, was variable, but against this background of groundwater evolution, it is difficult to interpret.

Conclusions

The Frio experiment has demonstrated the effectiveness of employing a number of relatively low-cost monitoring techniques in concert. This has built a strong case demonstrating the validity of modelling to accurately predict performance of the subsurface in retaining CO_2. High-quality characterization prior to injection including baseline hydrologic testing is important in designing a successful program, as well as essential to quantitative numerical modelling. Characterization was used to build predictive models, which were then used to design a parsimonious but effective selection of tools. Numerical modelling is recommended though all phases of the project from site selection, though design, field activities, and during analysis. The performance of a number of tools to detect and quantify the distribution of CO_2 was demonstrated, and comparison among the measurements increased confidence in each tool. Cross-comparison of multiple types of measurements is useful in interpreting plume evolution. Wireline logs were shown to be an effective tool for monitoring plume movement including the post-injection stabilization of the plume. Data collection focused on selected azimuths provided an adiquate understanding of plume evolution at lower cost and with higher sensitivity than coverage of the entire plume area with surface 3-D seismic. Above-zone monitoring for leakage at depth is suggested as alternative or complement to surface and near-surface monitoring. Detection of small amounts of leakage near the surface may be a challenge because of the large variability characteristic of the near surface zone.

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