Recovery of Methane from the Abandoned Golden Eagle Mine Property

Kenton L. Hupp,[1] Carol Bibler[2] and Raymond C. Pilcher[2]
[1]KLH Consulting, Wichita, Kansas 60202, U.S.A.;
[2]Raven Ridge Resources, Incorporated, Grand Junction, CO

ABSTRACT

The abandoned Golden Eagle underground coal mine in Colorado contains gassy coals from which Stroud Oil Properties, Inc. (Stroud) has been recovering gas since 1996. The mine closed permanently in 1996, and during its operation drained methane from gob and ventilation boreholes. Stroud currently produces about 1.8 million cubic feet of near pipeline quality gas per day from six of these boreholes.

Although the project has proven successful, gas recovery has been challenging because of low bottom hole pressure and variable borehole performance. Wellhead compressors are required to boost gas pressure for delivery to the main plant. Connecting additional boreholes to the gathering system often decreases production from existing production boreholes. Increasing gas removal has resulted in air leaks that lower gas quality. Stroud monitors the gas quality and blends any below-spec gas with its above-spec gas to ensure that the resulting product meets pipeline standards. This gas is then compressed for sale into a nearby pipeline.

Overburden relaxation and finite difference modeling indicate that overlying coal seams and the coal remaining at the margins of the mined out workings contribute a significant amount of gas to the current production.

KEYWORDS

Abandoned Coal Mine, Golden Eagle, Coalbed Methane, Gas Production, Coal Mine Methane, Numerical Modeling, Overburden Relaxation, and Gas Migration.

INTRODUCTION

The Golden Eagle Mine, an underground coal mine located about 30 miles west of Trinidad, Colorado, began producing coal in 1978 and ceased production in December 1995. During its operation, the mine drained methane from gob wells to control gassiness. After Basin Resources abandoned the mine, Stroud Oil Properties, Inc. (Stroud) recognized that converting existing gob boreholes and mine shafts to methane drainage wells could provide a relatively low-cost means of recovering methane from the mine. Stroud began this methane recovery project in 1996, and today, the abandoned mine produces about 1.8 million cubic feet per day (mmcf/d) of near pipeline quality gas.

This paper describes the history and current status of this gas recovery project. The techniques used and results achieved may be of interest to energy developers looking to recover methane from abandoned coal mines.

GEOLOGIC SETTING

The abandoned Golden Eagle Mine property lies within the Trinidad Coalfield in the central portion of the Raton Basin in south-central Colorado (Figure 1). The area is typified by flat-topped ridges, dissected by narrow canyons. The Purgatoire River divides the mine property into northern and southern sections. Elevation ranges from about 7000 feet in the river valley to 7800 feet in the surrounding hills.

Golden Eagle produced coal from the Maxwell Seam, one of several Raton Formation coal seams in the mine area (Figure 2). The Raton Formation was deposited during Late Cretaceous and Early Tertiary time. The Maxwell Seam occurs in the lower Raton Formation, and to the authors' knowledge, its stratigraphic position with respect to the Cretaceous-Paleocene boundary has not been determined. The Maxwell Seam thickness ranges from less than 5 feet to over 10 feet, averaging 8 feet, thinning to the east and northeast. The seam consists of relatively clean coal, with 1 to 3 carbonaceous shale splits 0.5 to 1.9 feet thick, and is interbedded with carbonaceous shale units. Total thickness of the overburden above the Maxwell seam ranges from about 500 to nearly 1200 feet in the mining area.

The Red Seam is a marker bed that stratigraphically overlies the Maxwell Seam by 55-120 feet (Figure 2). About 175 feet above the Red Seam is the Blue Seam, which ranges to five feet thick in some locations of the mine area. Carbonaceous shale and mudstone envelop the Blue Seam. Two thin coal seams, the Weston and Wet Canyon Seams, overlie the Blue Seam. Both the Blue and Maxwell

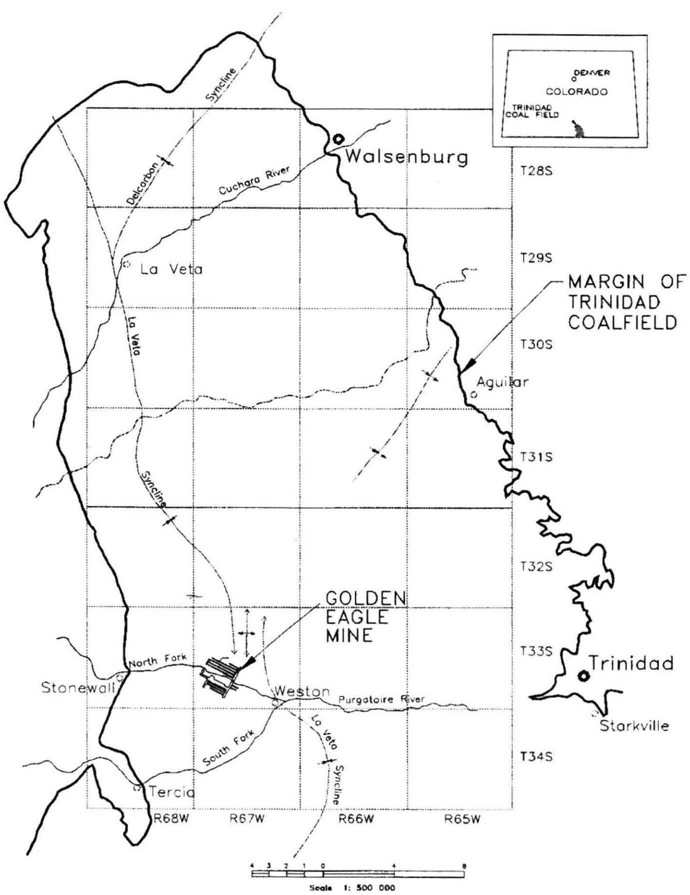

Figure 1. Location of the Golden Eagle Mine within the Trinidad Coalfield.

Seams dip 1-2½° to the northeast, striking generally northwest and locally to the north. The variation in strike may be a result of its proximity to the north-south trending axis of the La Veta syncline (Figure 1), and the fact that the area has been intruded by sills.

Although faulting is present in the Golden Eagle Mine area, only one fault having appreciable displacement was encountered near the eastern edge of the mine during mining operations (Thompson, 1998). The fault trended north-south, however, the amount of displacement is not known. Smaller faults with minor displacement were encountered laterally approximately every 3,000 to 4,000 feet.

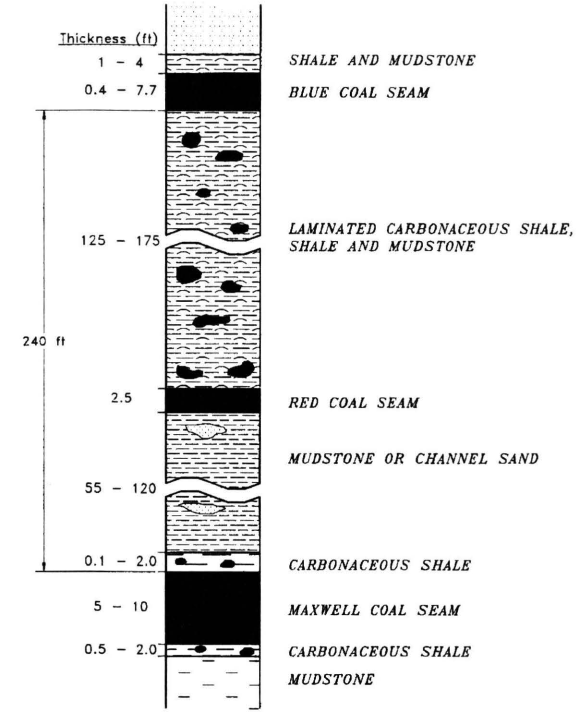

Figure 2. Stratigraphic column of the lower portion of the Raton Formation at the Golden Eagle Mine (modified from Doupé and Thompson, 1996).

Regional hydrologic flow in the central portion of the Raton Basin is toward the east and southeast, following topography (Stevens, *et al*, 1993). Coal seams are the only aquifers in the vicinity of the Golden Eagle Mine property. The mine produced, on average, about 100,000 gallons of water per day during the latter years of coal production (Thompson, 1998). Of this volume, about 70% were produced from the north side of the mine property. During mining of the first longwall panel north of the highway (Figure 3), large volumes of water were encountered, but mining activity (including development) tended to dewater the coal seams, and subsequent panels produced lesser volumes of water. When mining operations encountered faults, water production increased, however additional pumping was not required (Thompson, 1998).

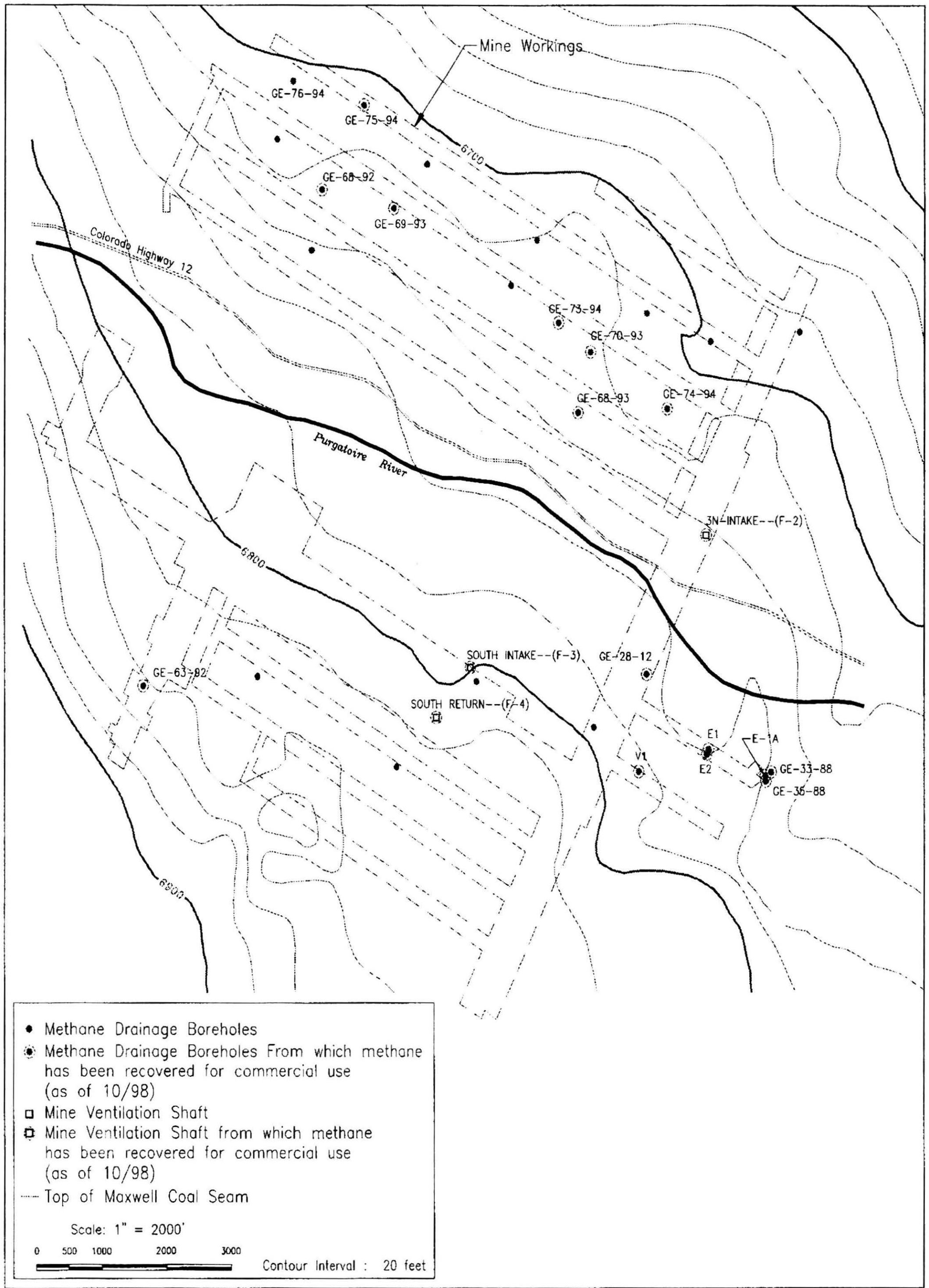

Figure 3. Structure contour map on top of Maxwell Coal Seam showing location of methane drainage boreholes and ventilation shafts.

MINING ACTIVITY AND ABANDONMENT

Coal mining activity in the Trinidad Coal Field began in 1873 and peaked between 1900 and 1930 (Johnson, 1961). Mining activity continued throughout subsequent decades and coal production began at the Golden Eagle Mine in 1978. The mine employed about 180 underground and 50 surface workers, producing about 1 million tons of coal annually, most of which was shipped to Arizona and Texas for power generation and industrial uses (Kuhn, 1990). The coal is high volatile bituminous, with a low sulfur content (0.5%) and an average heating value of 12,000 Btu/lb.

Golden Eagle typically liberated about 4-6 million cubic feet per day (mmcfd) of methane, depending on the level of coal production (U.S. EPA 1994, 1997). The mine employed three ventilation fans, generating a total of 1.2 mmcf per minute of air, to remove methane from the workings (Fleshman and Stanton, 1995). The mine also drained about 1-3 mmcfd from gob areas. In 1991, a methane explosion occurred at the mine during the setup for mining of a longwall panel injuring 11 workers. According to MSHA (1996), the accident was related to the failure of "temporary ventilation controls" (e.g. the use of curtains, as opposed to stoppings or air bridges).

Basin Resources, a subsidiary of Entech, purchased with the Golden Eagle Mine from KN Energy in 1991, KN Energy still retaining ownership of the oil and gas production rights. Due to economic losses, the mine ceased production at the end of 1995, and began abandonment procedures in 1996. They sealed each of the mineshafts with a 15-inch-thick slab of steel-reinforced poured concrete, hoisted and lowered by crane. Grout was then injected between the shaft and concrete slab (Thompson, 1998). Despite efforts to completely seal the shafts, air leakage did occur, as discussed below.

HISTORY OF POST-ABANDONMENT METHANE RECOVERY PROJECT

When Basin began abandonment of Golden Eagle, Stroud negotiated to retain the existing drainage wells and purchase the gas rights, relieving KN Energy of any obligation to plug the boreholes as required by state regulations. Stroud tested the wells during June and July 1996 to determine if economic methane production was possible. Typical shut-in pressures were only about 2.0 ounces per square inch, so conventional gas flow rate measurement via orifice testing was not possible. Stroud therefore used a Davis anemometer to estimate flow rates. Basin Resources personnel continued to monitor methane content, observing a rapidly increasing percentage of methane as the wells were allowed to vent. Based on the data collected, Stroud concluded that production of the mine gas would be economic, and began constructing the gathering system in 1996.

Due to the low mine pressure, it was necessary to install compressors at or near each production well. Gathering lines were constructed from these compressors to Stroud's main plant for injection into the Colorado Interstate Gas (CIG) pipeline. Initially, Stroud produced methane only from boreholes in the southern area, to confirm whether sustained volumes would be available. Stroud hooked up only a portion of these boreholes to the gathering system, and continued to monitor surface pressures and methane content at boreholes and shafts where gas was not being collected. Stroud gradually tested additional wells, some of which yielded gas, and some of which did not; those that failed to produce gas usually did so because of air leaks at the wellhead due to casing splits or near-surface mechanical problems. Production volume reached 1.8 mmcfd after all of the producing wells on the south side of the mining property were hooked up to the gathering system.

Production patterns, along with various tests, suggested that the north and south mine areas were isolated, and that additional gas could be recovered if boreholes north of the Purgatoire River were also hooked up to the gathering system. In August 1997, Stroud hooked up the F-2 ventilation shaft on the north side of the property, and in 1998, Stroud hooked up several wells from the north side. Unfortunately, there was no sustained increase in production, as discussed further below.

CURRENT METHANE PRODUCTION

By the second half of 1998, Stroud had connected wells from the north side of the mine property to the gathering system. Since that time, the company has consistently been selling about 1.8 mmcfd of gas (Figure 4) produced from six boreholes, four on the south side of the property and two on the north side (Figure 3). Many other boreholes and vent shafts could be tied into the gathering line, but it does not appear that this would result in additional gas recovery, because methane flow into the mine workings is limited by the rate of diffusion of the gas from the coal and surrounding strata. Stroud selected certain boreholes for tie-in based on their performance during testing. The producing boreholes tend to be at the far corners of the mine, and are thought to be near faults. Some of the producing boreholes are in areas isolated from the main mine entry. Performance to date indicates tremendous flow capacity in the main entries, in spite of the presence of air seals.

Since the project's inception in 1996, a total of 17 boreholes and three ventilation shafts have produced gas for sale to the pipeline, although no more than 11 boreholes/shafts have been in production in any given month. Six boreholes (E1A, 33-88, 35-88, 63-92, 69-93, and 75-94) were responsible for all of the gas sold from the abandoned Golden Eagle Mine from April 1998 through December 1998. Figure 5 shows the production histories of each of these six boreholes together with the combined production history of the other 14 boreholes/ventilation shafts.

The current production of 1.8 mmcfd of coal mine gas appears to be the optimum rate possible without excessive

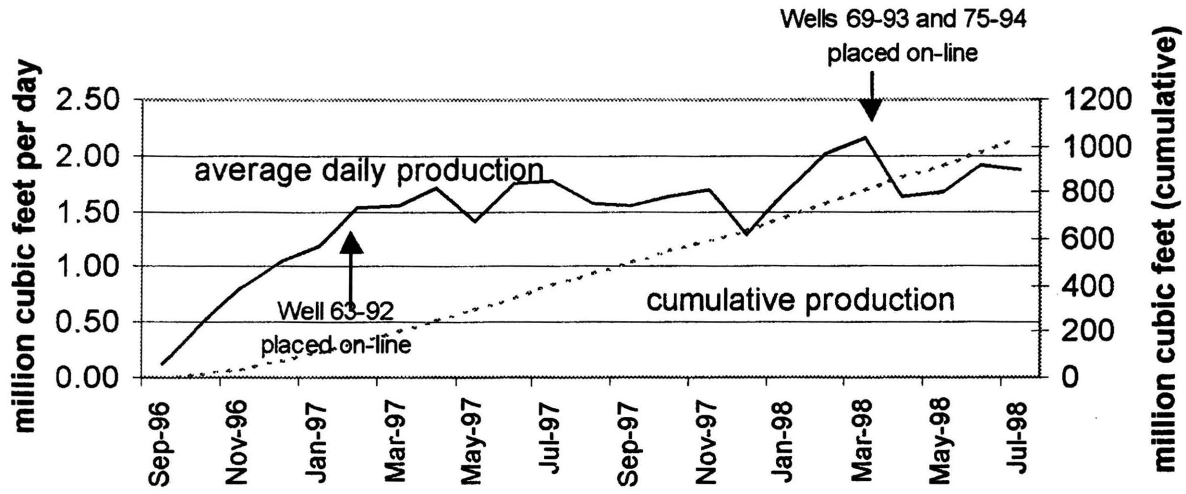

Figure 4. Combined production from all boreholes and ventilation shafts at the abandoned Golden Eagle Mine.

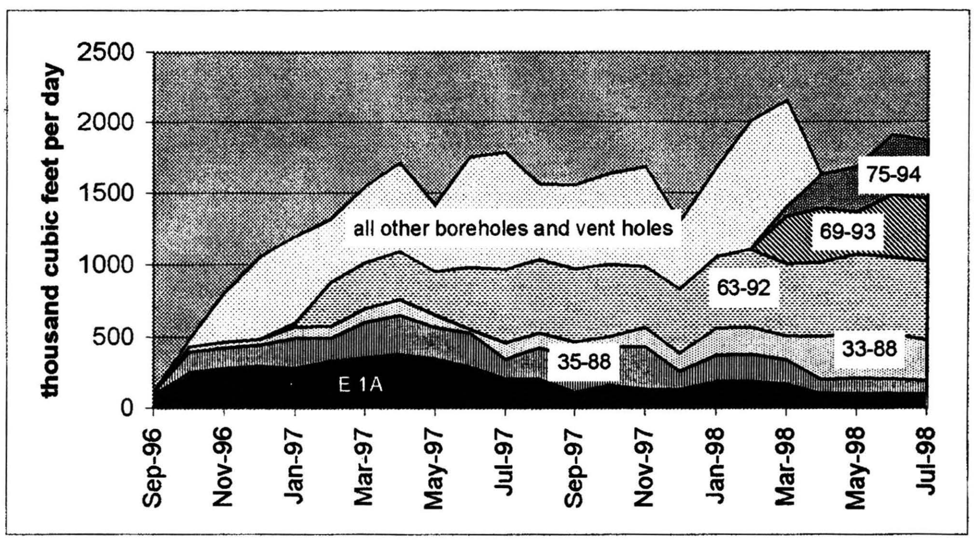

Figure 5. Contribution of individual boreholes to total coal mine gas production from the abandoned Golden Eagle Mine.

air influx. Stroud currently blends this coal mine gas with approximately 2.2 mmcfd of higher-heating value gas produced from a nearby conventional coalbed methane field to the south of the mine property. If this blending gas were not available, Stroud could still produce gas from the mine that meets pipeline requirements, but at a rate lower than 1.8 mmcfd. Conversely, if more blending gas were available, Stroud would be able to increase production of gas from the mine. The existence of these conventional wells has been key to success of the project because, in addition to providing the blending gas, it also encouraged CIG to install a pipeline.

Four gas engine screw compressors are used to boost pressures from ±2.0 inches of vacuum up to the approximately 50 psi required to move the gas to the main plant. Stroud continually adjusts the vacuum on the compressors to a level that maximizes production without pulling in oxygen.

It has never been necessary to use artificial lift to recover water. Stroud used a hand-held fluid sounder to measure fluid levels in order to determine if water buildup could be hindering methane recovery, but results were negative. All producing wells have continued to flow (i.e., required no artificial lift) since Stroud completed them. The gas is fully water saturated, requiring "drips" or "knockouts" in the gathering system (these are areas where gas can expand, allowing moisture to accumulate and fall out after the gas is compressed).

ISSUES ENCOUNTERED DURING PROJECT DEVELOPMENT

Recovery of methane from the abandoned Golden Eagle Mine has proven challenging in several regards. The mountainous and rocky terrain made pipeline construction and access difficult. Many of the roads that were originally used to monitor the drainage boreholes required modifications to allow passenger truck travel and access for pipeline equipment.

Although Basin Resources supplied adequate records on borehole and shaft locations, the original surface and downhole equipment and materials were not well-suited to methane recovery under a vacuum. Stroud had to modify the surface piping and valves of several boreholes in order to produce gas. Some boreholes could not accept a vacuum without causing air leakage at the wellhead resulting in high oxygen concentrations. Subsequent downhole testing revealed split casing. This most likely occurred due to relaxation and subsidence caused by the longwall operations, as evidenced by the fact that all boreholes found to have split casing are located over longwall areas. Overburden relaxation modeling, per-formed in 1998 by Raven Ridge Resources, Incorporated using Roofgas™, likewise predicts that the area of collapse over the longwall is approximately 40 feet above the panel.

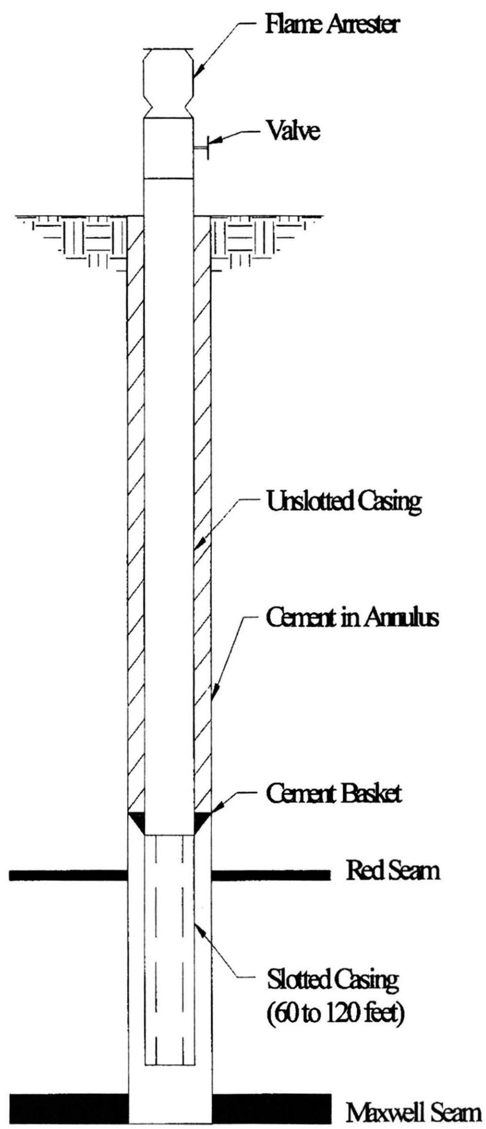

Figure 6. Generalized methane drainage borehole completion diagram.

In most cases, Basin Resources had completed the boreholes with slotted casing set to just above the Maxwell Seam. Figure 6 shows a diagram of a typical wellbore (older wells in the southern area were generally completed directly into the mined area, using open-hole methods). For unknown reasons, the casing above the seam is cemented at the top and bottom, but not in the middle. The middle section is the area in which the splits occurred. (One borehole was "cased" with PVC pipe, and appears to be broken in several places, even though a wireline log was run to its reported total depth). Attempts to repair the casing were unsuccessful, and Stroud abandoned those wells.

Stroud originally believed that the intake and exhaust air shafts (F-2, F-3, and F-4 in Figure 3) would be the best means of efficiently producing gas from the abandoned mine with little pressure loss. However, none of these shafts ultimately proved useable for this purpose, due to near-surface cracks in the concrete that allowed air to enter when a vacuum was applied. Stroud did produce methane from the F-2 shaft from August 1997 through January 1998, but when they began to produce gas from boreholes on the north side of the river, F-2 began drawing in unacceptable quantities of air, forcing them to discontinue production from this shaft. Stroud has since made efforts to only produce gas from boreholes located as far from the shafts as possible.

Initially, air contamination from leaking drainage boreholes hindered the project because it diluted the gas below pipeline requirements. Stroud solved the air contamination problems by sealing the shafts and boreholes, and by reducing suction to a level that did not pull in excessive amounts of air.

Basin Resources had reported that airtight shaft doors between the north and south areas were closed when the mine was abandoned. Consistent positive pressures on the north and south sides suggested that the two sides of the mine were indeed isolated. Stroud conducted further tests, and injected mercaptan (gas odorant) into the boreholes on the north side. They did not find any evidence of the mercaptan in the producing boreholes in the south side, further suggesting that the two sides were isolated. However, when Stroud began producing gas from the northern wells, there was a nearly identical loss in volume of gas produced from the southern wells. This demonstrates that there is excellent communication throughout the mine, even though the doors between the north and south sides are reportedly closed. This communication may be a result of the collapse of roof strata over the mined out panels, increasing exposure to any fracture systems that connect the north and south areas of the property. As to the inability to detect the mercaptan on the south side, it apparently became too diluted to detect, perhaps as a result of adsorption by the coal. Alternatively, it is possible that airlocks were not closed as was originally reported.

Stroud has found that gas production is directly affected by barometric pressure. With only two ounces per square inch of surface shut-in pressure, the wide barometric pressure swings experienced determine the amount of air influx into the mine, and the amount of gas available for sale. High barometric pressure increases the air content and reduces gas sales, while low barometric pressure reduces air content and consequently increases gas sales. Stroud routinely monitors the barometric pressure to anticipate problems and, when necessary, slows certain compressors in order to minimize air influx during high pressure periods.

Figure 3 is a structure contour map on top of the Maxwell Seam showing the locations of the boreholes and shafts. Performance tests indicated that methane in the main mine entries was rapidly depleted and not likely to yield economic gas flow rates. Interference between inter-shaft boreholes was common. The E-1A group of boreholes (including E-1A, GE-33-88, and GE-35-88) in the southeast, and the GE 63-92 borehole in the southwest are

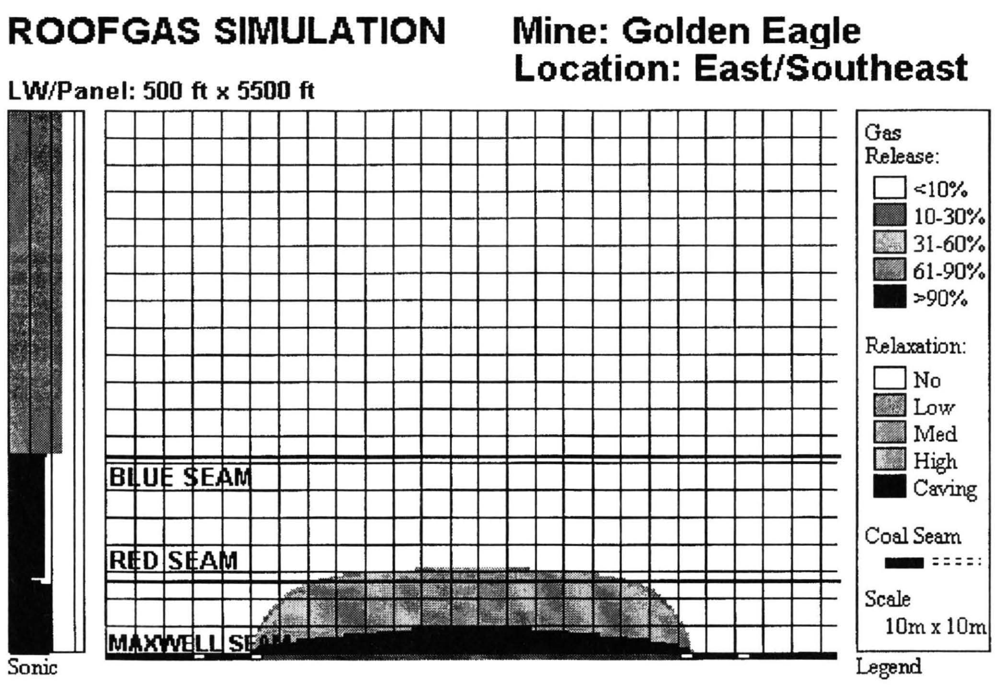

Figure 7. Results of relaxation modeling 100 feet from the end of the longwall panel.

two producing areas that, based on Basin Resources records, were sealed from the main entry because of excessive gas encountered due to faults in the room and pillar section of the mine. These boreholes are in the room and pillar section of the mine (south of the river). The other two boreholes currently producing are GE 69-93 and GE 75-94, both north of the river. Since Stroud tied in the latter two wells, the other wells on the north side of the river have consistently been on a vacuum, and overall gas production did not increase as much as anticipated. Again, this may be due to collapse of the roof rock, giving access to fracture systems connecting the north and south areas of the mine property.

ASSESSMENT OF GAS PRODUCTION POTENTIAL

Using the Roofgas™ overburden relaxation model, the potential extent of roof strata involvement in gas migration into the abandoned workings was determined. The modeling indicated that at only 100 feet behind the mine face (or from any load-bearing pillar), roof relaxation has reached the Red Coal Seam (Figure 7). Within 500 feet of the mine face, the Red Coal Seam is in the highly relaxed zone, and relaxation has reached the Blue Coal Seam (Figure 8). The presence of these overlying coal seams in the relaxed zone indicates that they are partially in the gob, and likely to contribute a significant amount of gas to the current production. This is especially true for the Red Coal Seam, which falls in the highly relaxed zone of the roof and appears to be the gassiest seam according to desorption data. It is likely that as the Maxwell Coal Seam becomes increasingly depleted, the major contributor of gas production may become the Red Coal Seam. This is especially true for, but not necessarily restricted to, the areas that were mined by the longwall method.

The results from the Roofgas™ simulation, along with lithologic data supplied by Basin Resources, were input to Porflow™. Porflow™ is a finite difference model for fluid flow through porous media. The results from this modeling indicate that most of the gas originally in the gob has migrated into the workings and been emitted. The model results indicate two significant features of the gas migration into the workings. The first is that the hydrostatic pressure in the relaxed roof strata is reduced to atmospheric. This indicates that the gas migrating into the workings is almost all from the coal remaining at the margins of the mined-out workings. The second significant feature is the high pressure "bulge" in the vicinity of the Red Coal Seam. This indicates, as predicted by the gas content data and the Roofgas™ output, that the Red Coal Seam is a major contributor to the gas migrating into the workings.

It is possible that positive pressures observed on the northern wells during production from the southern area may be due to shallower coals exposed during collapse of the overburden as a result of longwall mining. Stroud attributes areas of low gas production to shallow coals, and high gas production to faults in the Maxwell. Other Raton coal seams are known to exist in the mine area, but these other coals are not in the affected collapse zone and this methane could be developed only through conventional coalbed methane production practices.

Based on the performance of wells to date, it appears that increased rates of production from the abandoned Golden Eagle Mine are not likely. However, it is likely that the boreholes will continue to produce commercial

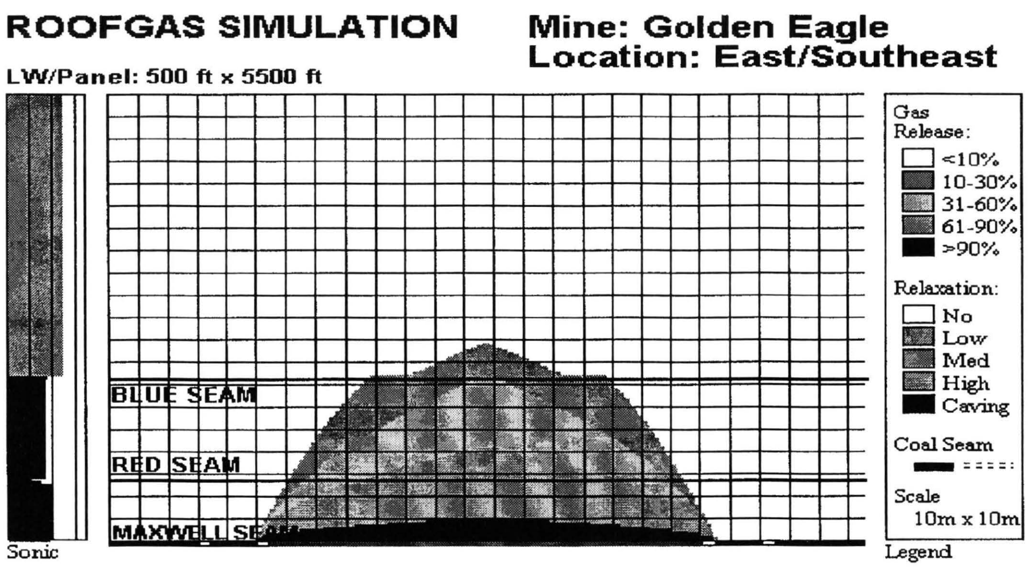

Figure 8. Results of relaxation modeling 500 feet from the end of the longwall panel.

quantities of gas for many years to come. Desorption testing performed in 1994 on eleven core samples taken from the Golden Eagle mine indicates a very slow rate of desorption. Data collected on methane production from other non-flooded abandoned mines (for example, the Nelms Mine in Ohio) indicate that gas production from abandoned mines tends to decline very slowly compared to typical conventional natural gas wells. Preliminary predictive calculations of future long-term methane emission rates, using a recently developed methodology (U.S. EPA, 1998) indicate that production rates will remain relatively steady for several years.

Stroud has also purchased the methane rights to the nearby New Elk Mine. The New Elk Mine is abandoned, but unlike Golden Eagle it was never reported to be gassy. A few shafts are still open, and Basin is monitoring them. Efforts to test these shafts using a compressor were unsuccessful. As of this report, Stroud has elected not to recover gas from the New Elk Mine.

SUMMARY

Methane production from the abandoned Golden Eagle Mine is commercial. The project produces coal mine gas from pre-existing gob drainage boreholes, and has also produced gas from mine ventilation shafts. Currently, the mine produces about 1.8 mmcfd of coal mine gas from six boreholes. Since the heating value of this coal mine gas is slightly below pipeline quality, Stroud blends it with approximately 2.2 mmcfd of higher-heating value gas produced from a nearby conventional coalbed methane field. Preliminary calculations indicate that the production rate of the coal mine gas wells will decline slowly relative to conventional coalbed methane wells.

Some experimentation was necessary to find the optimal number of boreholes and production rates. Since the beginning of the project in 1996, gas has been produced from 17 different boreholes and three mine ventilation shafts, though never from more than 11 boreholes/shafts at any given time. Stroud had assumed that production would increase substantially when boreholes from the north side of the property were hooked up to the gathering system. However, despite the fact that the north side of the mine was sealed off from the south side, communication between the two mine areas has been evident in the mine's gas production patterns. This may be due to collapse of the roof rock, giving access to fracture systems connecting the north and south areas of the mine property.

The success of this coal mine gas recovery project suggest that there may be opportunities for profitable coal mine methane projects at other gassy abandoned coal mines in the United States and elsewhere.

ACKNOWLEDGEMENTS

The authors wish to thank the U.S. Environmental Protection Agency for supporting the preparation of this paper, and George R. Jones of Stroud Oil Properties, Inc. for allowing the data to be published. James Marshall of Raven Ridge Resources, Incorporated provided valuable insight and editorial comment. James Huddleston of Raven Ridge Resources, Incorporated performed the overburden relaxation modeling and finite difference modeling. Ron Thompson of Basin Resources provided helpful information about geologic and hydrologic characteristics of the mine.

REFERENCES

Doupé, T., and Thompson, R. (1996), "Geology of the Golden Eagle Mine Coal Deposit," Internal Report obtained from Stroud Oil Properties Inc.

Fleshman, J. and Stanton, M.C. (1995) "Accident Investigation Report – Underground Coal Mine Fatal Fall of Roof Accident," U.S. Dept. of Labor (MSHA), October, http://www.msha.gov/FATALS/.

Kuhn E.A. (1990), "Directory and Statistics of Colorado Coal Mines with Distribution and Electric Generation Map, 1989," Colorado Geological Survey Resource Series 29.

Johnson, R.B. (1961), "Coal Resources of the Trinidad Coal Field in Huerfano and Las Animas Counties, Colorado," U.S.G.S. Bulletin 1112-E.

MSHA (1996), "Safety Standards for Underground Coal Mine Ventilation – Final Rule," MSHA Federal Register Document Rules and Regulations, Volume 61, No. 18, Page 2543, http://www.msha.gov/regs/fedreg.

Stevens, S.H., Oldaker, P., Lombardi, T.E., Kelso, B.S., and McBane, R.A. (1993), "Geologic and Hydrologic Controls on Coalbed Methane Resources in the Raton Basin," *Proc. Int. Coalbed Methane Symp.*, May 17-21, Volume 1, p. 69-78.

Thompson, R. (1998), personal communication between Ron Thompson of Basin Resources, Weston, CO, and Carol Bibler.

U.S. EPA (1994), "Identifying Opportunities for Methane Recovery at U.S. Coal Mines: Draft Profiles of Selected Gassy Underground Coal Mines," EPA 430-R-94-012.

U.S. EPA (1997), "Identifying Opportunities for Methane Recovery at U.S. Coal Mines: Draft Profiles of Selected Gassy Underground Coal Mines," EPA 430-R-97-020.

U.S. EPA (1998), "Draft Analysis of Abandoned Coal Mine Methane Emissions Estimation Methodology," prepared by Raven Ridge Resources, Incorporated for U.S. EPA's Coalbed Methane Outreach Program.