# Characterization of a Coalbed Fire Near Durango, Colorado: Pilot $CO_2$ Injection Test Summary

**Investigators**

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**Abstract**

This report describes results from the final six months of research on the physical mechanisms that control the behavior of uncontrolled fires in subsurface coal beds. For a detailed discussion of background and previous work on this project, please see the 2009 progress report (Harris et al., pp. 117-144[1]). New results include sensitive magnetometer surveys that revealed the locations of zones where the coal is currently burning, zones that have burned previously, and zones that have not been affected by the fire. Based on previous modeling and field measurements, a pilot test of $CO_2$ injection was designed. Subsequent to the completion date of the project (December 31, 2009), the pilot test was conducted. Preliminary results of that test are also described.

**Introduction**

The objective of this research effort has been to develop a detailed understanding of the geomechanical and flow mechanisms that make it possible for coalbed fires to continue to burn for decades or more. That understanding is the basis for the design of an inert gas injection scheme aimed at extinguishing the fire.

The project has investigated an existing fire located in southwest Colorado that was discovered in 1998 (though it is likely that it started well before 1998) and has continued to burn since then. Previous investigations have included drilling of boreholes in which thermocouples for temperature measurements were installed, surface topography, detailed characterization of fissures (types, orientations, apertures, temperatures and lengths), well logs, driller's logs, subsurface temperature, gas composition, subsurface images using seismic and ground penetrating radar, and regions of snowmelt over the coalbed fire. In addition, numerical simulations of the geomechanical response of the overburden rocks to the conversion of solid coal to combustion product gases and flow simulations have been conducted. A detailed report is available that describes the background of the project, the field site location and geology, and the results of all the previous measurements and simulations (Harris et al., 117-144[1]).

Very useful new evidence was obtained from two surveys conducted with a sensitive magnetometer, which showed the current location of the combustion zone in addition to unburned regions and those that had burned previously. Results of those surveys are reported here.

The combination of field characterization data and simulations was sufficient to build a conceptual picture of the sequence of events that sustains a coalbed fire, and that picture was used in the design of a pilot test of inert gas injection at the field site. That pilot test was carried out in April, 2010, and preliminary results of the test are also reported here.

**Results**

Over the past three and a half years, one of the four known coal fires on the Southern Ute Tribal Land has been studied in detail. This fire, known as North Coal Fire, is located along the western rim of the Hogback monocline, just south of the Iron Springs Gulch and Soda Springs Canyon junction. In previous years, efforts were concentrated on characterizing the fire, which includes identifying possible air inlets, delineating the extent of the fire zone, and developing conceptual pictures of the North Coal Fire. Based on our current understanding of the North Coal Fire, a pilot $CO_2$ injection test at the fire site was designed. This pilot test tested whether inert gas injection could be used to extinguish the fire.

There are currently two active regions over the North Coal Fire—one to the North, called the Crestal Extension Fire, and one to the South. We focused on the Crestal Extension Fire for the $CO_2$ injection pilot test. **Figure 1** is a contour map of the North Coal Fire area, with the Crestal Extension Fire circumscribed by the red box. Fissures that have formed over the coal fire are also shown. The Fruitland Formation—which contains the lower coal that is burning—outcrops between the two green lines extending from the SW towards the NE.

**Figure 2** illustrates the conceptual picture assembled from geomechanical simulations of the stresses created as the overburden rock sags as the solid coal beneath is removed by combustion. Two potential sources of combustion air exist. These fires most likely start near the outcrop, and in the early stages, air is drawn in from the outcrop. As the fire continues to burn, however, the weight of the rock above the coal seam causes the roof to sag and eventually collapse. That collapse causes cracks (fissures) to form where the rock layers are already fractured. Fissures that form near the advancing combustion front provide a pathway for hot combustion product gases to escape. As the combustion front advances past these fissures, air flows in subsequently through one or more of the fissures in the previously burned zone. Rock cuttings, well logs, drillers' logs, and surface observations suggest that the Crestal Extension Fire is now drawing air from cool fissures in the area. Compacted ash layers and a lack of big void regions on the outcrop side make it less likely that the air is being delivered now to the combustion zone from that direction. In contrast, subsurface voids and fractures encountered during drilling and steep temperature gradients are observed in the subsurface between the fissures. These observations suggest that volumes of gases sufficient to support combustion could flow into and out of the subsurface through fissures.

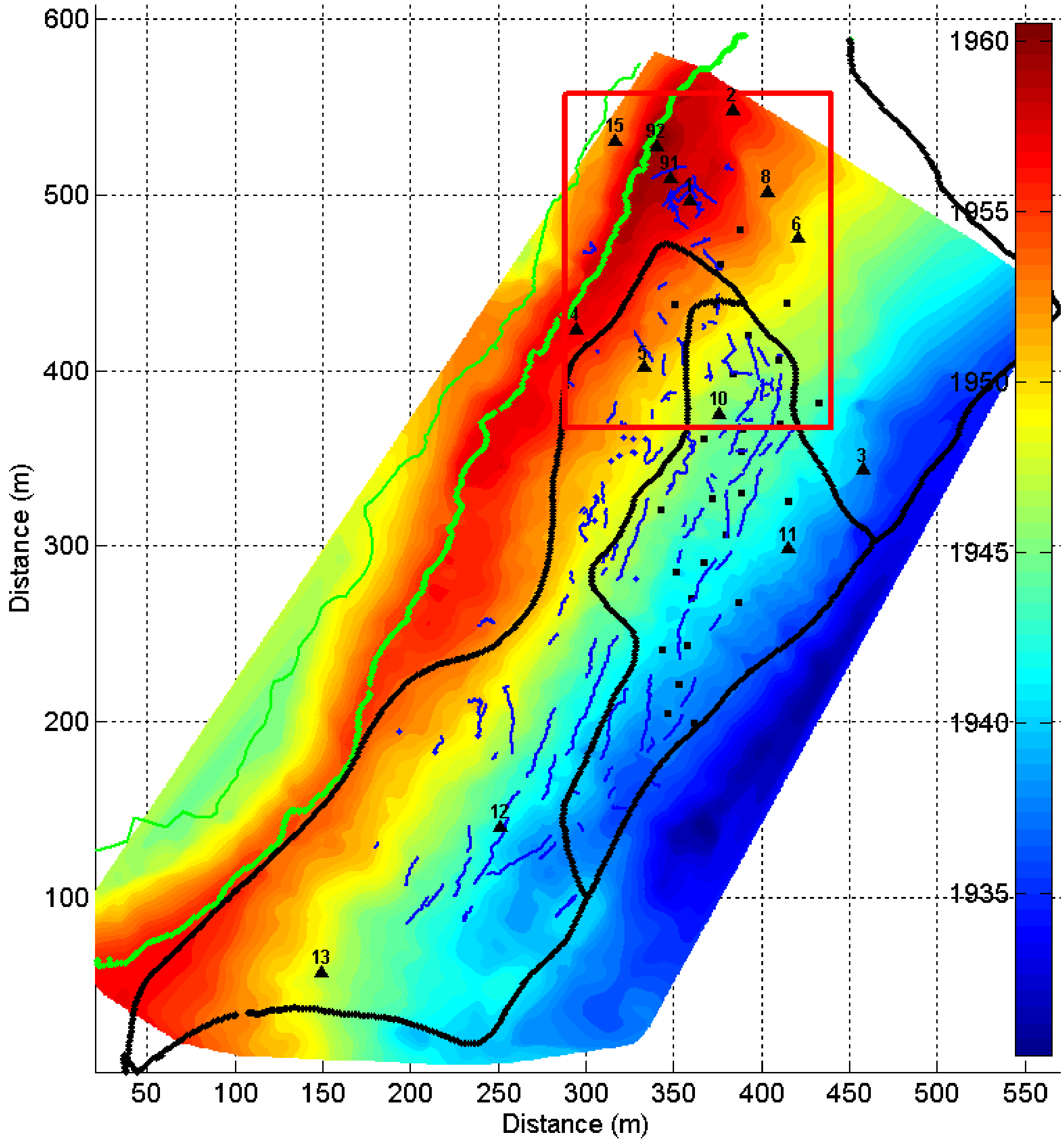


**Figure 1:** A contour map of the region over the North Coal Fire (NCF) created using a pack-mounted global positioning system receiver. The scale on the right side shows surface elevation in meters. Fissures over the coal fire are shown (red = thermal elevation, blue = ambient temperature). Borehole (solid squares) and thermocouple (solid triangles) locations are also shown. The red box encompasses the region over the NCF where the fire is most active. The Fruitland Formation Outcrop is located between the two green lines. The thick black line represents service roads. Color bar in m.

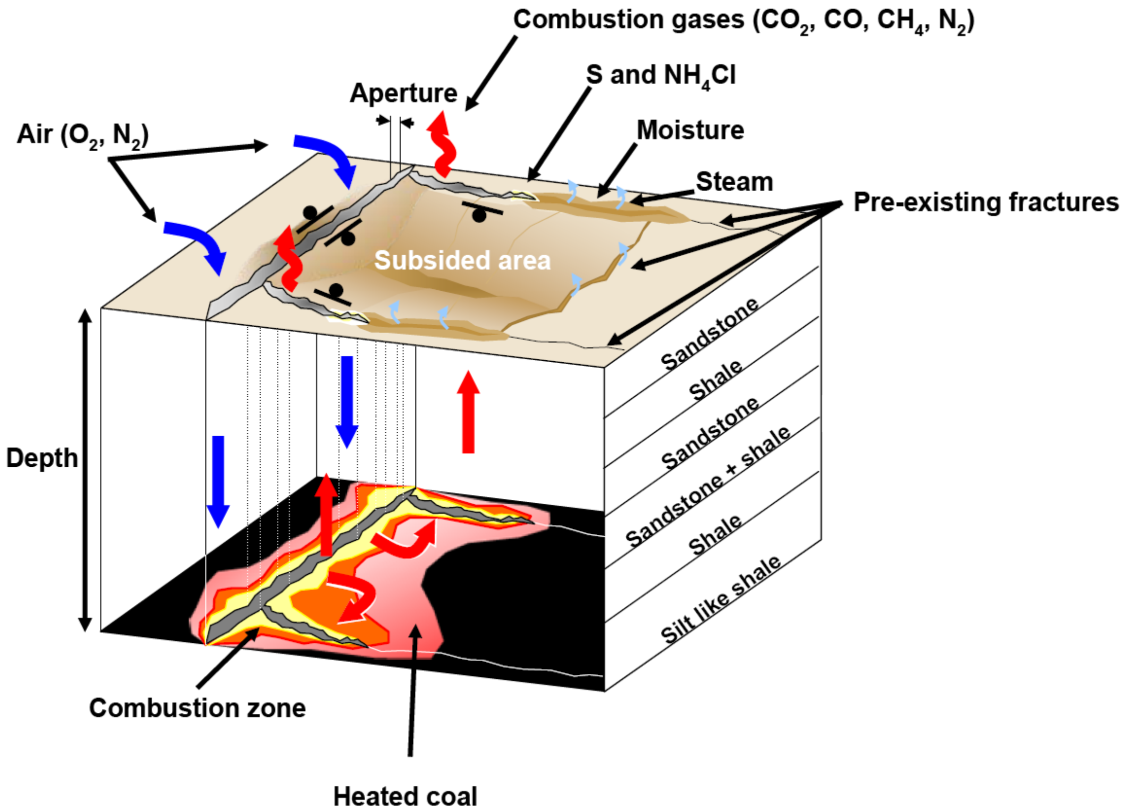


**Figure 2:** Conceptual picture of a coal fire with subsidence. Fresh air and hot exhaust gases enter and leave the subsurface through high permeability fissures that connect the coal seam and the surface.

Magnetometer measurements were used to determine where the fire is currently burning. A magnetic anomaly map is shown in **Figure 3**. The magnetic anomalies differentiate between hot burning zones, cooled ash zones, and regions that are unaffected by the fire. When the sandstone above the coal is laid down, the orientation of the magnetization of minerals in the sandstone is random. If it is then heated above the Curie temperature for those minerals, there is no magnetic signature. When the rock cools again below the Curie temperature, magnetic dipoles in the minerals align with the Earth's magnetic field. Also shown in Figure 3 is the region of snowmelt shortly after a snowfall. The magnetometer measurements are consistent with all of the temperature data from thermocouples, drillers' logs, observations of cuttings, the locations of hot and cool fissures, and the snowmelt data. Thus, we conclude that magnetic anomaly measurements are a very useful way to determine the location of the combustion zone.

The pilot test was designed to determine if it is possible to flood the combustion zone by injection of an inert gas ($CO_2$). The injection wells were located in an area suitable for drilling and casing the boreholes. **Figure 4** shows the fissure distribution over the Crestal Extension Fire. In this figure, the red fissures are venting hot combustion gases, and the blue fissures are at ambient temperatures. Regions around the blue fissures in the subsurface have measured gas compositions close to that of air, and thus air is likely being drawn into the subsurface from the blue fissures.

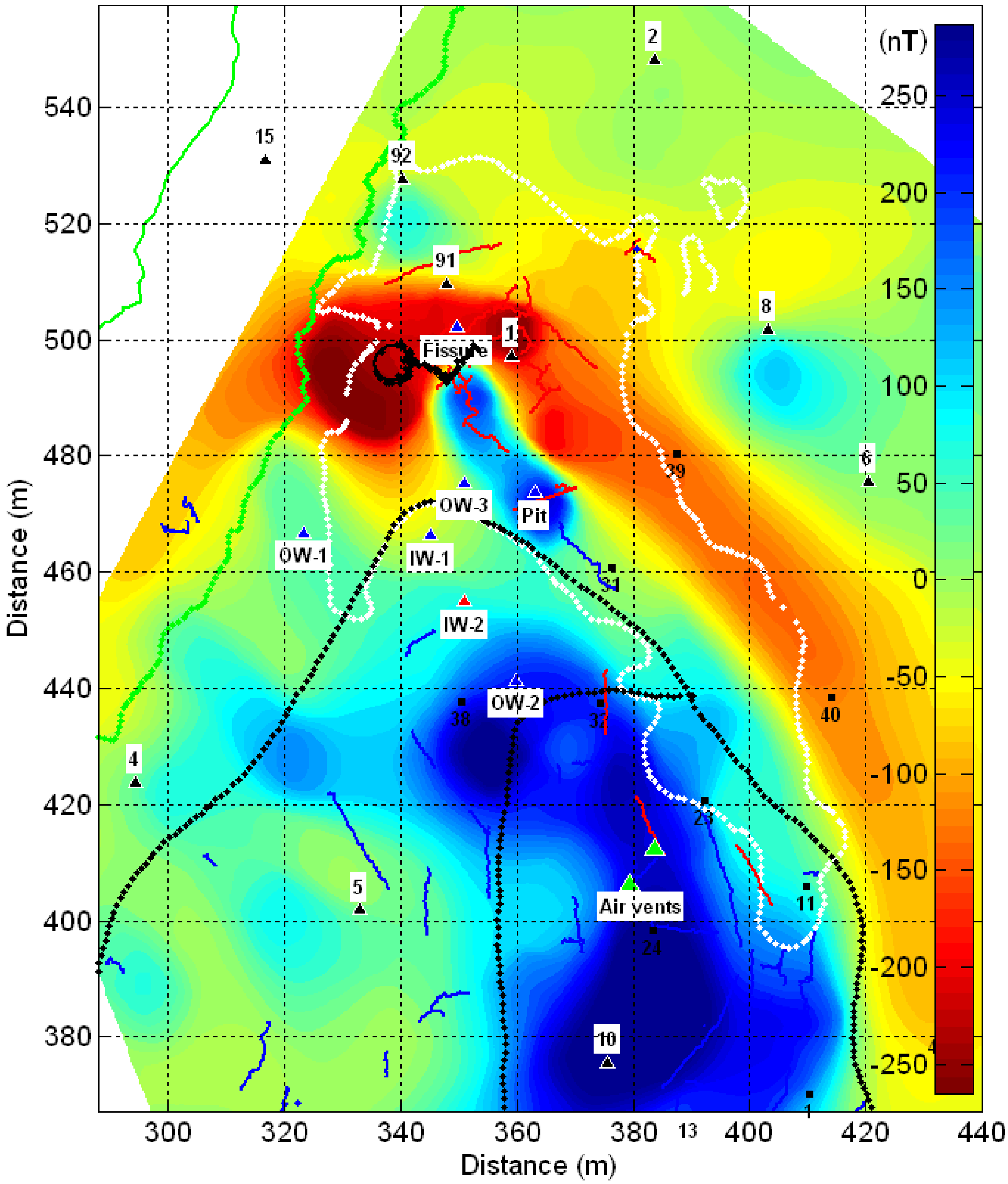


**Figure 3:** Magnetometer and snowmelt data in the Crestal Extension Area of the North Coal Fire. Blue indicates a previously burned region, red denotes the current combustion zone, and yellow to green, unburned coal. The snowmelt location (one day after a snowfall) is indicated by a white dotted line. Locations of injection and observation wells are shown. IW-1 and IW-2 were used for $CO_2$ injection. OW-1, OW-2, and OW-3 were observation wells, as was the labeled fissure location. Fissures emitting hot gases are indicated by red lines; those with ambient temperatures are in blue.

Five wells were drilled for the pilot test. Their locations are shown in **Figures 3** and **4**. In this area, the top of the coal is at a depth of about 12 m, but in these boreholes, nearly all of the coal was missing. Instead a fractured zone was encountered with some ash returns during drilling, an observation that is consistent with the subsidence of the overburden after the coal was consumed. A borehole camera was deployed in IW-2 to investigate the flow setting. Numerous fractures with apertures of order 1 cm, were observed.

Heated air (at 126 C), with a slightly elevated $CO_2$ concentration (3.9%), was observed flowing from borehole IW-2, and the borehole camera indicated that the flow was fracture dominated. $CO_2$ concentrations in other boreholes nearby are shown in **Figure 4.** Similar $CO_2$ concentrations were observed in other boreholes located in the previously burned region (according to the magnetometer survey and from cuttings obtained during drilling). Those gas samples also contained $N_2$, $O_2$, and small amounts of CO. In contrast, samples taken near the fissures emitting hot gases showed $CO_2$ concentrations near 20% and no $O_2$. These observations are consistent with the conceptual picture of air being drawn in through cool fissures and flowing through and being heated by rocks in the fractured zone where the coal had burned previously, to the combustion zone near the fissures emitting hot gases, where the $O_2$ is consumed.

Wells IW-1 and IW-2 (see **Figures 3** and **4**) were used for injection in different tests. Wells OW-1, OW-2, and OW-3 were used to monitor gas compositions, temperatures, and flow rates. Hot gas flow rates were estimated from video measurements for the large fissures closest to the injection wells. $CO_2$ was injected for periods of a few hours at several flow rates. A total of 20 tons of $CO_2$ was injected during the three-day test. Isotope measurements were performed with a cavity laser ringdown instrument (Picarro, Inc.). Methods were devised to track the injected $CO_2$ using this instrument.

**Figure 5** reports values of $\delta^{13}C$ measured prior to $CO_2$ injection. The average values measure prior to injection suggest that the $CO_2$ being emitted from the hot fissures is a

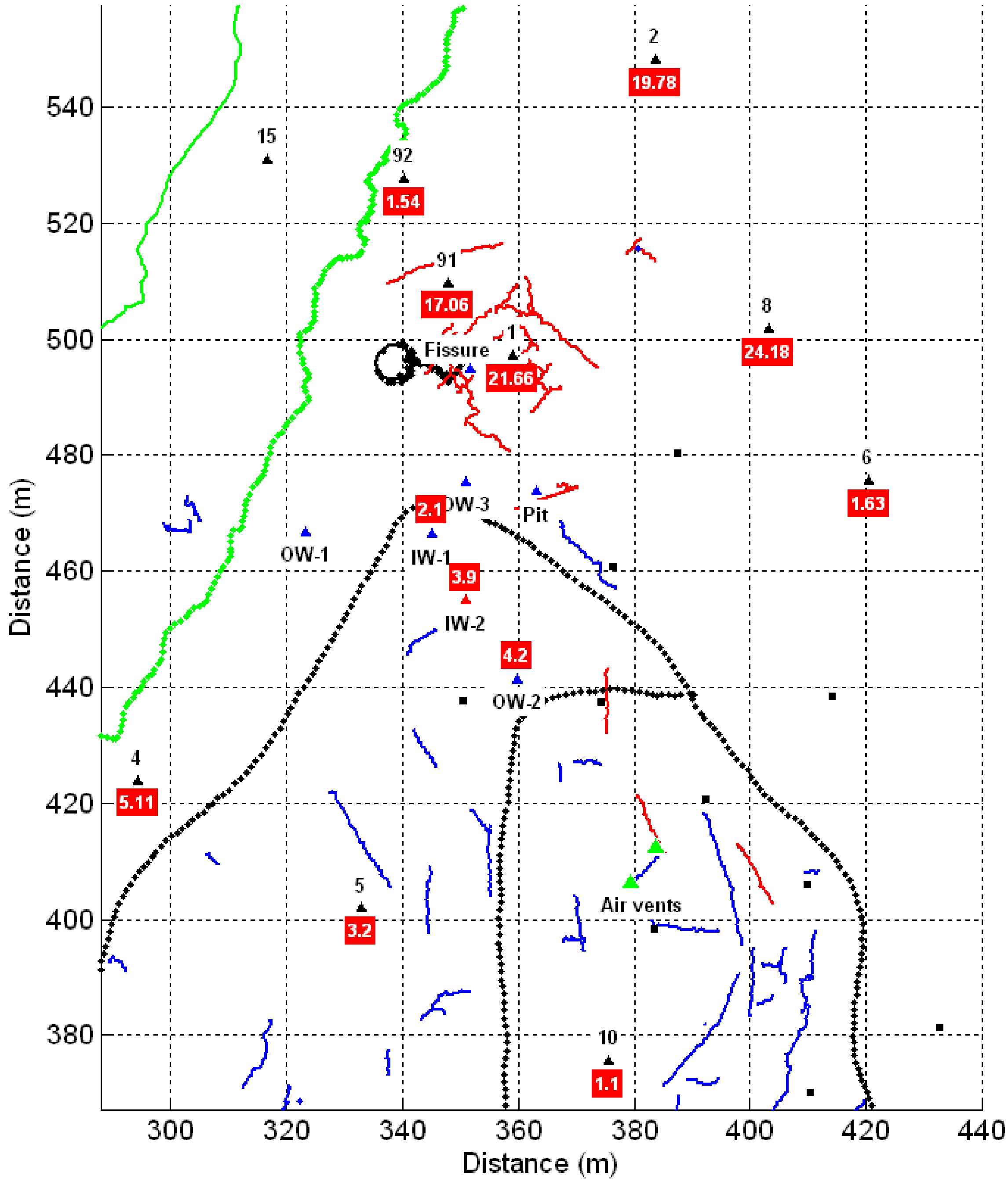


**Figure 4:** $CO_2$ concentrations at boreholes and fissures (in red) prior to $CO_2$ injection. Gases with $CO_2$ concentrations of 1-5% also contained about 80% $N_2$ and the remainder was $O_2$ and small amounts of CO. Samples with $CO_2$ concentrations near 20% contained $N_2$ and CO but no $O_2$.

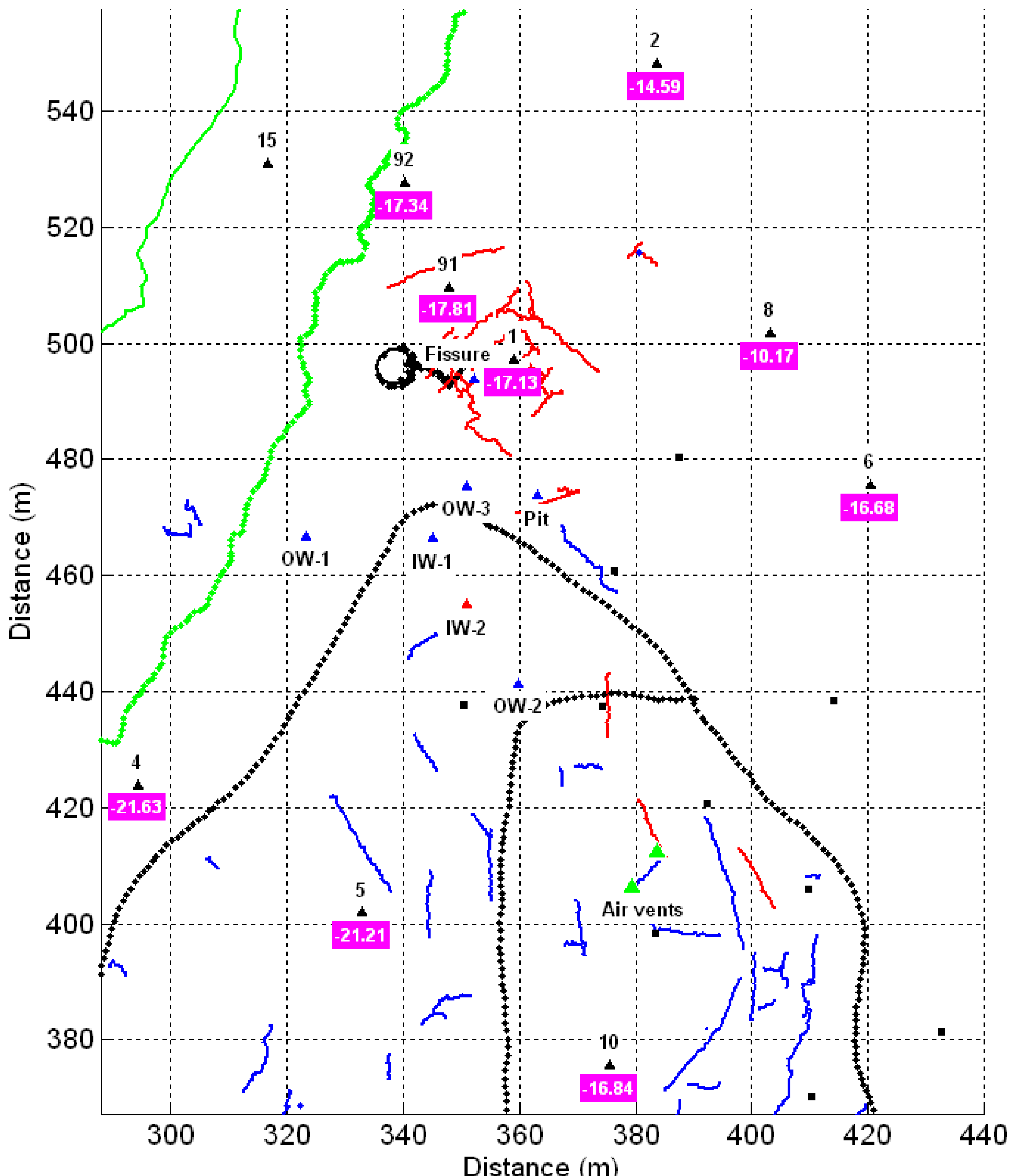


**Figure 5:** $\delta^{13}C$ values for gases sampled at boreholes and fissures (in magenta) prior to $CO_2$ injection.

mixture that results from combustion of coal, combustion of $CH_4$, and some of the native $CO_2$. The contribution of $CO_2$ from air is too small relative to other $CO_2$ sources to have any meaningful impact on the isotpope readings at the North Coal Fire. The observed values are quite different from the isotope signature of the injected $CO_2$, which allows use of that $CO_2$ as a tracer even when $CO_2$ is present in the combustion product gases

Cold liquid $CO_2$ was vaporized at the site and injected for a few hours at rates of 37-45 metric tons of $CO_2$/day. The $CO_2$ flowed easily into the fractured zones, with only slightly elevated pressures at the bottom of the injection wells. No evidence of increased flow rate was observed in the observation wells or fissures. That observation is consistent with the idea that injected $CO_2$ replaced air being drawn toward the combustion zone through fractures by the pressure gradient created by the density-driven flow of hot gases upward through the fissures emitting combustion products.

Breakthrough of injected $CO_2$ was observed in the nearby observation wells and at the fissure at the crest. Times required for $CO_2$ response ranged from 9 minutes for the nearest observation well to approximately one hour for the fissure that was about 35 m from IW-1. **Figures 6** and **7** show examples of the data obtained.

**Figure 6** demonstrates that injected $CO_2$ was detected in the combustion product gases. Note that the fraction of $CO_2$ is lower than that in samples taken from the gases sampled from borehole 1 that are reported in **Figure 4** (21.2%). Due to temperature limits for the isotope instrument, samples were taken from the fissure near the surface, where some mixing with ambient air was inevitable. Even so, the rise in $CO_2$ fraction in that gas clearly indicated breakthrough.

**Figure 7** shows that the $CO_2$ that contributed to the rise in $CO_2$ fraction came from the injected $CO_2$. The $\delta^{13}C$ value increased from the pre-injection value of about -17‰ to about -9.5‰ at the lower injection rate, and then increased again to about -8‰ when the rate was increased. The sampled gas was clearly still a mixture of some injected $CO_2$ and some $CO_2$ that resulted from combustion. These results demonstrate that the $CO_2$ was injected into the fractured zone where the coal had burned reached the area where combustion is occurring now.

Reductions in temperature at the fissure were not observed, despite the fact that the injected $CO_2$ was quite cold (-33 C at the highest injection rate). That observation is an indication that combustion continued with remaining air in the gases flowing toward the combustion zone and that large quantities of heat are stored in the rocks upstream of and in the neighborhood of the combustion zone. These preliminary results from the pilot suggest that $CO_2$ can be introduced into the combustion zone. It will be important, however, to remove enough of the heat from that zone so that the density-driven flow of air will not restart when injection ceases.

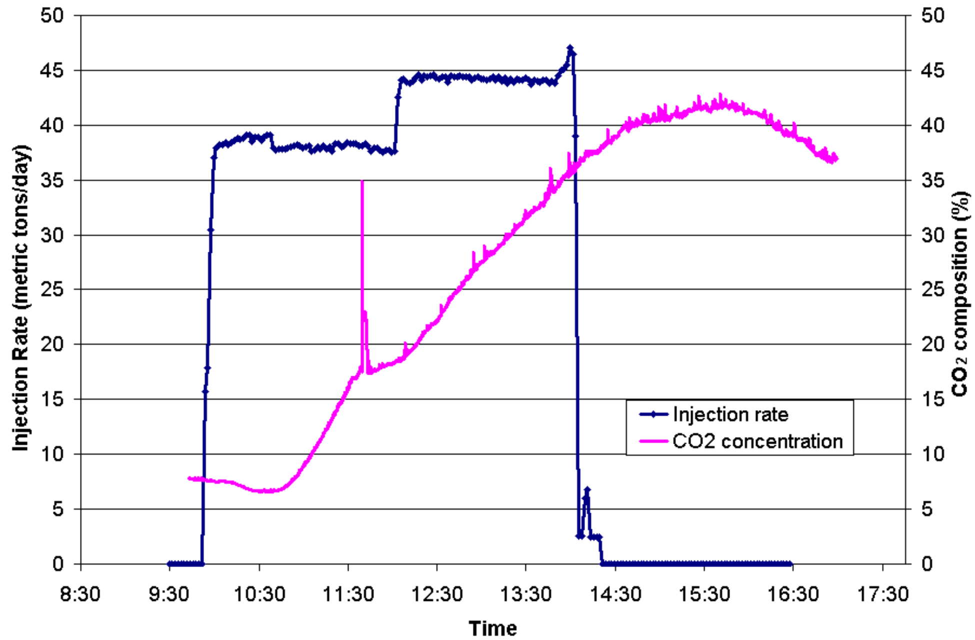


**Figure 6:** Injection rates (blue) and $CO_2$ fractions (%) (magenta) calculated from measured $\delta^{13}C$ values for gases sampled at one crest fissure located about 35 m from the injection well. Breakthrough of injected $CO_2$ was detected by the rise in $CO_2$ fraction about one hour after injection began. The $CO_2$ fraction began to decline again about an hour and a half after injection ceased.

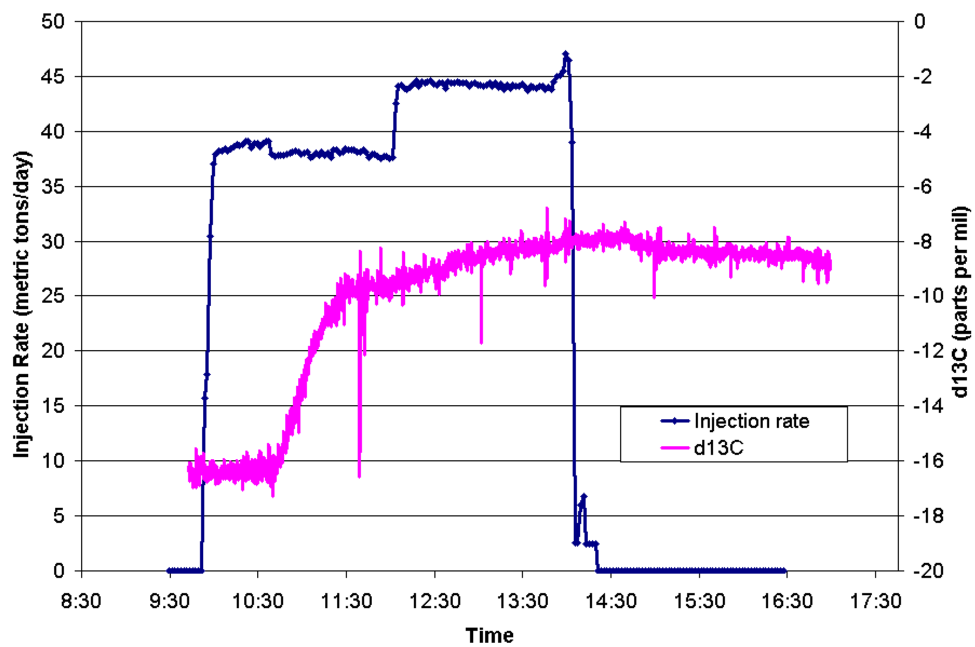


**Figure 7:** Injection rates (blue) and $\delta^{13}C$ values (magenta) for gases sampled at one crest fissure located about 35 m from the injection well.

**Conclusions**

Additional field observations at a subsurface coalbed fire and a pilot test of $CO_2$ injection at the site lead to the following conclusions:

1. Well logs and one borehole video observation (for Injection Well 2) confirmed that previous magnetometer measurements accurately determined where the coal had burned previously.

2. Borehole video indicated that the primary flow of air that is supporting the coal combustion is taking place through fractures.

3. Baseline gas composition measurements prior to injection showed that the gas in the subsurface at the observation well locations was air (nitrogen and oxygen) with 1.5 to 5% $CO_2$. Prior to injection, hot gases being emitted from fissures contained essentially no oxygen and about 22% $CO_2$.

4. An increase in $CO_2$ concentration was observed in nearby wells soon after injection began. Timescales for an increase in $CO_2$ concentration depended on the injection rate, and ranged from 9 minutes to an hour or more, depending on the injection rate and location of the observation. Measured $\delta^{13}C$ values indicated clearly that the injected $CO_2$ was being detected.

5. No increase in flow rate was detected from observation wells or from the fissures emitting hot gases. Injection pressures in the wells were quite small, even at high injection rates, an indication that $CO_2$ entered the fractured zones easily. These results suggests that the chimney effect of the coal fire determines the flow rate through the system and that injected $CO_2$ must be drawn by that flow toward the hot zone just as air to support combustion is drawn to the fire when $CO_2$ is not being injected.

6. Temperature responses in surrounding wells were small or nonexistent, despite the fact that the injected $CO_2$ was quite cold. This result is consistent with the observation that the amount of heat stored in the rocks in the fractured zone and above is quite large compared to the heat capacity of the injected $CO_2$.

7. After injection of about 10 tons of $CO_2$ in three hours injection at the highest rate (about 45 metric tons $CO_2$/day), the $CO_2$ concentration at the crest fissures had doubled. The $\delta^{13}C$ measurements confirmed conclusively that this was injected $CO_2$. This result indicates that even with a relatively small amount of total $CO_2$ injection, a significant change in $CO_2$ concentration near the combustion zone was achieved.

8. The composition and $\delta^{13}C$ measurements demonstrate that $CO_2$ can be injected into flow dominating fractures and that the $CO_2$ injected at appropriate depths reaches the fissures where hot gases are being emitted. This result indicates that if enough $CO_2$ can be supplied to the fracture system that is transporting air to the combustion zone, it will replace the air that is supporting combustion now.

These results set the stage for a larger-scale test of the use on inert gas to control coalbed fires. If sufficient $CO_2$ or other inert gas is available, it should be possible to control subsurface fires, which are significant sources of $CO_2$ and pollutant emissions worldwide. It will also be important in any attempt to extinguish a coalbed fire to manage the heat retained in the overburden rocks in a way that prevents a restart of the density-driven flow that sustains combustion.

**Acknowledgment**

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## Publications

1. Orr, F.M., Jr.: "Carbon Capture and Storage: Are We Ready?" Energy & Environmental Science, 2009, DOI: 10.1039/B822107N.
2. Orr, F.M., Jr.: "Onshore Geologic Storage of $CO_2$" Science 325 (2009) 1656-1658, DOI: 10.1126/science.1175677.
3. Ide, T.S., Pollard, D., and Orr, F.M., Jr.: "Fissure formation and subsurface subsidence in a coalbed fire," Int. J. Rock Mech. 47 (2010) 81-93, doi:10.1016/j.ijrmms.2009.05.007.

## References

1. Harris, J., Kovscek, A., Orr, F.M., Jr., and Zoback, M.D., "Geological Storage of Carbon Dioxide," http://gcep.stanford.edu/pdfs/-IUwoO0omIeF6HDYZPqYeg/2.5.3_Harris_Web_Public_2009.pdf), pp. 117-144.

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