

Frio Brine Pilot: the First U.S. Sequestration Test

Susan D. Hovorka – Gulf Coast Carbon Center, University of Texas at Austin.

Sandstones of the Frio Formation east of Houston, Texas were selected to test the feasibility of using carbon capture and storage (CCS) in geologic formations to reduce atmospheric buildup of greenhouse gases. The Frio Brine pilot study was based on two small-volume, short-duration carbon dioxide (CO₂) injections into two previously unperturbed brine-bearing sandstones. These injections were designed to answer questions about CCS using a process of intensive multiphysics monitoring before, during, and after injection, with subsequent history-matching to test the accuracy of numerical models of flow and geochemical changes.

Prior to this study, experience with trapped buoyant fluids such as oil, methane, and CO₂ provided reason for optimism that CO₂ injected for storage would be retained in analogous settings for long periods of time. But previous storage experience was only in formations (reservoirs) from which hydrocarbons had been extracted. The volume of those fluids constitute a fraction of the CO₂ produced from combustion of fossil fuel; if significant CCS is to occur, injection into brine-bearing formations that have never held hydrocarbons will be needed. Moreover, the natural accumulation of hydrocarbons is typically much slower than the rate of injection that would be used to sequester large volumes of CO₂.

Thus, testing was needed to examine storage in unperturbed formations. A pre-injection study showed that a small area could be more

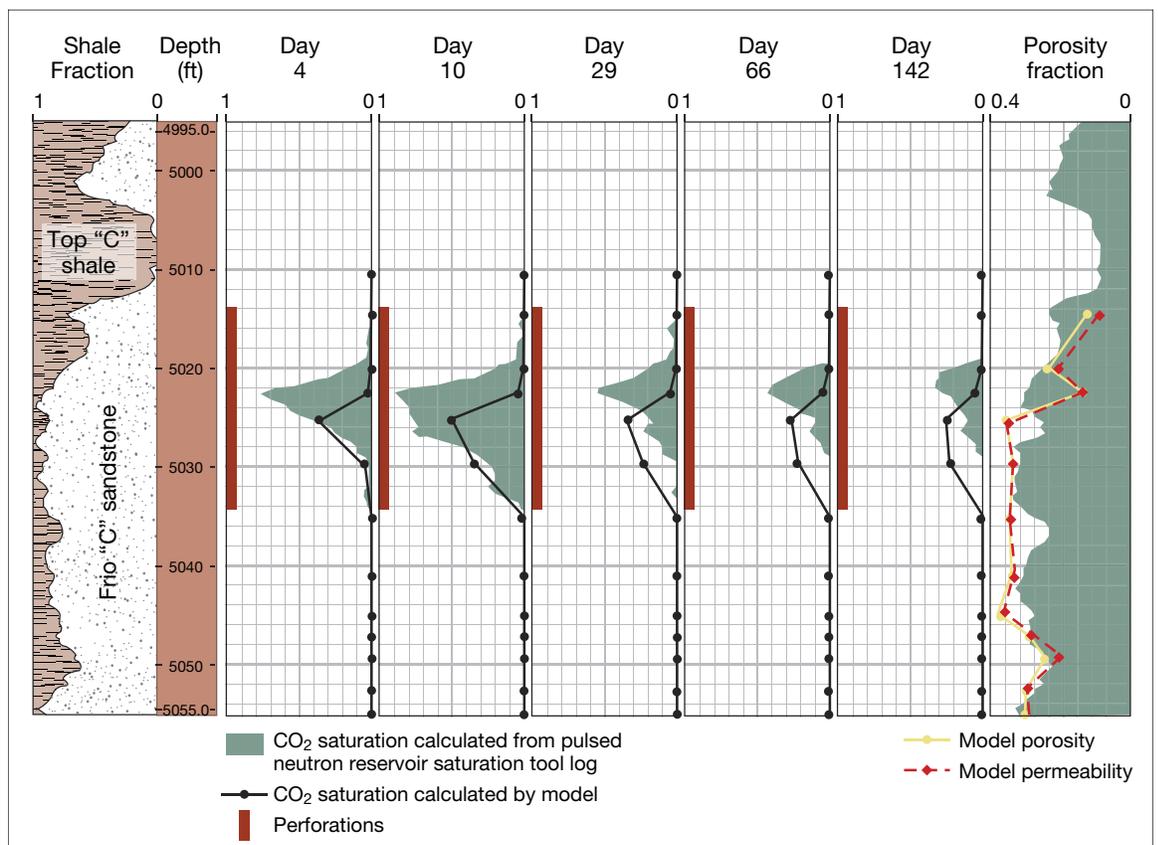
rigorously monitored than a large area, and that limiting injection time to a short period would allow observation and monitoring through all stages of the process through post-injection stabilization, thus providing critical information relevant to the performance of large-scale, long-duration tests.

Finding a Site

High permeability, steep local dip, and limited lateral flow were considered desirable formation characteristics that would allow rapid equilibration within the experiment. The need for a well-characterized site, as well as budgetary and public-acceptance considerations, led us to seek brine-bearing sandstones within an oil-field

setting. Texas American Resources Company made available a site in South Liberty Field, south of Dayton, Texas, where the upper Frio Formation lies between a shale confining zone above and an oil-producing formation below. A new injection well was drilled and an existing production well was modified to serve as an observation well.

Existing and new borehole-based geophysical measurements, a 3-D seismic survey, geochemical sampling, and core analyses provided detailed characteristics of the formation that were used to test conceptual hydrologic and geochemical models in advance of the injection tests. Additional hydrologic and tracer tests provided data on permeability between wells. Detailed modeling using



Permeability from log calculations and averages used in TOUGH2 simulation. Saturation logging illustrates the displacement of brine by CO₂. Shaded areas show calculated CO₂ saturation with depth in the observation well; at the end of injection (Day 10), saturation was the maximum observed. After injection, CO₂ saturation decreased as the plume spread. The black lines show the modeled concentration of CO₂. During injection, CO₂ moved outward more rapidly than predicted. The slight offset in the location of the plume between the model prediction and test results is due to higher reservoir heterogeneity (lower bed continuity) than in the model. The key result is that the CO₂ was trapped in the formation by capillary forces as predicted. Figure prepared by Christine Doughty from data provided by Shinichi Sakuri.

TOUGH2, a numerical simulation model for multiphase flow, was performed throughout the tests (Doughty and others, 2007). Good matches between modeled and observed CO₂ saturation imparted confidence in model predictions of CO₂ movement and permanent storage.

Post-injection measurements showed that CO₂ migration under gravity slowed greatly two months after injection.

Geophysical logging, pressure and temperature measurement, and geochemical sampling were also conducted during injection to allow comparison of pre- and post-injection conditions (Hovorka and others, 2006). Monitoring objectives were to measure changes in CO₂ saturation during the months following injection in cross-section and aurally, and to document accompanying changes in pressure and temperature using gas-phase and aqueous tracers and brine chemistry.

Test No. 1

The first test, conducted in September 2004, injected about 1,600 tons of CO₂

at a depth of 5,050 feet below the surface over 10 days; observations were collected over 18 months. Initially the front of the CO₂ plume moved more rapidly than had been modeled, but by the end of the 10-day injection, the plume geometry in the plane of the observation and injection

wells had thickened to a distribution similar to that modeled (see figure, left).

As expected, part of the CO₂ dissolved rapidly into brine, causing pH to fall and calcite to dissolve (Kharaka and others, 2006). Unexpectedly large amounts of iron (Fe) and manganese (Mn) were also dissolved in the initial fluids as CO₂ moved through the rock-water system. Concentration decreased after injection but did not fall to initial values. Geochemical modeling conducted by Lawrence Livermore National Laboratory predicted that iron would be present only in trace amounts. No manganese phase was predicted from

mineralogic study, however the Fe-Mn spikes were duplicated in the laboratory in follow-up testing. We deduce that these metals were released by small amounts of high-surface-area, reactive trace minerals such as clay or fine pyrite, which were then depleted. In addition, contamination by fluids that reacted with the steel tubing contributed to the amount of iron released.

Post-injection measurements showed that CO₂ migration under gravity slowed greatly two months after injection. This matched modeled predictions that a significant amount of CO₂ would become trapped as relative permeability to CO₂ decreased as a function of saturation, a common two-phase capillary trapping process known from hydrocarbon production. A production test months after the end of injection was unable to produce significant CO₂, demonstrating that it was effectively trapped because saturation had decreased to near-residual and relative permeability to CO₂ was near zero.

see Frio Brine, page 31



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Test No.2

In September 2006, the second injection test was conducted using the same injector/monitoring wells, but the injection was into the Frio Blue sandstone, a hydrologically separate formation 390 feet below that investigated in the first test. This test injected a smaller volume (about 250 tons) of CO₂ over five days into the lower part of a 30-foot-thick unit in a heterogeneous fluvial sandstone and monitored the stabilization. A low injection rate was used to simulate processes at the edge of the plume, where attenuated injection pressure causes buoyancy to exert a significant influence on flow processes, as was observed in the results. A seismic source-and-receiver system set up by Lawrence Berkeley National Laboratory provided CO₂ migration data that could be fully integrated with other concurrent borehole measurements (Daley and others, 2007).

Seismic data were collected every 10 seconds during injection and provided 3-D information on CO₂ migration. During injection it traveled vertically near the injection wall and laterally through a thin

high-permeability zone; it was detected near the top of the Frio Blue sandstone at the observation well 100 feet away. Differences in measurements from the two different injections illustrate the interactions among injection rates, injection strategy, the heterogeneity of the injection interval, and their impact on plume evolution.

Meanwhile, Back on Top...

The feasibility of near-surface monitoring in this setting using soil-gas fluxes and concentrations, introduced tracers, and shallow-aquifer response was also tested. High complexity in seasonal aquifer level and composition was noted in this high-water-table, warm environment that had been perturbed by the developed oil field with roads that pond drainage. Introduced tracers were used to document no leakage of CO₂ to the surface. The test site was closed when the experiment ended in May 2009.

Another important objective of the Frio Brine study was to gain public acceptance of CCS. This was accomplished through outreach, which included site visits by researchers, local

citizens, and environmental groups; media interviews; and an online log (www.gulfcoastcarbon.org). The public and environmental concerns expressed were moderate, practical, and proportional to the minimal risks taken by the project, and generally related to issues such as traffic and potential risks to water resources. Overall, press coverage was positive. ■

Contact Susan Hovorka at susan.hovorka@beg.utexas.edu.

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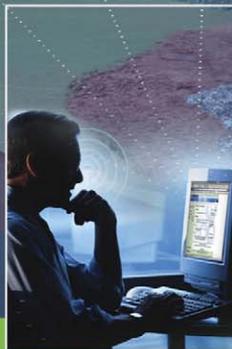
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