

Assessment of CO₂ Enhanced Gas Recovery in Shale Gas Reservoirs (Preliminary)*

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Abstract

In 1993, the U.S. DOE conducted five CO₂/sand hydraulic fracturing in the Devonian Ohio Shale in eastern Kentucky to compare the effectiveness of cryogenic with hydraulic and nitrogen stimulations. The study concluded that CO₂ hydraulic fracturing cleans up faster and demonstrate higher flow rates than conventional stimulations. Subsurface assessment of sequestration opportunities suggests black shale is both an effective seal for carbon storage in deeper reservoirs and a potential target for sequestration. In 2005, a study of adsorption in the Ohio Shale in Kentucky concluded CO₂ is preferentially adsorbed with respect to CH₄ at an average volumetric ratio of 5:1. Preferential adsorption may contribute to the enhancement of CH₄ production rates. In 2007, the Kentucky General Assembly passed an energy incentives bill that included a mandate and funding to test the black shale for CO₂ enhanced gas recovery. A new study was initiated to identify candidate wells, conduct reservoir modeling to design a test protocol, and conduct a pressure transient test simulating recompletion of a well to acquire data to improve understanding of enhancing production from gas shales.

An existing vertical shale well in Johnson County, eastern Kentucky, was identified for CO₂ injection testing. The site also includes a shallow twin well drilled to the Mississippian Big Lime carbonate and two offset shale wells for pressure monitoring. The test well was drilled in 2002 and is cased, cemented, perforated in the Mississippian Berea Sandstone and Devonian shale, completed with a nitrogen hydraulic fracturing, and exhibits a shut-in pressure of 320 psia. Pretest spinner and reservoir saturation logs were run and will be compared to a suite of post-test logs. Downhole memory gauges were installed to acquire a continuous record of bottom-hole temperature and pressure. Surface pressure and temperature data loggers were installed on the test well and each monitoring well. Tubing and packer were run to isolate the perforated interval in the Ohio Shale below 1,264 feet. Up to 100 tons of CO₂ was injected over three days in September 2012 at up to 980 psi and flow rates to 1.5 Mcf per minute with shut-in periods allowed for pressure fall-off. This presentation will summarize the results of analyses conducted to date on the data collected during this test. Data and insights acquired during this test are expected to improve understanding of CO₂ utilization and the possibilities for enhanced recovery in shale gas reservoirs.

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Presenter's notes: On going data collection, analysis, and modeling suggest CO₂ injected into organic-rich gas shales may sequester CO₂ and enhance natural gas production. I'd like to review our current project to test CO₂ enhanced gas recovery in shale. This is a joint research project with Advanced Resources International and the participation of Schlumberger Carbon Services.

Motivation

- **1993 DOE study of cryogenic/sand frac**
 - Cleaned up faster
 - Higher flow rate than conventional
- **CO₂ EGR in coal, San Juan Basin**
- **CO₂ preferentially adsorbed**
 - Immobile
- **Storage capacity assessments (MGSC, MRCSP, SECARB)**

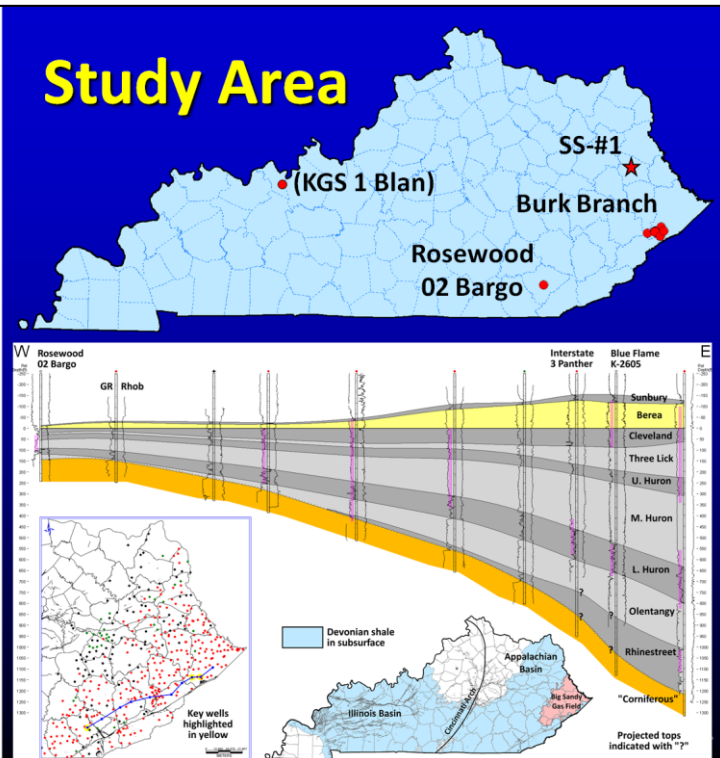
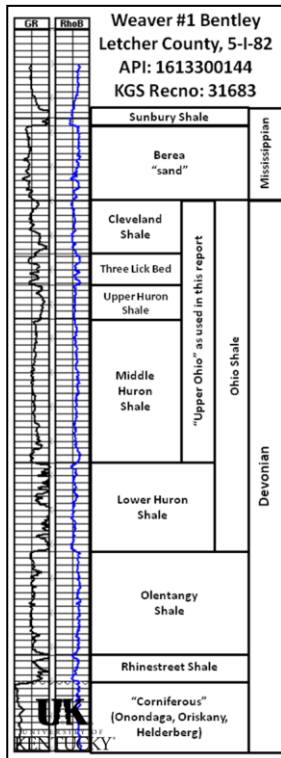
Presenter's notes: This project is motivated by several factors. DOE studies found that CO₂ fracs cleaned up faster and had higher flow rates than conventional stimulations. CO₂ enhanced gas recovery in coals of the San Juan Basin have been demonstrated. Studies have shown that CO₂ is preferentially adsorbed in organic-rich shales. Based on these indicators, CO₂ storage capacity in organic-rich shales has been assessed, but it remains a speculative option.

House Bill 1, 2007

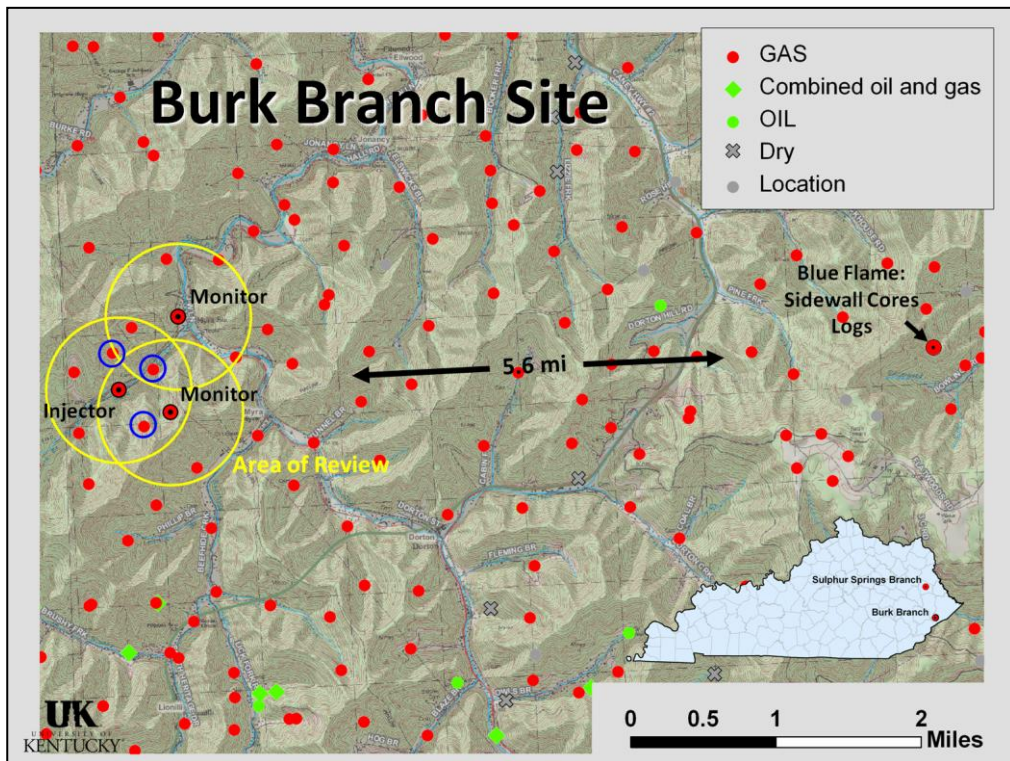
- **Mandated KGS to study carbon storage**
- **Granted \$5 million**
 - West Kentucky
 - Deep test (Hancock County, complete, TD 8,126 ft)
 - EOR (Hopkins & Henderson Counties, complete)
 - East Kentucky deep test (TD 4,835 ft)
- **East Kentucky Devonian Shale pilot test**



Presenter's notes: In 2007, the Kentucky General Assembly adopted House Bill 1, the Incentives for Energy Development and Independence Act. The proactive act recognized Kentucky's dependence on coal and the need to address future environmental concerns. The act directed the Kentucky Geological Survey study carbon sequestration and granted \$5 million in seed funding to jump start the research. The eastern Kentucky Devonian shale pilot test is one of the mandated research areas.



Presenter's notes: Initially, the Burk Branch Site in southwest Pike County, eastern Kentucky was identified. The Rosewood 02 Bargo well is a key well used in the study because of the core, log suite, and core analyses available. Shale rock properties data have also been acquired from the KGS 1 Blan deep saline injection test well in the New Albany Shale of the Illinois Basin. In eastern Kentucky, the shale sequence is thickens eastward with the Lower Huron being the most persistent and consistently completed zone across Kentucky. Note that the Rhinestreet is the lowermost of the organic-rich Devonian shales in the subsurface of eastern Kentucky; the older Marcellus shale pinches out westward along the basin margin before extending into Kentucky.



Presenter's notes: The Pike County Fiscal Court nominated a potential test well and nearby wells for subsurface monitoring. The test well is a cased hole completion in the Lower Huron. This ruled out additional logging and coring to better characterize and model the shale in the test well. To complement the data available for the Rosewood well, data were acquired from the Blue Flame K-2605 Batten and Baird well.

Blue Flame K-2605 Batten & Baird

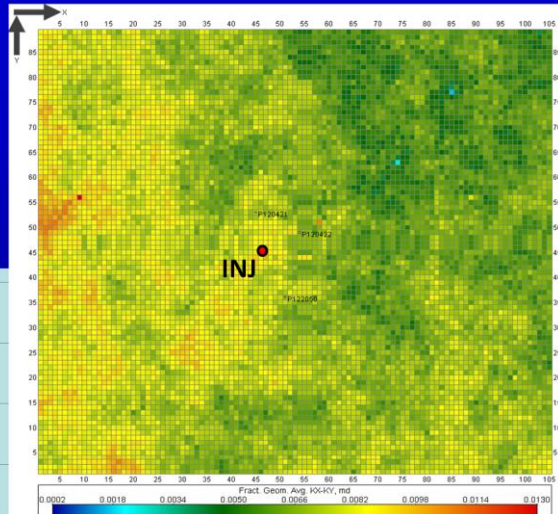
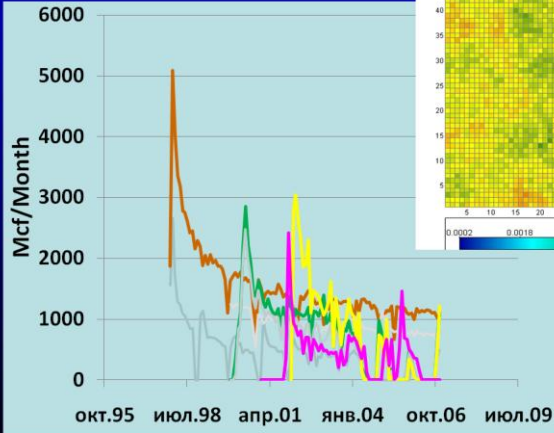
- Standard open-hole logs
- ECS (for shale analysis)
- 19 rotary sidewall cores and drill cuttings (calibrate ECS)
- Tight rock analysis:
 - ϕ , k , XRD, TOC, SEM, thin sections

Funding and support from:
Battelle/MRCSP – Piggy-back well program
Chesapeake Appalachia
State of Kentucky (House Bill 1)
Schlumberger Carbon Services

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Presenter's notes: The Blue Flame well was drilled using air rotary tools to a depth of 5,036 feet. A standard open-hole nuclear suite and elemental capture spectroscopy logs were acquired along with 19 rotary sidewall cores and cuttings for shale characterization and tight rock analysis were acquired.

Permeability Distribution



Shale Gas Production

Presenter's notes: Production and rock properties data were then used to model the permeability distribution and other reservoir properties for simulating injection and to provide insight into designing a well test.

Comparison of Recoveries

320 Acres, 300 tons CO₂

		Injection		Base Case (no injection)	
Case		Cum Prod (MMcf)	Recovery (%)	Cum Prod (MMcf)	Recovery (%)
Full thickness (200 ft. L. Huron)	Huff-n-Puff	7.5	0.2	7.9	0.2
	Continuous Injection	43.6	1.4		
Half thickness	Huff-n-Puff	5.8	0.4	6.1	0.4
	Continuous Injection	33.8	2.2		
Tenth thickness	Huff-n-Puff	3.8	1.1	4	1.2
	Continuous Injection	22.8	6.5		

Presenter's notes: Huff-and-puff scenarios did not indicate incremental recoveries using the expected test volumes of CO₂. Continuous injection scenarios showed incremental recoveries over the base case and is better testing procedure. Funding limitations controlled the available test options.

Interstate #3 Panther Land

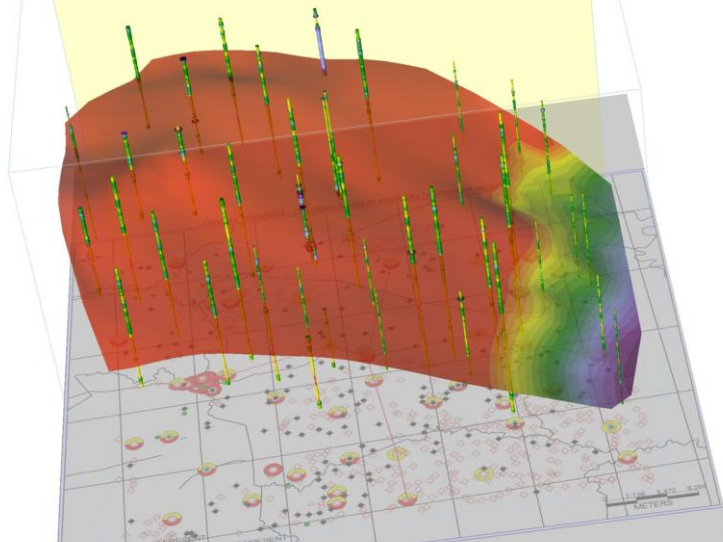


Presenter's notes: The test well is located beside an access road across an embankment in an inactive area of a coal mine site. However, during site access and well test negotiations, the site owner decided it was not in the best interest of their future plans to participate and the site was withdrawn.



Presenter's notes: A new eastern Kentucky site was identified in Johnson County, Eastern Kentucky that includes an test well and 3 monitor wells. The minerals, surface, and wells are owned by Crossrock Drilling of Pikeville, Kentucky.

Site Characterization



Presenter's notes: Characterization of the new site proceeded with digitized well logs, stratigraphic analysis, and isopach and structure mapping.

Crossrock SS-#1 Well Site



Presenter's notes: In May 2002, the SS-#1 well was drilled to a total depth of 1,910 feet in the Silurian below the Devonian Olenitangy Shale. 4.5-inch casing was cemented, perforated from the Mississippian Sunbury Shale to the Devonian Ohio Shale, a nitrogen fracture stimulation was conducted, and then the well was shut-in. The SS-#1A was drilled in June 2002 to a total depth of 825 feet in the Mississippian Big Lime to exploit a porosity zone identified in the Big Lime of the SS-#1. The SS-#1A was also shut-in. This provided an ideal situation for earliest possible detection of CO₂ leakage toward the surface.

Baseline Logging



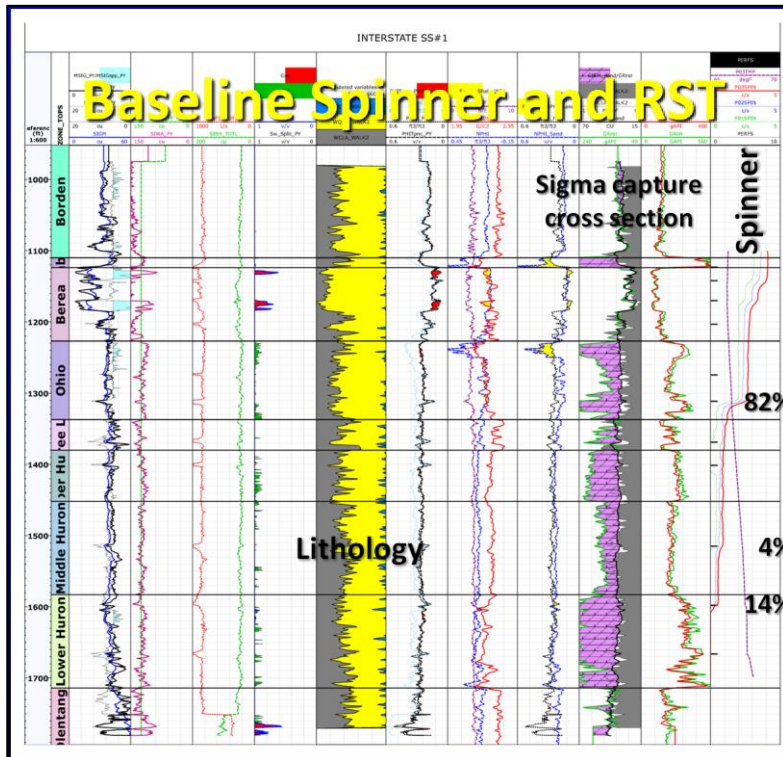
**Multi-arm caliper
(perfs and casing collars)**



**Spinner
(flow profile)**



Presenter's notes: The SS-#1 is cased and perforated across the Devonian Ohio Shale. As such, production logs were the only option for acquiring additional reservoir information and, being a Kentucky shale well, no fluids could be loaded into the gas-filled hole. A multi-arm caliper tool was run to acquire data on the casing and to verify the locations of perforations and a spinner log was run to get a flow profile.



Choice of production logging services was limited by gas-filled borehole.

RST is a pulsed neutron tool.

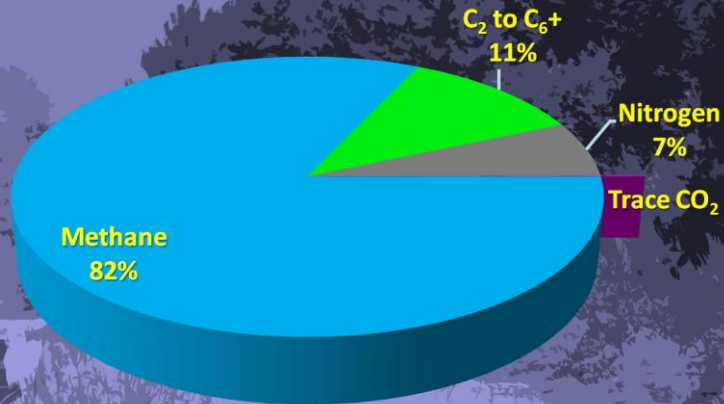
Presenter's notes: To supplement a suite of standard open hole nuclear logs run before the well was cased, a reservoir saturation tool (RST) was run in both lithology and sigma capture cross section modes to acquire baseline reservoir data. It is thought that by comparing pre- and post-test sigma logs CO₂ may be detected in the formation.

DataTrap for Surface Monitoring



Presenter's notes: Multiple, baseline, pre-test gas analyses were acquired from all wells. The test well and each of the monitor wells were equipped with surface monitors to continuously record pressure and temperature data.

SS-#1 Pre-test Gas Analysis



High N₂ from N₂ fracture stimulation



Presenter's notes: The pre-test gas analyses revealed an average of 93% hydrocarbon gases, some nitrogen remaining from the fracture stimulation and a trace of CO₂.

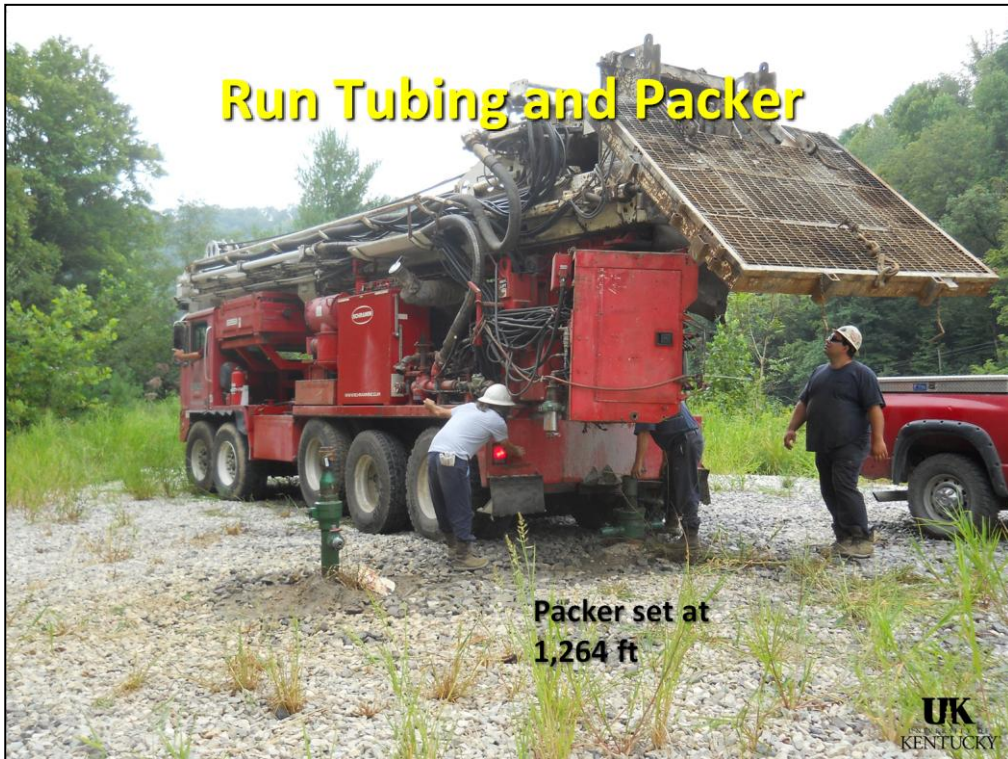
Rigging Up to Run Bottom Hole PT

Dual monitors set at
1,724 ft

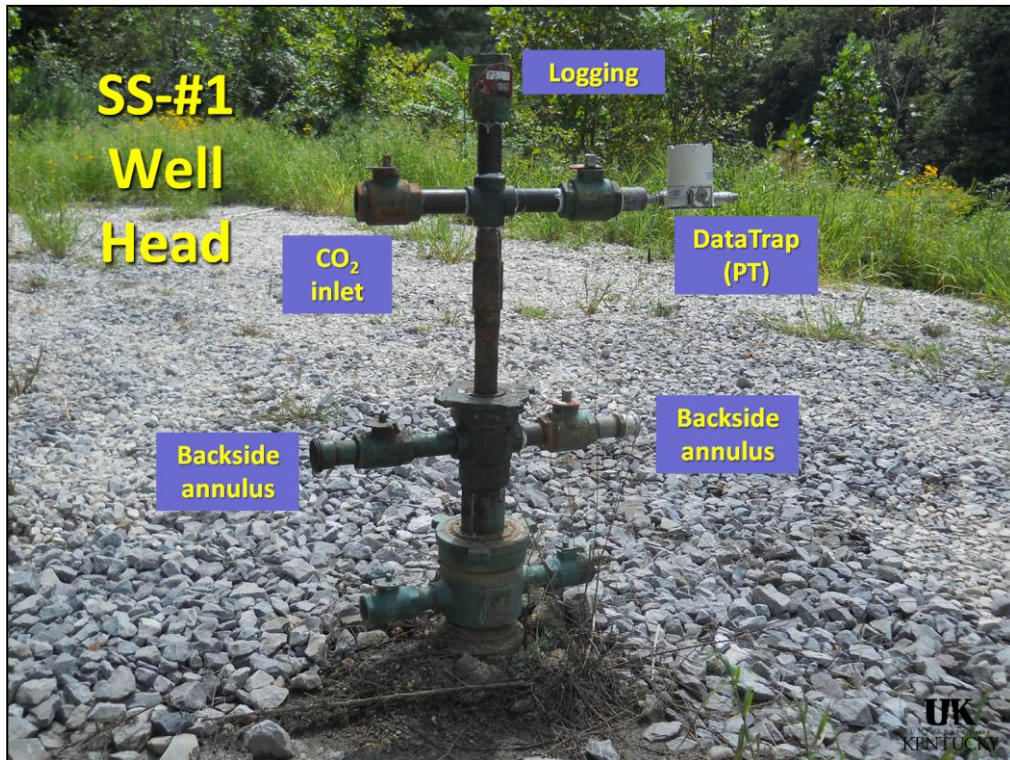


Presenter's notes: A final test protocol was established to use CO₂ to conduct a pressure falloff test to acquire reservoir performance data. To record a continuous record of downhole pressure and temperature redundant downhole memory gauges were deployed on a casing hanger set at 1,724 feet, below the deepest perforation.

Run Tubing and Packer

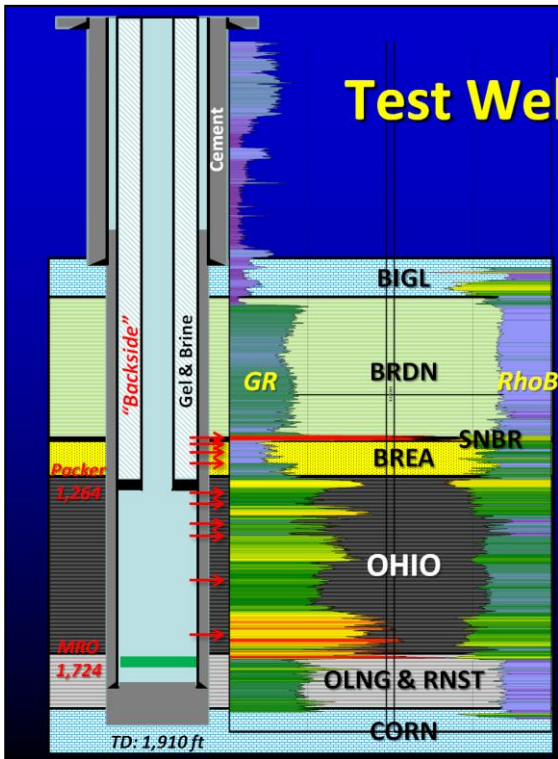


Presenter's notes: Tubing and packer were run to 1,264 feet to isolate perforations in the shale. The backside casing-tubing annulus was filled with gel across the perforations in the Sunbury and Berea and then filled with brine to surface.



Presenter's notes: The well head provided full-port ball valves for access to the tubing for logging, surface pressure and temperature monitoring, and CO₂ injection. Two additional valves provided access to the annulus between the tubing and casing, the "backside." Additionally, two full-port ball valves provided access to an annulus between the 4.5-inch and 7-inch casing that were unused in this test.

Test Well Schematic



- **Tubing & packer at 1,264'**
 - Gel across perfs & KCl brine to surface on backside
- **Perfs**
 - 4 above, 1,126' to 1,204'
 - 6 below, 1,274' to 1,672'
- **Downhole memory gauges at 1,724'**
 - Continuous pressure & temperature

Vertical scale approx.

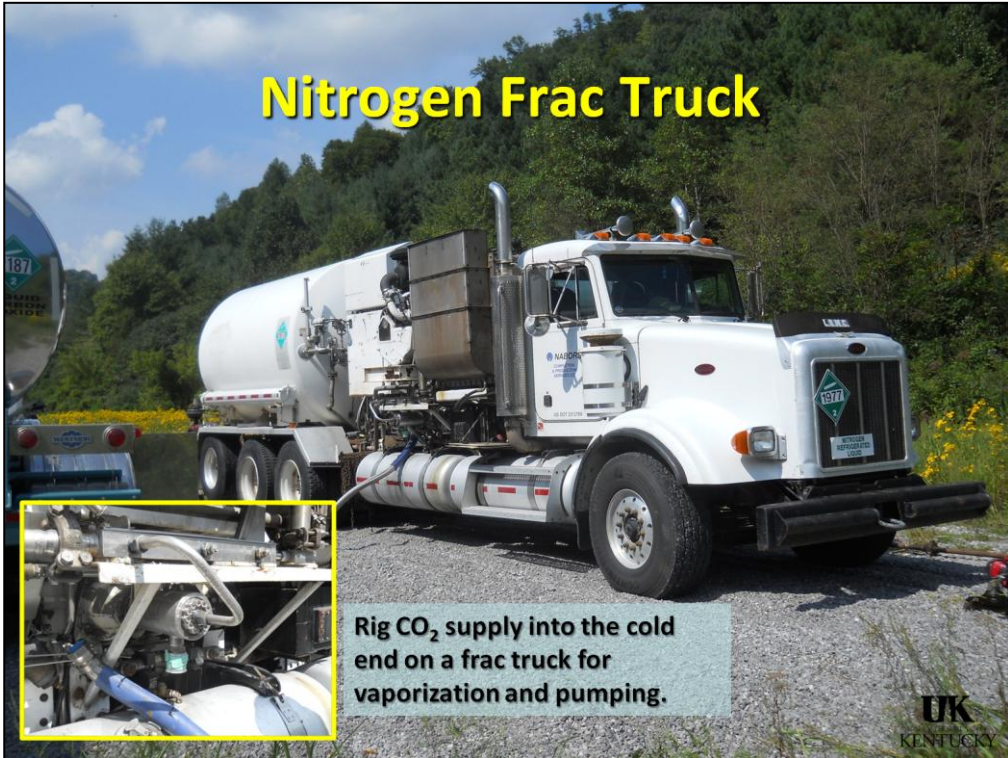
Presenter's notes: The final well configuration includes both surface conductor and 7-inch casing cemented to surface, 1,810 feet of 4.5-inch casing perforated from the Sunbury Shale to the Ohio Shale that were nitrogen fracture stimulated. CO₂ was introduced through 2-inch tubing with a packer at 1,254 feet and recorded bottom hole data using redundant memory readout gauges set at a depth of 1,724 feet.

Onsite CO₂ Storage and Transport



Presenter's notes: CO₂ on site included a bulk storage tank (90 to 100 tons) and a CO₂ transport with transfer pump for delivering liquid CO₂ to our pumping system.

Nitrogen Frac Truck

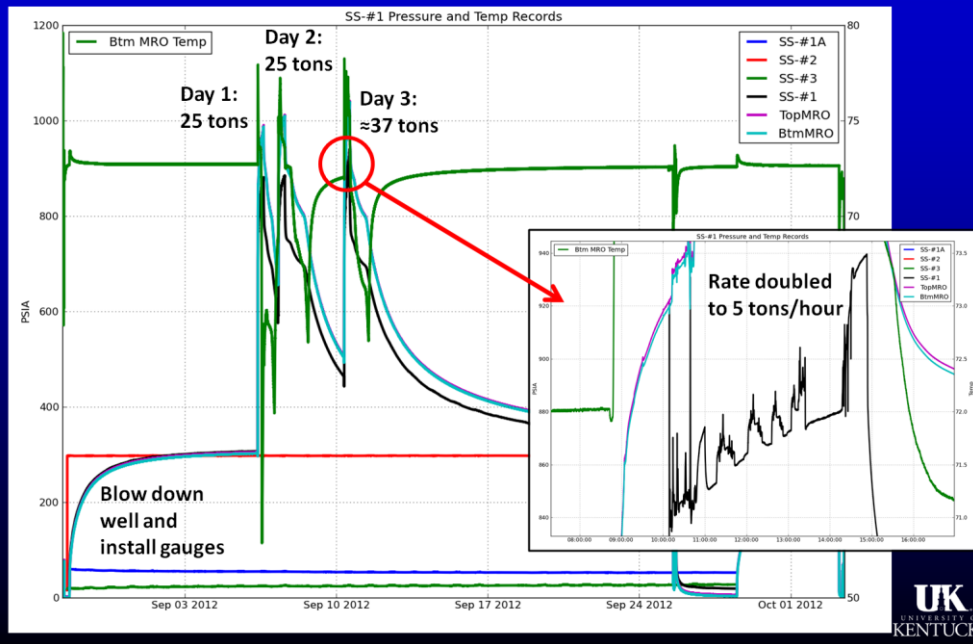


Presenter's notes: An industry-standard nitrogen frac truck provided a vaporizer to heat the CO₂ and pump it at various rates to the well head. The frac truck and associated data van provided means to record pump rates, pressures, and temperatures. CO₂ was heated to 100 degrees which then cooled along the supply run to about 90 degrees by the time it reached the wellhead.

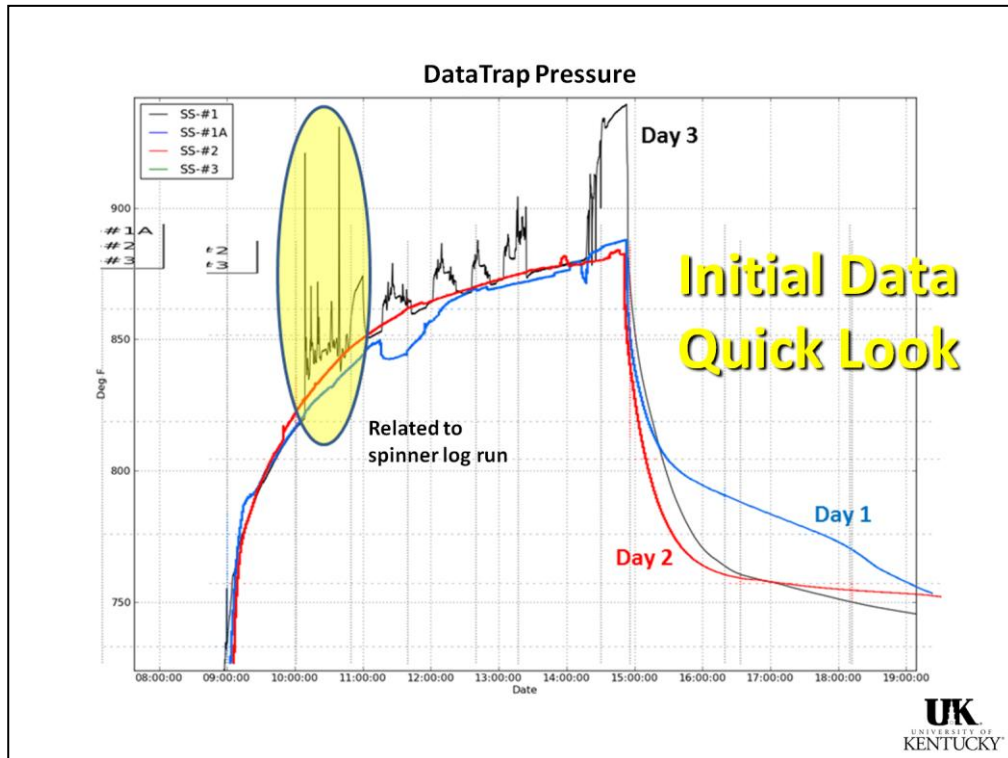


Presenter's notes: Active injection testing occurred over 10 hour stretches for 3 days with allowances for pressure falloff. The injection rate was held at 2.5 tons of CO₂ per hour with the surface pressure response rising throughout an injection phase to 900+/- psi. Rates were selected to keep the pressure below the frac gradient to prevent inducing additional fractures.

Continuous Pressure Record



Presenter's notes: Continuous pressure and temperature records were acquired. The records for the monitor wells apparently do not show pressure changes that would indicate migration out of the completed zone (SS-#1A) or displacement of natural gas to surrounding wells (SS-#2 and SS-#3).



Presenter's notes: Operations ceased October 3 when the tubing and packer were pulled and the down hole gauges retrieved. A second spinner survey run on slickline during the final day of testing was unsuccessful due to a memory card failure. A backup plan was adopted to run the spinner survey during flowback of the well.

Backside Annulus Pressure



Presenter's notes: A pressure gauge installed on the backside annulus indicated the possibility of a packer failure or communication through the formation into the Berea (perforations above packer). Consensus was reached to discontinue the test having injected approximately 87 tons of CO₂. Backside pressure was observed to fall off.

Meter Run for Flowback



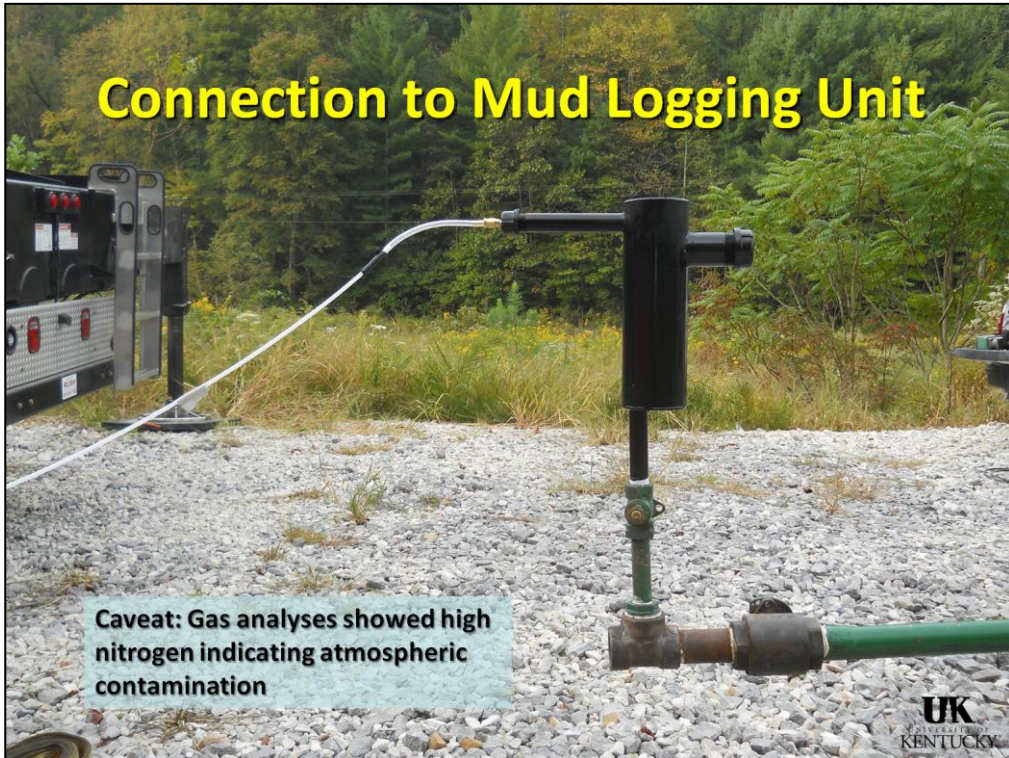
Presenter's notes: At the end of the test, a meter run was rigged to measure the flowback and acquire gas samples to monitor the CO₂ recovered. Here, a spinner run is being rigged in to acquire data during the flowback.

Orifice Meter to Monitor Flow Rate, Pressure, and Volume



Presenter's notes: A standard digital orifice meter was used to monitor and record the flow volume.

Connection to Mud Logging Unit



Caveat: Gas analyses showed high nitrogen indicating atmospheric contamination

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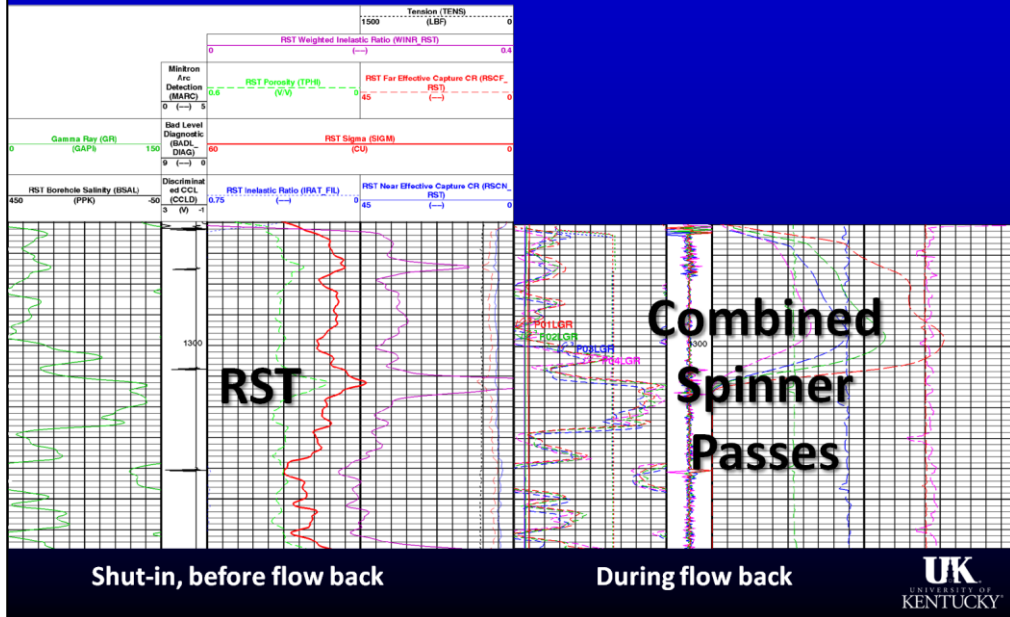
Presenter's notes: An isolation chamber was rigged to provide a low-pressure feed for a chromatograph usually used for mud logging.

Bloodhound and Gas Sampling



Presenter's notes: The Bloodhound is a compact, self-contained gas chromatograph used for mud logging. It measures C_1 to C_4 , CO_2 , and H_2S . Isotube samples were collected to calibrate the "gas units" output by the Bloodhound to mole percent and to acquire data on additional gases (N_2 and O_2).

Post-test Logging



Presenter's notes: The post-test logging suite included a second RST run in sigma mode (before flowback) and multiple spinner passes (during flowback).

Packer Assessment



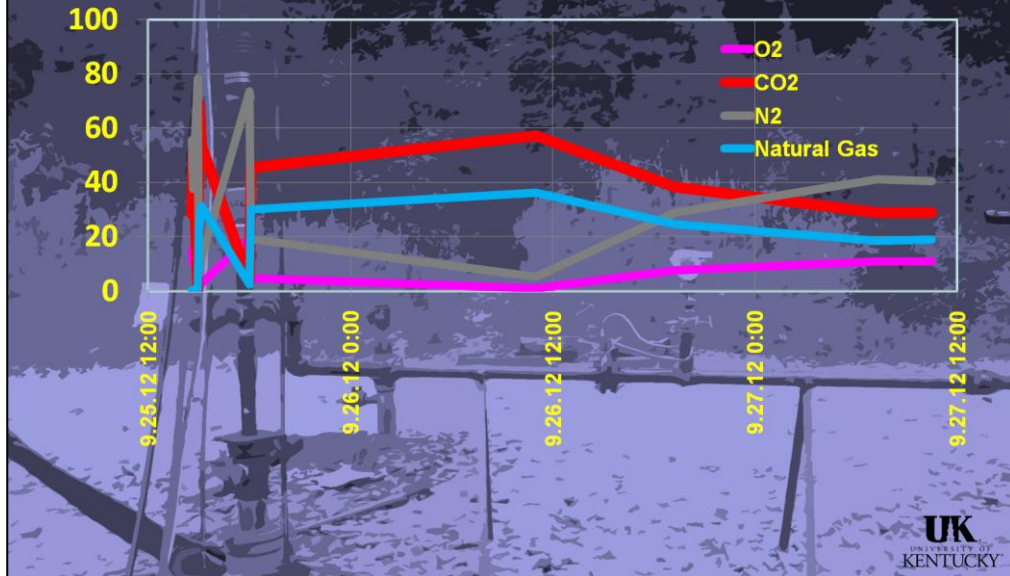
Presenter's notes: The packer was inspected after pulling it. Consensus was that the packer set properly and did not fail. This indicates communication through the formation was responsible for the increased pressure observed on the backside annulus. Almost all of the brine and gel in the annulus was recovered indicating only a small volume may have been lost to the formation through the open perfs above the packer.

Cumulated variables
$\hat{\mu}_1$ $\hat{\mu}_2$ $\hat{\mu}_3$



Presenter's notes: The similarity of the sigma capture cross section responses of hydrocarbon gases and CO₂ rendered it difficult (if not impossible within the resolution of the tool) to differentiate between the gases in a gas-filled hole. However, the sigma as an analog of resistivity can be used to estimate water saturations. Log analysis indicates bound water was likely moved by CO₂, suggesting CO₂ interactions with the shale matrix.

Gas Composition During Flowback



Presenter's notes: During flowback, as flowing tubing pressure declined, gas compositions stabilized. Near the end of the flowback, increasing nitrogen (gray) and oxygen (magenta) fractions indicate atmospheric contamination at lower pressures.

Preliminary Findings

- Can pump CO₂ with a N₂ frac truck
- No migration of gas to monitor wells was observed
- Well test analysis (on going)
 - Communication to backside annulus was through formation
 - Effective permeability increase
 - Linear flow indicates open fractures
- CO₂ can be detected with RST tool in a gas-filled hole

Caveats

- Ideal well
 - Cored with modern log suite geared to shale
 - Cased and completed only in target interval
 - Several years of production data
 - Beggars can't be choosy
- Isolation chamber for gas sampling unit should be farther away from discharge end of meter run

Thanks. Questions?

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