Innovative In-Mine Gas Recovery Techniques Implemented by Resource Enterprises

Stephen J. Kravits
Jianliang Li
REI Drilling, Inc., Salt Lake City, UT, USA

ABSTRACT: Adverse geologic conditions including less than desirable reservoir conditions, have required the development of innovative techniques to improve gas recovery. Such techniques include in-mine horizontal gob boreholes, in-mine hydraulic fracture stimulation and in-mine reservoir testing. These techniques have been formulated, implemented and evaluated by Resource Enterprises and demonstrate considerate potential for increasing gas recovery.

1. BACKGROUND

REI Drilling, Inc., (REID) a wholly owned subsidiary of Resource Energy, Inc., dba, Resource Enterprises, based in Salt Lake City, Utah, USA, began directionally drilling long (>800 m) in-seam boreholes on its pilot gas recovery project at Soldier Canyon Mine, near Price, Utah in 1982 (Schwoebel, 1987). In the spring of 1990, REID began an expansion of its underground contract directional drilling services ultimately to a four drill capacity. Since that time, REID has drilled approximately 50 kilometers of in-mine borehole primarily for methane drainage, for fourteen mines in seven North American coal basins. During this period, REID developed and implemented several innovative gas drainage techniques tailored to satisfy specific and sometimes, adverse geologic, reservoir and mining conditions. The purpose of this paper is to briefly describe three of these techniques and their results. The techniques discussed include: (1) in-mine, directionally drilled horizontal gob (goaf) boreholes, (2) hydraulic fracture stimulation of in-mine, directionally drilled boreholes to enhance gas recovery, and (3) reservoir testing of in-mine boreholes to estimate cleat permeability and reservoir pressure.

2. INNOVATIVE TECHNIQUES

2.1. *In-Mine Horizontal Gob Boreholes*

Of the three gob degasification techniques available, surface drilled gob wells are the most commonly practiced technique in the United States (Figure 1). Three to six gob wells are typically installed per longwall panel to capture gas before it migrates into the mine ventilation. Gob gas can flow to the surface by natural convection via the well, however, blower/exhausters are typically used to significantly increase gas flow. Gob gas quality can range from greater than 90 percent to 25 percent methane (whereupon federal mandatory statutes require well shut-in). Gob gas flows can also vary greatly. Generally speaking, peak gob gas production, and highest quality gas occur when the gob well is intercepted by mining, and then decrease as the longwall face advances beyond the well. Surface access to drill vertical gob wells is not always available. Severe topography, urban areas or lack of rights-of-way can prevent gob well installation. Furthermore, the effectiveness of gob wells can be reduced significantly when water-bearing zones are intercepted and when tight compaction of the fractured gob occurs.

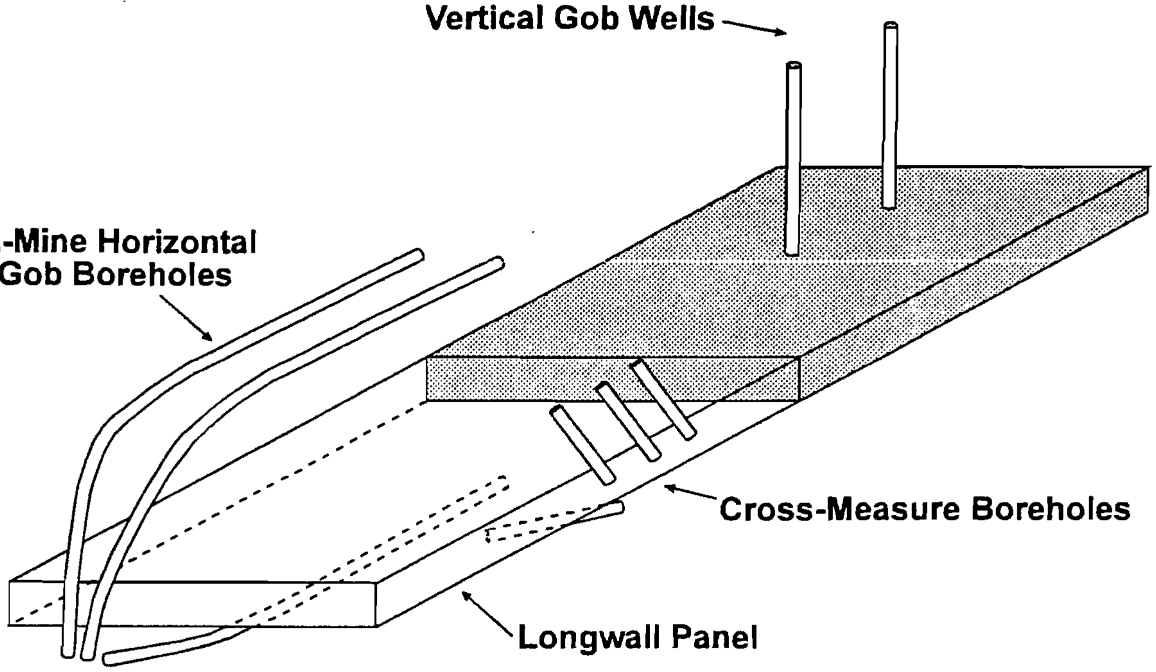


Figure 1. Gob degasification techniques.

Cross-measure, rotary drilled boreholes into the roof and/or floor strata, are the most common gob degasification technique employed in coal mines worldwide (except the United States). Mines utilizing cross-measure boreholes usually drill a high density of boreholes. This is labor intensive both during drilling, and during the installation and maintenance of the pipeline transporting gas from the boreholes.

REID developed an alternative gob gas drainage technique to supplement or replace surface-drilled gob wells and cross-measure boreholes. This technique incorporates the use of directionally drilled, in-mine horizontal gob ventilation boreholes installed over and/or under the longwall panel. Targeting specific vertical horizons and lateral placement relative to the longwall panel, the technique was designed to: (1) provide continuous communication for gas migration from newly-created fractures developed from longwall mining, (2) effectively shield gob gas emissions from the mine ventilation, (3) eliminate the need for surface access, and (4) reduce the overall cost, labor and material required for cross-measure borehole installation.

2.2 *In-Mine Hydraulic Fracture Stimulation*

Coal seams often exhibit fairly high gas contents. but less than desirable reservoir characteristics including low cleat permeability and low reservoir pressure. These conditions contribute to poor gas production rates from degasification techniques, requiring longer degasification times. These reservoir conditions exist in the Rock Canyon and Sunnyside coal seams mined at the Soldier Canyon Mine where average gas production of 800 m long in-seam boreholes is about 850 m^3/d (30 Mcfd). Consequently, REID developed permissible equipment and procedures for in-mine hydraulic fracture stimulation. These procedures included the use of proppant-laden fluid as the fracturing fluid to enhance gas production of in-seam horizontal boreholes.

2.3. *In-Mine Reservoir Testing*

Representative in-situ values for coalbed reservoir parameters (including cleat permeability and reservoir pressure) are not readily available for mine degassification applications. REID developed in-mine water injection testing procedures using permissible pumping and data acquisition equipment to collect transient pressure data as a function of time and injection rate. This data is used to estimate cleat permeability and in-situ pressure which can be used as input data for coalbed reservoir simulators. These simulators can be used as an engineering tool to design an effective degasification strategy by estimating the rate of gas emissions into mine workings and production rates of degasification techniques.

3. CASE STUDY RESULTS OF INNOVATIVE TECHNIQUES

3.1. *In-Mine Horizontal Gob Boreholes at Cambria 33 Mine*

Background - Longwall operations mining the Lower Kittanning coalbed at the BethEnergy Mines Inc. Cambria Slope No. 33 Mine (Cambria) were experiencing excessive gob gas emissions even though an average of twelve surface vertical gob wells were installed in the previous six longwall panels (Kravits, et al, 1993). Production delays persisted requiring an alternative gob gas drainage approach. REID conceptualized, designed and implemented 16,000 feet (4,900 m) of 89 mm (3.5 inch) in-mine, directionally drilled horizontal gob boreholes over two longwall panels to supplement and compare results to surface gob wells (Figure 2).

Borehole flow capacity was designed at about 20,000 m^3/d (700 Mcfd) considering, 760 m (2,500 feet) borehole length, 89 mm (3.5 inches) diameter, and available vacuum of 305 mm (12 inches) mercury using the Weymouth formula. U.S. Bureau of Mines research indicated that 91 percent of the gob gas captured originated from the overlying coalbeds (Diamond, et al, 1991). Consequently, it was initially decided to target several vertical horizons in the vicinity of these coalbeds. Lateral placement with at least one borehole positioned close to the tailgate entry was based on (1) the ventilation system providing a pressure differential from the headgate to the tailgate return, and (2) U.S. Bureau of Mines' (Diamond, et al, 1993) subsidence information indicating a zone of tension at the longwall perimeter, perhaps providing increased fracture conductivity.

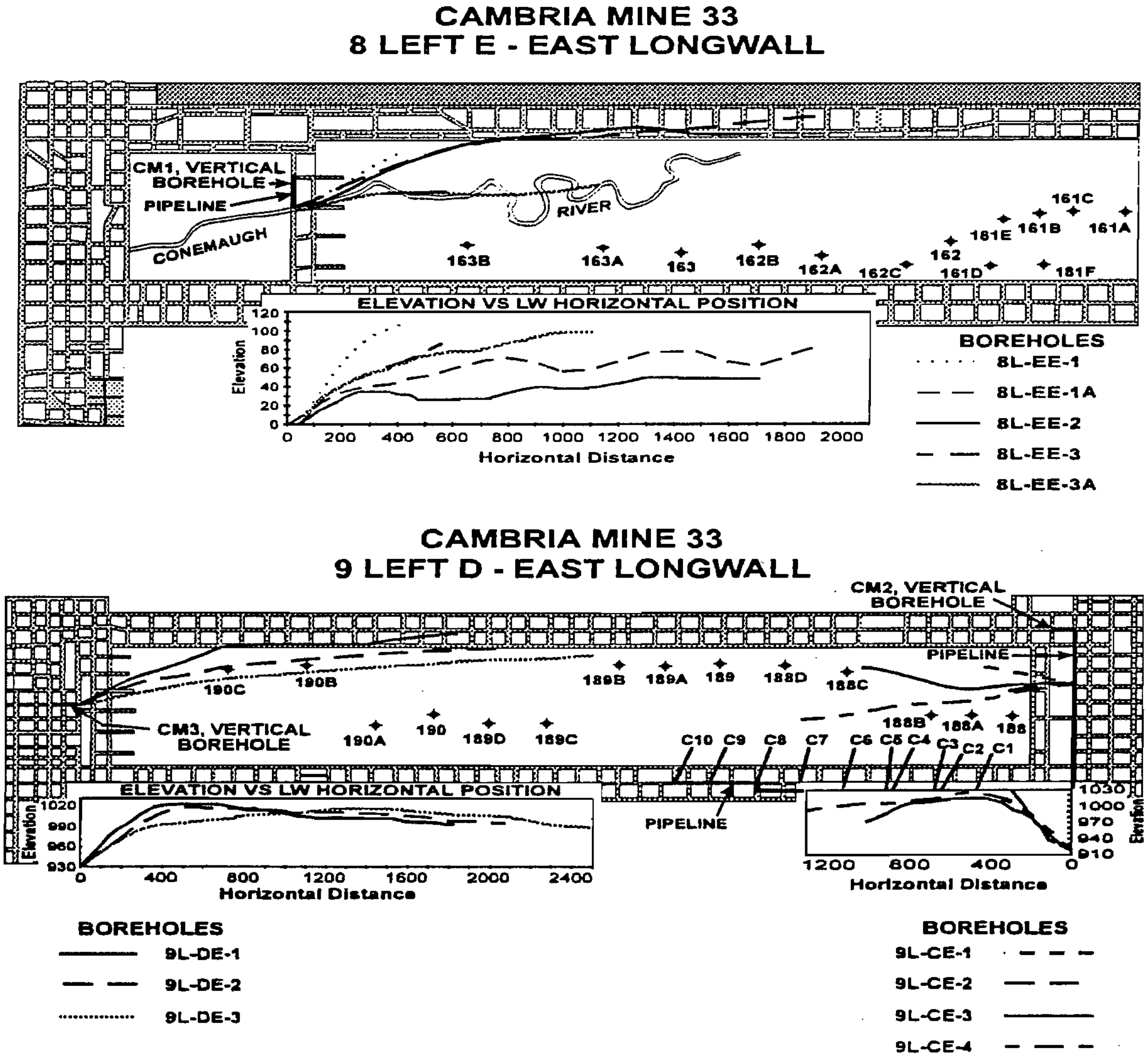
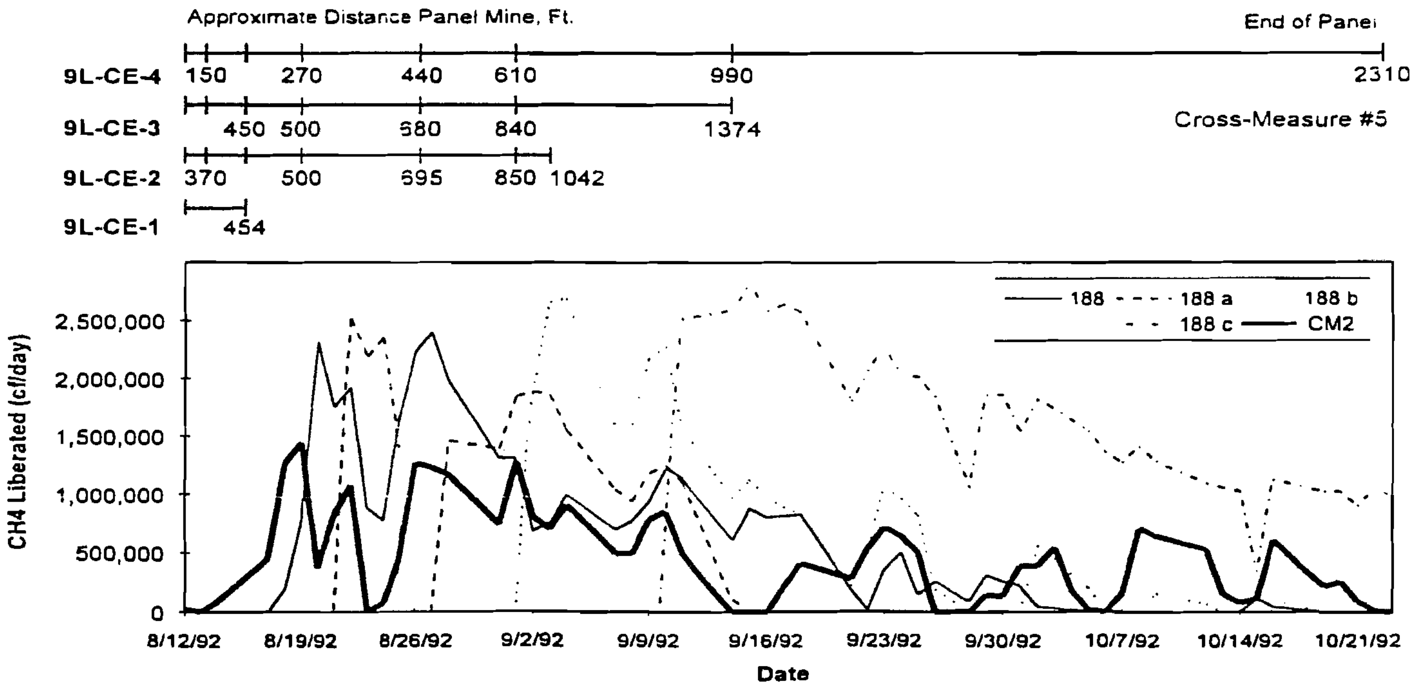


Figure 2. In-mine horizontal gob boreholes.

8 Left E-East Panel Results - The three horizontal gob boreholes drilled from the completion end of panel 8 Left E-East targeted three vertical horizons above the Lower Kittanning coalbed. Gas production from the boreholes was connected to the CM1 vertical access well and partial vacuum applied. About 90 percent of the gob gas produced from the three horizontal gob boreholes was from borehole 8L-EE-1A (76 mm diameter), 18 m above the Lower Kittanning coalbed, averaging about 8,500 m^3/d (300 Mcfd). Gas production from 8L-EE-2 borehole, 9 m above the Lower Kittanning coalbed did not exceed 25 percent methane concentration (obviously communicating with the ventilation air). Water production of 755 liters per minute (200 gallons per minute), at times rendered 8L-EE-3A ineffective (this borehole intercepted the C' coalbed). 8L-EE-3A stopped producing water 61 m (200 feet) from panel completion and averaged 11,400 m^3/d (400 Mcfd). Evaluation of the gob gas flows indicated that swags or dips in the boreholes had to be eliminated to facilitate dewatering of the boreholes and prevent gas flow stoppage. The horizontal gob boreholes and four surface gob wells maintained methane levels at mandatory limits.

9 Left D-East Panel Results - Horizontal gob boreholes were drilled from the C-East and D-East ends of panel 9 Left. The C-East horizontal gob boreholes (connected to vertical access well CM2) were drilled much shorter than 750 m due to concern that the boreholes would shear with the first major roof cave. Cambria also installed four vertical gob wells and seven cross-measure boreholes into the roof strata because the highest gob gas emissions were experienced at the beginning of the longwall panel. Shearing did not occur as gob gas continued to flow from boreholes 9L-CE-3 and 4 as the longwall face had advanced 300 m (1000 feet) past their ends (Figure 3). 9L-CE-1 and 2 did not produce gob gas as well as 9L-CE-3 and 4, perhaps because they did not extend far enough into the fractured gob. Gas production from 9L-CE-3 and 4 peaked at about 43,000 m^3/d (1.5 Mmcfd) and for the most part was close to estimated flow capacity. However, communication in the gob between the horizontal boreholes and the vertical gob wells was very noticeable. For example, gas production from 9L-CE-3 and 4 decreased immediately as gob well 188 was put on production. As the longwall face advanced past the terminus of 9L-CE-3 and 4, CM2 was throttled back and shut-in when the methane concentration decreased to 25 percent. However, several times CM2 was produced to reduce methane concentration buildup in the tailgate return.



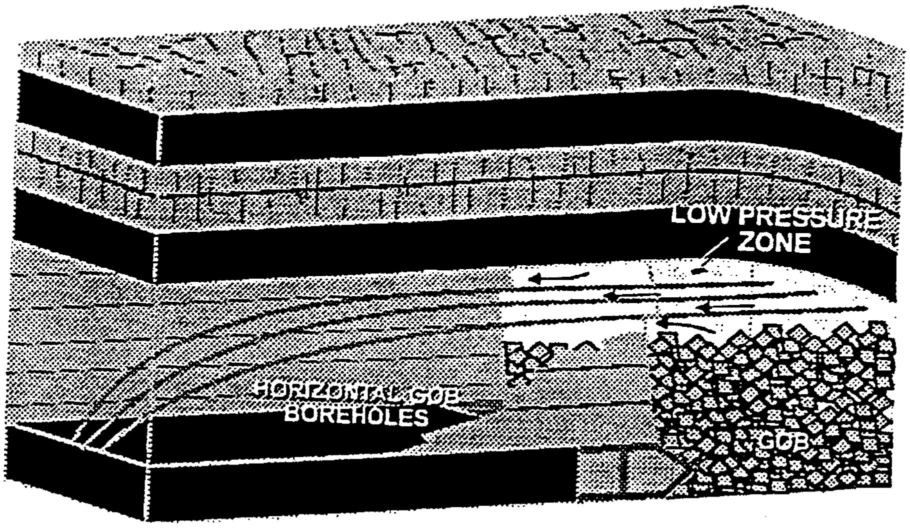


Figure 4. Low pressure zone created by horizontal gob boreholes.

Three horizontal gob boreholes were drilled from the D-East completion end of the panel, all targeting 6 m (20 feet) below the C' coalbed, and were connected to the CM3 vertical access well. Unfortunately, during the drilling of 9L-DE-3, the directional drill was lost in the borehole, severely restricting gas flow. Gas production from surface gob wells resulted in decreased gas flow from 9L-DE-1 and 2. Several vertical gob well shut-in tests suggested that the horizontal gob boreholes under partial vacuum created a low pressure zone in the gob, thereby shielding gas migration from mine ventilation (Figure 4).

In-Mine Horizontal Gob Borehole Summary - In-mine horizontal gob boreholes used in conjunction with vertical gob wells proved effective in controlling gob gas at Cambria. With proper vertical and lateral placement, and an adequate number of boreholes (four were estimated to be required at Cambria), it is believed horizontal gob boreholes effectively shield the mine ventilation from gob gas emissions. The use of horizontal gob boreholes may have widespread application in foreign coal mines. REID will directionally drill (~1000 m) in-mine horizontal gob boreholes in a Chinese coal mine (under United Nations' sponsorship), potentially eliminating gas drainage galleries installed below the mined seams from which cross-measure boreholes are drilled.

3.2 In-Mine Hydraulic Fracture Stimulation

Background - The Sunnyside and Rock Canyon coalbeds being mined at Soldier Canyon Mine exhibit low cleat permeability and are underpressured. In addition, in-seam boreholes are drilled 8 degrees downdip with mining direction. Poor production rates averaging 860 m^3/d (30 Mcfd) from 700 m (2,300 feet) in-seam boreholes require significant degasification time. Consequently, in 1984, REID experimented with in-mine hydraulic fracture stimulation of in-seam boreholes using plain water as the fracturing fluid. Although significant increases in gas flow were realized, increased flow rates were short lived. Through a funding from the State of Utah, Office of Energy Services, REID engaged in a contract to develop, implement and evaluate in-mine hydraulic fracture stimulation techniques using proppant laden fluid as an enhanced in-seam borehole completion technique.

Drilling and Pumping Results - Two in-seam horizontal methane drainage boreholes were directionally drilled into the Sunnyside coal seam at Soldier Canyon Mine, namely, SS-1F-1E to 610 m (2,000 feet) and, SS-2F-1E to 764 m (2,505 feet) (Figure 5). An average dry, ash-free, gas content of coal core samples collected from SS-2F-1E using a spot coring technique (adapting a short core barrel to the downhole motor), was determined to be 7.43 m^3/ton (262.2 scf/ton). Pressure transient analysis of the water injection/fall-off borehole test conducted in SS-1F-1E indicated an absolute cleat permeability of .21 millidarcies, average seam pressure of 1 mPa absolute (142 pounds per square inch) and no near wellbore damage (skin). Two in-mine permissible electrohydraulically-driven, triple piston frac pumps (designed and manufactured under the contract), another pump and a straddle packer to isolate selected zones, were used to conduct six hydraulic fracture stimulation treatments in the boreholes (Figures 6 and 7). The hydraulic fracture stimulation treatments were designed to use water, 6 percent potassium chloride and concentrations of up to .12 kg/liter (1 pound per gallon) of a light weight plastic proppant (1.06 specific gravity - divinyl benzene copolymer spherical plastic bead), 20-40 mesh, as the fracturing slurry. The light weight plastic proppant was chosen to simplify mixing procedures underground (e.g., not requiring a gel or other viscous fluid). Attempts to pump the slurry at .12 kg/liter during the first hydraulic fracture treatment in SS-1F-1E were unsuccessful. Modifications were made on the frac pump valves to increase tolerances, and on the slurry mixing system by recirculating unpumped slurry at a slight back pressure to keep the proppant in suspension. Subsequently, five hydraulic fracture stimulation treatments were completed in SS-2F-1E by decreasing the proppant concentration to .03 kg/liter (1/4 pound per gallon) on subsequent frac zones in an attempt to decrease treatment pump pressure and maximize installation of slurry volume (proppant) in the fracs created. This was performed because of poor pump efficiency as low as fifty-percent (50) when pumping the proppant slurry at pressures greater than 10 mPa (1,500 psi). A complete summary of the hydraulic fracture treatments, including slurry treatment volumes, treatment pressures, and total weight of the proppant installed in the fracture intervals is provided in Table 1. Compared to the designed installation of about 1,136 kg (2,500 pounds) per fracture stimulation treatment using proppant concentrations of up to .45 kg/liter (1 pound per gallon), the maximum proppant treatment installed was 400 kg (882 pounds).

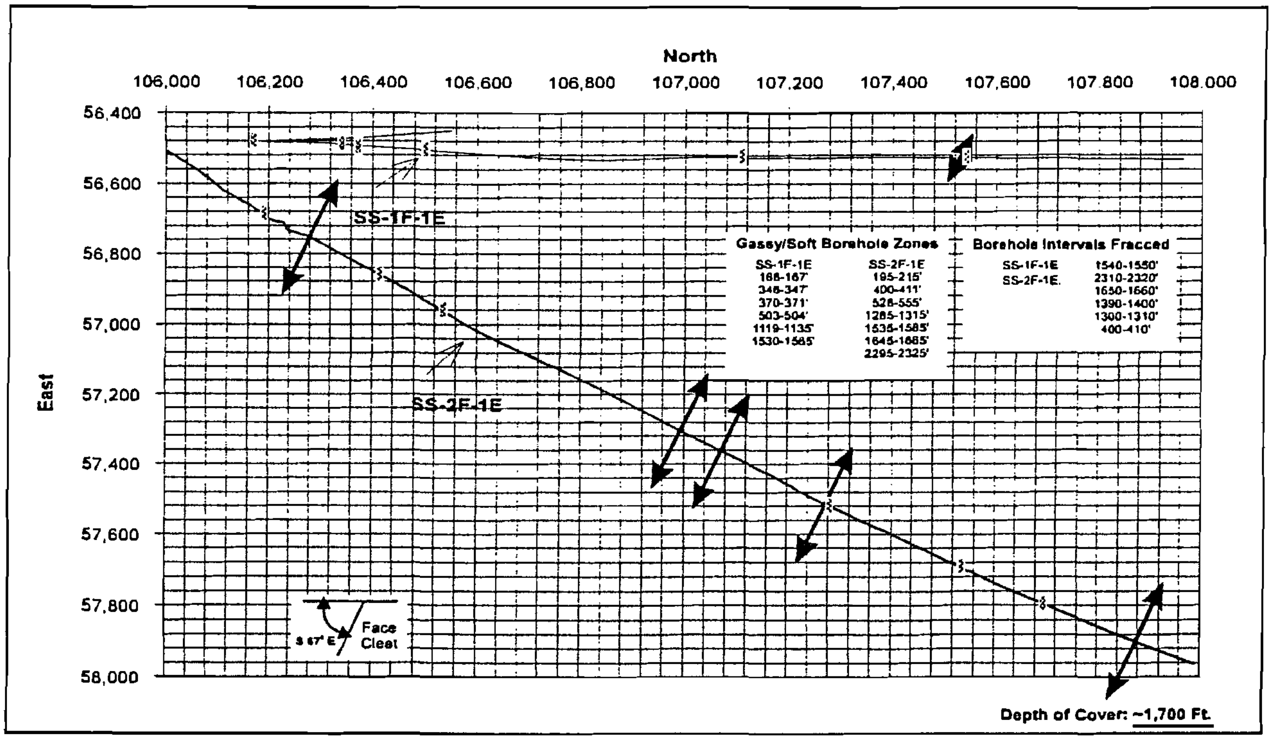


Figure 5. Plan view of SS-1F-1E and SS-2F-1E

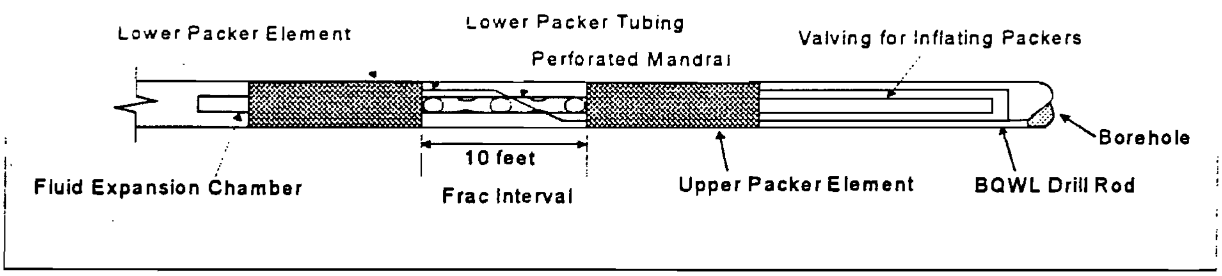


Figure 6. Balanced piston straddle packer.

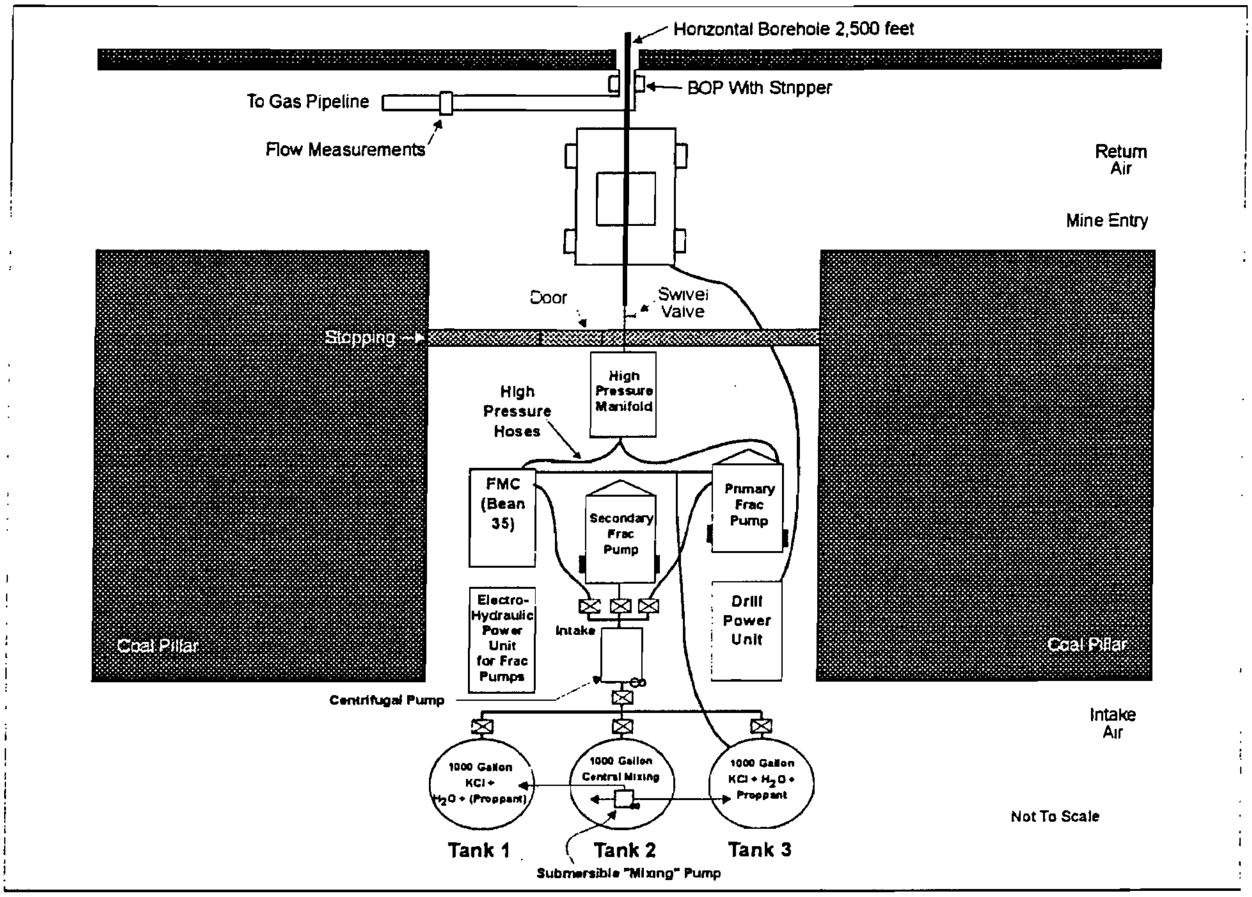


Figure 7. Set-up for in-mine hydraulic fracturing at SCCC mine

Gas Production and Fracture Analysis - The most important measure of how effective the hydraulic fracture treatments were is the resulting increase in gas production. Figure 8 indicates the gas production from the two boreholes before and after the hydraulic fracture treatments. Gas flow did not increase from the unsuccessful fracture treatment conducted in SS-1F-1E borehole, although the coal formation was broken down. SS-2F-1E borehole gas production increased from 992 m^3/d (35 Mcfd) to an average of 1,445 m^3/d (51 Mcfd) after five hydraulic fractures were completed. This increase in gas flow only lasted about four weeks.

Table 1 Summary of SS-2F-1E borehole hydraulic fracture treatments.

Borehole Interval, feet	STAGE 1 - 6% KCl + WATER				STAGE 2 - 6% KCl + WATER + PROPPANT								
					1/4 PPG PROPPANT				1/2 PPG PROPPANT				
	Pump Pressure, psig		Average Pump Rate, gpm	Total Gallons Pumped	Pump Pressure, psig		Average Pump Rate, gpm	Total Gallons Pumped	Pump Pressure, psig		Average Pump Rate, gpm	Total Gallons Pumped	Total Weight Proppant Installed In Frac, pounds
	Start	End			Start	End			Start	End			
2,310-2,320	920	1,500	70	979	N/A	N/A	N/A	N/A	1,350	2,400	24	1,127	564
1,650-1,660	850	1,700	70	979	1,600	2,600	36	363	N/A	N/A	N/A	N/A	91
1,390-1,400	750	1,325	58	979	1,300	1,650	43.5	1,958	1,650	2,500	30	785	882
1,300-1,310	850	1,550	38	979	1,550	2,500	38	177	N/A	N/A	N/A	N/A	44
400-410	800	1,450	71	979	1,500	2,500	50	844	N/A	N/A	N/A	N/A	211

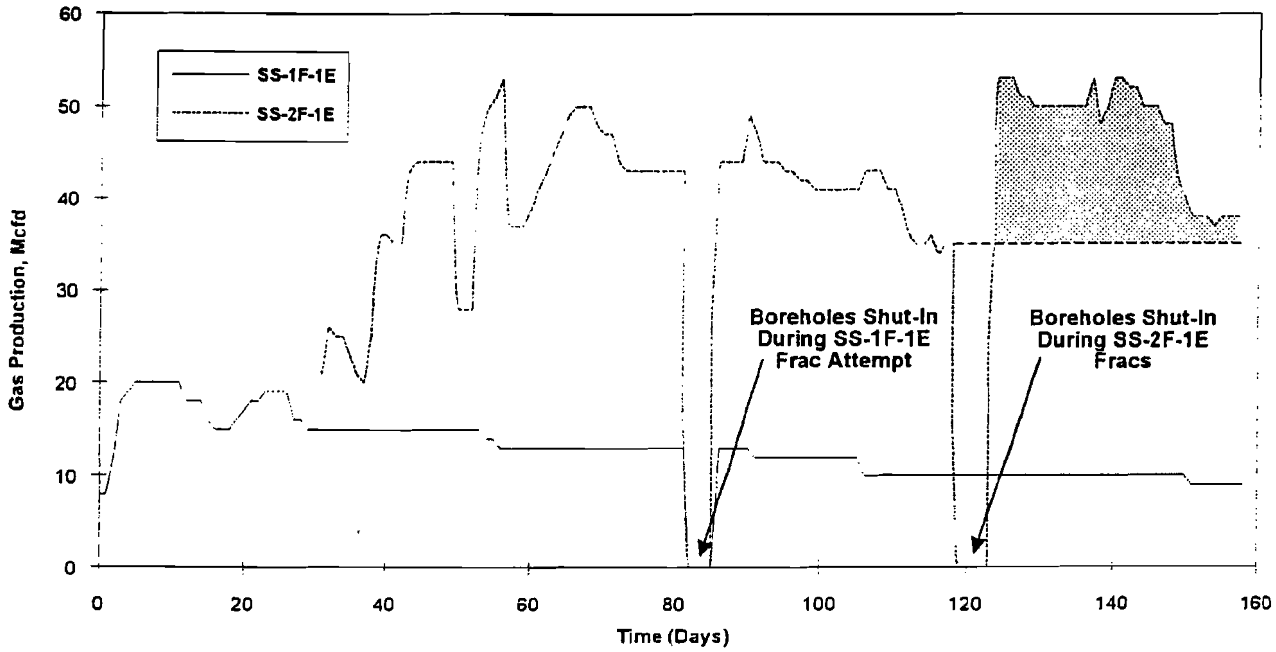


Figure 8. Gas production of boreholes SS-1F-1E and SS-2F-2E.

Analysis of the hydraulic fracture treatments using a state-of-the-art hydraulic fracture computer simulation model was completed. Minimum in-situ stresses in the roof strata were estimated at slightly higher than the Sunnyside coal and slightly lower in the floor strata based on actual minimum in-situ stress measurements made in similar lithologies in other areas. With greater in-situ stress in the surrounding strata compared to the coal, the further the fracture growth into the coal. Estimation of the in-situ stresses indicated a possible fracture height growth of 100 to 180 feet into the overlying and underlying strata. Fracture wing length was estimated to be 100 to 150 feet laterally into the coal. The fracture simulator indicated that the fractures were not effectively filled with proppant. Therefore, fracture conductivity was not maintained causing relatively small and unsustained increases in gas production. Interestingly, the estimated fracture lengths were not significantly different between the SS-2F-1E's five fracs, indicating smaller volume treatments of higher proppant concentration would have been much more effective. Furthermore, higher concentration, smaller total slurry volume treatments pumped at about 158 liters/minute (42 gallons per minute), of numerous intervals, were projected to significantly increase gas production an estimated 100 to 150 percent. Because the shorter length fractures would be effectively filled with a higher concentration of proppant, gas production increases would be sustained much longer. REID is currently evaluating: (1) redesigning the pump valve assemblies to increase slurry pump efficiency at proppant concentrations of .45 to .91 kg/liter (1-2 pound per gallon), and (2) redesigning the fracture treatment design using 40 mesh sand at concentrations of .45 to .91 kg/liter (1-2 pound per gallon) with gel water.

3.3 In-Mine Reservoir Testing

Background - Representative in-situ values for coalbed reservoir parameters including cleat permeability and reservoir pressure in the vicinity of mining are not readily available. REID has developed and implemented in-mine water injection testing procedures using permissible pumping and data acquisition equipment to collect transient pressure data as a function of time and injection rate. This data is used to estimate cleat permeability and in-situ pressure which can be used as input data for coalbed methane simulators such as COMETPC 3D and COALGAS to design an effective degasification strategy by estimating the rate of gas emissions into mine workings and production rates of degasification techniques (Mavor, et al, 1991). A water injection test conducted in the Sunnyside coalbed prior to the first hydraulic fracturing stimulation attempt will be discussed. REID has conducted water injection/fall-off tests in four separate mines.

Sunnyside Coalbed Permeability and Reservoir Pressure - A water injection test was performed in SS-1F-1E borehole interval 470 - 473 m (1,540 to 1,550 feet) prior to the first in-mine hydraulic fracturing stimulation to collect transient pressure behavior as a function of time and injection rate. This data was evaluated to obtain estimates of absolute permeability and in-situ pressure. The water injection test was performed by injecting water in a zone isolated between two inflatable packer elements constituting a balanced piston straddle packer (Figure 6). Water was injected at a constant rate of 3.8 liters/minute (1 gallon/minute) for four hours using a hydraulically powered positive displacement triple piston pump. The pump was then shut off and pressure falloff was measured for forty-two (42) hours as a function of time with a pressure transducer. The fall-off period data was analyzed to obtain an estimate of reservoir permeability and average reservoir pressure. The results of the test analysis included an absolute permeability of .210 millidarcies, average seam pressure of 1 mPa (142 psia) and no near borehole skin damage.

Multi-rate analysis was required for the tests performed during this study as the test consisted of an injection period during which the borehole pressure increased followed by a period of no injection (fall-off period), during which time the pressure decreased. Analysis of the single phase injection pressure data required evaluation of the total compressibility of the reservoir (Bump, et al, 1988). An estimate of pore volume compressibility was not available for the Sunnyside coalbed, therefore, data obtained from the San Juan Basin Fruitland coalbed was used in the analysis Cleat porosity estimates were also not available. San Juan Basin estimates have ranged from 0.25 to 2.8 percent from history matching field performance and interference test analysis, therefore a value of 0.5 percent was chosen (Young, et al, 1991 and Mavor, et al, 1991). Gas and water property estimates were based upon published correlations and were estimated at the initial reservoir pressure as determined from the testing (Numbere, et al, 1977 and Puri, et al, 1991). Analysis of the data was based upon diagnostic graph analysis, specific period analysis, and history matching. A diagnostic graph is a presentation of the logarithm of the pressure changes measured during a test period versus the logarithm of the elapsed time during the period. In addition to the pressure change, the derivative of the pressure change with respect to a multi-rate superposition function is calculated and graphed. The derivative graph is an effective diagnostic tool to determine the validity of the data and is used to determine which portion of the pressure data to analyze.

4. SUMMARY

Routinely practiced in-mine gas recovery techniques are not always effective in controlling methane emissions, resulting in costly coal production delays. As geologic, reservoir and mining conditions become more difficult, developing innovative drainage techniques to improve gas recovery become more critical. However, developing innovative and cost effective, gas recovery techniques take time and money, often requiring refinements during implementation. REID is committed to continuing its effort in developing, implementing, and refining innovative in-mine gas recovery techniques.

REFERENCES

Schwoebel, J.J., "Coalbed methane: conversion of a liability to an asset," *Mining Engineering,* April, 1987.

Kravits, S., Schwoebel, J. and Chiari, D., "Utilization of horizontal in-mine gob ventilation boreholes at Cambria Slope No. 33 Mine," *Proceedings of the 1993 International Coalbed Methane Symposium*, Paper 9338, May 13-16, 1993.

Kravits, S.J. "Evaluation of hydraulically-fractured in-mine horizontal wells as a completion approach for coalbed methane recovery independent of, and in conjunction with coal mining operations," Contract Number 92-2766, Office of Energy Services, Technology Demonstration Program, State of Utah, Division of Community Development, 25 pp., October 25, 1993.

Diamond, W.P., Ulery, J.P., and Kravits, S.J.: "Determining the source of longwall gob gas: lower Kittanning coalbed, Cambria County, Pennsylvania," *BuMines RI, 9430*, 1991.

Diamond, W.P., Jeran, P.J., and Trevits, M.A.: "An analysis of production trends and the potential for increasing gas flow from longwall gob gas vent holes," presented at the 1993 International Coalbed Methane Symposium, Birmingham, Alabama, May 17-21, 1993, pp.10.

Mavor, M.J. and J.J. Schwoebel, "Simulation based selection of underground coal degasification methods," *Proceedings of the 1991 Coalbed Methane Symposium*, Paper 9132, May 13-16, 1991.

Bumb, A.C. and C.R. McKee, "Gas-well testing in the presence of Desorption for coalbed methane and Devonian shale," *SPE Formation Evaluation* (March, 1988), pp. 179-185.

Young, G.G.B.C., J.E. McElhiney and G.W. Paul, "An analysis of Fruitland coalbed methane production, Cedar Hill Field, Northern San Juan Basin," paper SPE 22913 presented at the 66th AnnualTechnical Conference and Exhibition of the Society of Petroleum Engineers in Dallas, Texas, Texas, October 6-9, 1991.

Mavor, M.J., J, Close and T.J. Pratt, "Summary of the completion optimization and assessment laboratory (COAL) site," Gas Research Institute Topical Report No. GRI-91/0377, Chicago, Illinois (December 31, 1991).

Numbere, D., W.E. Brigham and M.B. Standing, "Correlations for physical properties of petroleum reservoir brines," Stanford University Petroleum Research Institute (November, 1977).